5. CHAPTER 5: INCENTIVISING FLOOD RISK ADAPTATION THROUGH RISK-BASED INSURANCE PREMIUMS - TRADE-OFFS BETWEEN AFFORDABILITY AND RISK REDUCTION[1]

Abstract

The financial incentives offered by the risk-based pricing of insurance can stimulate policyholder adaptation to flood risk while potentially conflicting with affordability. We examine the trade-off between risk reduction and affordability in a model of public-private flood insurance in France and Germany estimating household flood adaptation decisions in response to financial insurance incentives. An integrated model of household-level mitigation behaviour and insurance premiums is developed. The model investigates how aggregated household adaptation behaviour differs under financial incentives as compared to when households act on their own subjective risk beliefs. The results indicate that insurance based incentives are able to promote adaptation. The incentives could reduce residential flood risk by 12% in Germany and 24% in France by 2040. The higher level of flood risk in France results in a strong present incentive to reduce risk. Rapid growth of flood risks in Germany results in more effective incentives in later periods. Insurance is unaffordable for approximately 20% of households at risk. The cost of insurance vouchers, to correct for unaffordability, is lower than the total incentivised damage reduction after 2040. A policy recommendation is that strengthening the link between flood insurance and financial incentives can guide household-level adaptation

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5.1 Introduction

The previous chapters have highlighted the view that flooding has a great effect on humanity (UNISDR, 2011) and that a combination of socio-economic development and climate change means that flood risk could increase in the future (Jongman et al., 2014). Therefore, there is a growing interest in strategies that can be effective in adapting to future flood events; these strategies include both disaster risk reduction measures, such as flood-proofing buildings (Aerts et al., 2013), and financial risk transfer instruments, such as flood insurance (Botzen and van den Bergh, 2008). Insurance allows individuals to cope with risk by sharing financial risks across policyholders. However, insurance may become less attractive for households when insurance companies raise premiums to reflect increases in the underlying risk (Botzen et al., 2009a). The challenge is to design an insurance scheme that is affordable while offering financial protection and incentives for policyholders to reduce risk (Kunreuther, 1996; Botzen et al., 2009b; Kunreuther and Michel-Kerjan, 2009; Mechler et al., 2014; Penning-Rowsell and Pardoe, 2012; Surminski and Oramas-Dorta, 2014).

Risk-based insurance pricing is a key condition for incentivizing both risk reduction and the willingness of insurers to offer coverage (Blanchard-Boehm et al., 2001; Kunreuther and Michel-Kerjan, 2009). The reason for this is that it allows insurers to match premium income with the expected indemnity payments (Kousky and Kunreuther, 2013). Moreover, such a policy acts as a price signal of risk by charging premiums according to the risk encountered. This signal can provide an incentive for household-level adaptation if an insurer provides a premium discount to policyholders who reduce their risk; for example, risk can be reduced by having flood-proofing buildings.

The relevance of providing financial incentives to promote individual flood risk adaptation can be found in the observation that few floodplain inhabitants voluntarily invest in cost-effective flood risk reductions (e.g., Kreibich et al. 2005). Such behaviour can be explained by several individual decision-making processes (Kousky and Cooke, 2012). For example, many individuals underestimate flood risk and the benefits of reducing it (e.g., Bubeck et al., 2013; Poussin et al., 2014). Offering premium discounts means that the decision to invest in disaster risk reduction by policyholders is simplified to comparing the costs of the measure using premium discounts instead of the perceived risk reduction benefits, which are often

underestimated. However, the effectiveness of such financial incentives has hardly been studied empirically (Surminski, 2014). An exception is Botzen et al. (2009b) who used survey methods to show that many Dutch homeowners express the intention to take such measures for financial rewards.

Risk-based pricing and affordability are potentially contradictory aspects of the insurance scheme since risk-based premiums can make insurance contracts unaffordable for some households (e.g., Kunreuther and Michel-Kerjan, 2009a). This may be inferred from Zahren et al. (2009) who show that flood insurance uptake is positively related to community-wide implementation of flood risk reductions in the USA; the implementation is rewarded through premium discounts from the Community Rating System. However, flood insurance premiums in the USA are not fully risk-based, and that study did not examine the affordability of risk-based flood premiums for low-income individuals (Zahren et al., 2009; Michel-Kerjan et al., 2015).

To make flood insurance affordable, it is sometimes provided through public–private partnerships in which the government covers part of the risks instead of a private reinsurer (e.g., Paudel et al., 2012) or premiums are subsidized (Burby, 2001). Subsidization of premiums improves affordability, but this results in policyholders not fully made aware of their risk and thus generates incorrect incentives for risk management. This situation can be overcome by providing the subsidy in the form of a temporary voucher for low-income households, and the cost can be covered using overall taxation, as proposed by Kousky and Kunreuther (2013).

This chapter conducts an analysis of the effectiveness of flood insurance premiums as a means to provide financial incentives that can encourage policyholders to invest in flood-proofing measures, which can promote adaptation to changing future flood risk. The potential trade-off between risk reduction and the affordability of risk-based premiums is also investigated. In addition, this study develops a model of public–private flood insurance, which is combined with both a model of household flood preparedness decisions and a flood risk model that provides input for estimating insurance premiums at an aggregated level. The behavioural model is based on a cost-benefit framework that accounts for the role of individual risk perceptions and the perceived risk reduction of flood-

proofing in individual decision making as well as insurance incentives. Although this chapter's application focussed on France and Germany, there is a wider interest in linking natural disaster insurance and risk reduction incentives in the EU as is reflected by the publication of a Green Paper on this topic (European Parliament, 2013).

5.2 Methods: Integrated insurance, household flood preparedness and flood risk model

5.2.1 Insurance model

5.2.1.1 Modelled insurance scheme

It has been argued that the French and German insurance markets can provide better incentives for risk reduction. France has a compulsory natural hazard insurance scheme known as CatNat with flat-rate premiums unrelated to the natural hazard risk faced. This scheme offers reinsurance by the Central Fund for Reinsurance (CCR), which is owned by the French state. CatNat aims to promote risk reduction through risk prevention plans, which are community level plans to manage risk by using zoning regulations or by requiring households to employ risk reductions. The lack of risk-based pricing weakens the incentives for policyholders to go beyond these minimum requirements. Several studies have suggested differentiating CatNat premiums according to the risk faced by policyholders to provide stronger incentives for risk reduction (e.g., van den Bergh and Faure, 2006; World Bank, 2012; Poussin et al., 2013). Germany currently has a voluntary insurance scheme with a low take up rate of 19% for contents insurance and 33% for residential building insurance (GVD, 2013). Flood insurance premiums are based on the flood probability, but insurers do not actively promote household investments in risk reduction (Thieken, 2006). Moreover, the German government is able to provide ad-hoc disaster relief payments after natural hazard events occur. This kind of assistance can hamper the functioning of the private flood insurance market by introducing charity hazard. This charity hazard implies a reduction in demand for flood coverage since uninsured individuals expect compensation for flood damage from the government (Osberghaus et al., 2010; Raschky and Weck-Hannemann, 2007). Nevertheless, in voluntary insurance markets, ad-hoc disaster relief is important from a social perspective because uninsured households can receive assistance for recovery in the aftermath of a flood. Schwarze and Wagner (2007) have called for a scheme that promotes affordability by making flood insurance

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compulsory and by having the state cover part of the flood risk. In addition, investments in risk reduction should be encouraged by financial insurance incentives.

This study examines the introduction of a hybrid insurance scheme of the current French and German insurance market structures. The features of the proposed scheme are presented in Table 5.1 and are based on the work by Paudel et al. (2012). This insurance covers flood damage that is done to residential properties. Lamond and Penning-Rowsell (2014) state that a robust insurance scheme spreads insurable risk across a population that is aware of the risk faced and can afford the premiums charged. Moreover, they suggest there should be mechanisms in place to provide capital to insurers in case of abnormally large losses; for example, one possible mechanism is reinsurance. They also argue that an insurance scheme should integrate incentives for risk reduction as a mechanism to reduce potential pressure placed on the scheme in the future. Combining the above components of risk transfer, risk pooling and proactive risk reduction into a coordinated scheme helps to produce the optimal portfolio of economic risk management (Porcini and Schwarze, 2014). In addition, such a coordinated scheme across a country can have the effect of providing accurate information for policyholders to act upon the risk they face (Filatova, 2014).

The insurance scheme presented and investigated in this current chapter is concerned only with fluvial (river) flood risk, which is common for flood insurance applications as Blanksby and Ashley (2013) argue (see also Jongman et al., 2014; Aerts and Botzen, 2011). However, it must be noted that while this study will focus on riverine floods, flash floods are a major cause of flood damage as well. The investigated scheme is a layered public−private partnership where policyholders, private insurers, and a government reinsurer cover different parts of the flood losses incurred. The distributions of risks among these stakeholders are based on the optimal allocations as found in the work by Paudel et al. (2015). The objective of the study by Paudel et al. (2015) is to gain an insight into efficient and practically feasible allocations of risk in a public−private flood insurance system. In particular, Paudel et al. (2015) develop a model to estimate economically optimal deductible levels for policyholders and stop-loss levels for insurers that determine the proportion of losses that will be reinsured. They estimate that the optimal deductible level is 15%; primary

insurers cover damage between 15% and 84% and reinsurers cover the remainder that can be considered insurable. Losses beyond the insurable damage (assumed to be past the 99.9 tail value at risk) are covered by the government. This arrangement provides sufficient capital in the case of extreme events; this is made possible due to the borrowing and taxation powers of national governments.

The government can provide a voucher paid for by general taxation in order to overcome potential problems with flood insurance unaffordability (see Section 5.2.1.4). An additional role taken up by the government is to maintain a constant level of flood safety standards. This means that the government alters the height of dikes to match changes in the predicted water height due to future climate change, as proposed by Kundzewicz et al. (2010). For example, flood defences are built in 2015 at 1m above the expected water height of a flood that occurs with a probability of 1%. By 2050, the height of these defences has been increased to 3m to match the expected increased water height of a flood with a probability of 1% at that time. In other words, the government responds to changing hazard conditions by maintaining the flood probability that is currently deemed acceptable.[2]

The insurance scheme is mandatory for households that can be affected by river flooding, while households that do not face flood risks are not required to purchase the insurance. We define households as being vulnerable to flooding if they face a 0.2% annual exceedance flood probability or higher, which is the best estimate of the total number of households at risk of flooding[3].

Premiums are connected to risk because they are based on the average flood risk within a regional pool, and premium discounts are related to risk reduction measures implemented by the specific policyholder. Insurance premiums (as a baseline) are set at a NUTS 2 region level, which can be interpreted as risk pools (see Section 5.2.1.3). A NUTS 2 region is an EU

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[2] Alternatively, the government could maintain an economically efficient level of flood protection (Kind, 2014). Here the focus is on maintaining an acceptable level of safety standards, as has been argued to be a better reflection of actual government flood risk management policies (e.g., Jongman et al., 2014; Turner, 2007).

[3] Kunreuther and Michel-Kerjan (2009) argue that the 0.2% flood probability is an acceptable cut-off threshold for determining those not at risk of flooding since low probabilities imply a negligible risk.

geocode for spatial analysis.[4] Not all residents in a NUTS 2 region are at risk of flooding, which is accounted for by estimating risk and premiums only for households that face flood risk. A NUTS 2 region is rather large, but it is considered a suitable regional classification for the following reasons. First, this is the most detailed resolution for which flood risk data is available for a countrywide insurance-based assessment for Germany and France (Section 5.2.1.2); using more detailed data would be computationally very demanding. In practice, using more detailed data, such as a household-level assessment of premiums, would entail very high transaction costs for insurance companies, and hence it would be infeasible (Porrini and Schwarze, 2014). Moreover, such information is not freely accessible (Osberghaus, 2015). Second, the obligation to buy insurance along with the geographical size of the pool in which many risks are spread eliminates concerns about adverse selection (Porrini and Schwarze, 2014). Third, pooling risks in a larger area implies a degree of cross-subsidization of premiums, and this makes flood insurance more affordable (Schwarze and Wagner, 2007). There are 38 regional pools in Germany and 22 regional pools in France. The base premium charged in each regional pool is based on the average risk within a pool. Therefore, the average premium within a pool is initially flat, while the average premium differs between regions. Policyholders are promoted to invest in flood risk reductions through the use of premium discounts. Households only receive a premium discount for mitigation when they have applied the risk reduction in their home (Section 5.2.1.3). Offering premium discounts only to households that employ risk reductions further differentiates premiums. Thus, the financial incentive for mitigation operates on an individual level. Moreover, the deductible of 15% of the damage incurred is a part of each policy, and it acts to prevent moral hazard. The financial incentives are a key element of the investigated scheme since the overall risk faced in a region is reduced when these incentives are in place.

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[4] The German NUTS 2 regions correspond to a *Regierungsbezirke* with an average population of 2.2 million. NUTS 2 regions in France correspond to *Région* with an average population of 2.5 million. However, not all are at risk of flooding. Approximately 3% of households within NUTS 2 regions in both France and Germany are at risk of flooding by this chapter's estimates.

Table 5.1 Features of a public-private flood insurance scheme

Feature	Description
Public sector responsibility	Maintain flood protection standards; provide reinsurance; provide vouchers to overcome insurance unaffordability
Private sector responsibility	Provide (re)insurance policies at the predetermined rates
Risk zoning and risk maps	Yes at the level of NUTS 2 regions
Damage covered	Residential property and contents damage
Policy deductibles	15% of damage suffered
Premium setting rule	Risk-based between NUTS 2 regions; flat within regions; alters due to risk reduction actions at an individual level
Reinsurance	Risk neutral government reinsurer for rare flood events; private reinsurers cover more common events
Purchase requirement	Flood coverage is compulsory for households at risk of flooding
Risk reduction incentive	Premium discounts

5.2.1.2 Flood risk model

The first step in developing the integrated model of insurance premiums and household risk reduction activities is to produce an estimate of the flood risk in a region. Moreover, the spatial extent of flood-prone areas is estimated in order to determine the households that participate in the flood insurance scheme.

A coupled hydrological-flood damage model at the European scale is used to estimate the risk of riverine floods. These flood risk estimates are used as an input for calculating insurance premiums. Details of the model and the modelling are found in Feyen et al. (2012), Rojas et al. (2013), and Jongman et al. (2014). In this model, the loss from a flood with an occurrence probability of p in region j at time t for a given occurrence probability $[L(p)_{j,t}]$ is a function of hazard $[H(p)_{j,t}]$, exposure $(E_{j,t})$, and vulnerability $(V_{j,t})$, as shown in eq. (5.1).

$$L(p)_{j,t} = f\big(H(p)_{j,t}, E_{j,t}, V_{j,t}\big) \tag{5.1}$$

This study uses socio-economic and climate change projections to estimate future values for exposure. Socio-economic projections at a national level

were obtained from the Center for International Earth Science Information Network (CIESIN).[5] This data enables us to estimate the future value of exposed assets where the ratio between the future and baseline GDP is used as a rescaling value. The exposure growth scenario is a uniform regional exposure growth rate that matches the national exposure growth rate. Climate change projections based on the SRES A1B greenhouse gas emissions scenario were used to simulate changes in flood hazard in view of climate change. Land use classifications are assumed to remain constant over time; due to this assumption, changes in exposure alter the value of land parcels.

Vulnerability is accounted for in the flood risk model in two ways. The first is through the state-damage curves used to convert inundation depths into monetary damage values. Each land exposure class has a separate state-damage curve, whereby less vulnerable land classes require a greater degree of inundation to suffer the same degree of damage as compared to more vulnerable land classes. The second is through the employment of risk reduction measures. When more measures are employed, vulnerability is reduced more considerably (see Table 5.2 for an indication of by how much).

5.2.1.3 Premium and discount rules

The insurance premium is calculated following the price rule developed in the work by Paudel et al. (2015). A key element of the insurance premium is presented in eq. (5.2), which is the expected net insured loss (NIL) for region j at time t. For a flood of a given occurrence probability (p) in region j at time t, the net insured loss is the difference between the losses suffered and the deductible $D(p)$. The expected net insured loss is given by the probability weighted integral of the net insured losses for a range of flood events generated by the flood risk model. The probability range used to establish the integral bounds is determined by the protection standards present in a region.

$$E\big(NIL_{j,t}\big) = \int_0^{\bar{p}} p\big(L(p)_{j,t} - D(p)_{j,t}\big)dp$$
(5.2)

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

The term $\bar{\pi}_{j,t}$ in eq. (5.3) presents the regional baseline for the insurance premium, which is set at the start of the period t. The regional baseline is the expected net insured loss with an additional surcharge for the risk aversion of the insurers, which is given by the product of insurer risk aversion (r) and the variance of losses over the range covered by private insurers ($\sigma_{0 \leq L < \gamma}$). The constant γ is set at the 99.8[th] quantile. This means that a risk neutral government provides reinsurance for flood events with an occurrence probability of 0.2% or smaller following the suggestion of Schwarze and Wagner (2007) for extreme events. The coefficient r indicates the degree of insurer risk aversion and is set at 0.0005.This estimate and functional form is based on the work by Paudel et al. (2015), who based this estimate on a literature review of estimates of insurer risk aversion to natural disaster risk. Average baseline policyholder premiums are estimated for each period by the division by the number of households (NH) region j at time t in eq. (5.3). In other words, the baseline premium depends on both risk and the number of households in a region. The average premium is sensitive to the number of households because the expected annual damage is independent of the number of households. Therefore, allocating the population at risk to a greater number of households will result in premiums falling as there are more policyholder units to share total damage.

$$\bar{\pi}_{j,t} = \left(\frac{E\left(NIL_{j,t}\right) + r * \sigma_{0 \leq L < \gamma}}{NH_{j,t}} \right) \qquad\qquad (5.3)$$

A household that employs a given risk reduction measure will receive a discount to their premium that is proportional to the effectiveness of the measure. The reduction in the baseline premium is given by the effectiveness ratio (ER_{DRR}), which differs depending on the kind of risk reduction measure. The effectiveness ratio is calculated as the ratio of the average damage prevented by a particular measure relative to the average damage suffered during a flood event see eq. (5.4).

$$ER_{DRR} = \frac{Damage\ Prevented_{DRR}}{Average\ Damage} \qquad DRR = \{Dry\ flood-proofing, Wet\ flood-proofing\}$$
(5.4)

The estimates of risk reduction measure effectiveness are taken from Chapter 3; average damage suffered is taken from the work by Kreibich et al. (2011). Household flood risk reductions can be broadly categorized into dry or wet flood-proofing methods. Dry flood-proofing measures attempt to

prevent water entering a building; an example of this is the use of mobile flood barriers. Wet flood-proofing measures aim to limit the damage once water has entered a building; an example of this is the use of adapting interior fittings to flooding. Financial incentives are only offered for this sub-set of risk reducing measures because this is a common feature of insurance schemes in practice (see e.g., Surminski et al., 2015); it is possible that this feature is used for the reason of minimizing the transaction costs of offering premium discounts. This study focuses on these particular measures because Chapter 3 showed that these two measures have been effective in limiting flood damage during a major flood event. The uncertainty around the risk reduction from the measures is modelled using the 95% confidence interval around the prevented flood damage ratios in Table 5.2 in order to capture both the uncertainty in risk and mitigation effectiveness.[6] The values are {0.082, 0.174} for the selected dry flood-proofing measure and {0.191, 0.301} for the wet flood-proofing measure. The households may employ either or both of the investigated measures.

The final premium that is offered to a household is displayed in eq. (5.5). In case a household employs a risk reduction measure, the premium is then lowered in line with the first element of eq. (5.5); otherwise they are charged the baseline premium, which is the second element of the eq. (5.5) that is set at the start of period t.

Table 5.2 A summary of the benefits and costs of household flood risk reductions

Name of risk reduction measure	Description	Effectiveness ratio (upper/lower bound)	Investment cost (upper/lower bound)
Wet flood-proofing (DRR=1)	Avoid valuable fixed units and or interior fittings in flood endangered floors	0.246 {0.191,0.301}	€2,389 per building[a] {€800,€7250}[b]
Dry flood-proofing (DRR=2)	Mobile barriers to prevent water entering the building	0.128 {0.082,0.174}	€471 per building[c] {€$^{265,€845}$}[b]

Notes: [a] The estimate is based on (Aerts et al., 2013) and has been converted into EUR from USD using the average PPP exchange rate over 2004-2011.
[b] Based on Poussin et al. (2015).
[c] Estimated on the basis of communications with: www.boxbarriers.com; www.slamdam.nl

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[6] This was calculated by assuming a normal distribution and using the variance of dry or wet flood-proofing measure effectiveness from Chapter 3 and the variance of the risk data from Kreibich et al. (2005). The confidence interval is calculated as $ER \pm 1.96 * \sqrt{Var\left(\frac{Damage\ Prevented}{Damage\ Suffered}\right)}$.

Separate discounts are offered for each measure employed. Therefore, premiums are further differentiated at the household-level based on the risk reductions implemented. This implies that incentives to free ride on mitigation investments from others are limited since households who do not employ risk reductions are not eligible for premiums discounts. The baseline premium also does not change due to the employment of risk reduction measures. In both cases, insurers will charge a fixed loading factor (λ) in order to cover the costs of conducting business. The loading factor is assumed to equal 30% of the baseline premium as is common in the insurance literature (e.g. Gollier, 2003).

$$\pi_{i,j,t} = \begin{cases} (1 + \lambda)(1 - \sum ER_{DRR,i})\bar{\pi}_{j,t} & \text{if DRR measure(s) is employed} \\ (1 + \lambda)\bar{\pi}_{j,t} & \text{if no DRR measure(s) is employed} \end{cases} \quad (5.5)$$

The number of households at risk of flooding in a regional pool $NH_{j,t}$ is an important factor in calculating the premium to be charged. This number changes over time in accordance with eq. (5.6) where $P_{j,t}$ stands for regional population within a regional pool and $\left(\overline{\frac{NH}{P}}\right)_j$ is the average ratio of households to population within a region:

$$NH_{j,t} = P_{j,t}\left(\overline{\frac{NH}{P}}\right)_j \quad (5.6)$$

$P_{j,t}$ is based on the results given by Rojas et al. (2013), who provide an estimate of the number of people at risk of a flood event under the SERS A1B climate scenario while assuming a constant population. In this study, changes in future population are accounted for by rescaling the baseline number of people exposed to flooding based on a regionally disaggregated EUROPOP2010 projection up to 2060.[7] This projection assumes a constant number of individuals per household based on the ratio of average households and population over 1999–2013. However, this may be an underestimate of the number of households since there may be a movement towards more single occupant households. This implies that the estimate for future households is a possible lower bound.

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[7] The SERS A1B and EUROPOP2010 population projections differ slightly. However, they both follow the same trends. The EUROPOP2010 projection has been used as it is more suitable for further regional differentiation.

5.2.1.4 Affordability of insurance and insurance vouchers

A common approach to judge the affordability of expenditure is based on residual income (e.g., Blumberg et al., 2007; Stone, 2010). This approach regards insurance coverage as unaffordable when both the insurance premium and the expected value of the deductible exceed a certain percentage of disposable income (Blumberg et al., 2007). There is also a strand of literature arguing that individuals should not be forced into poverty because of insurance (e.g. Kunreuther and Michel-Kerjan, 2009). In Europe, the poverty line is officially defined to be at 60% of median disposable income. Given the importance of preventing poverty, insurance is considered to be affordable when purchasing it does not reduce a household's disposable income below the poverty line.

The affordability indicator is presented in eq. (5.7). In eq. (5.7), q is the qth percentile, $Income_{j,q}$ is the qth income percentile in region j, $E(D_{i,j,t})$ is the expected deductible, and the poverty line is taken using the national poverty line.

$$affordable_{j,q} = \begin{cases} 0 & if\ \pi_{i,j,t} \geq Income_{j,q} - Poverty\ Line - E(D_{i,j,t}) \\ 1 & if\ \pi_{i,j,t} < Income_{j,q} - Poverty\ Line - E(D_{i,j,t}) \end{cases} \quad (5.7)$$

In eq. (5.7), insurance is unaffordable if affordable$_{j,q}$ = 0 as insurance costs would cause a household to fall below the poverty line. Eq. (5.7) is estimated using the disposable income of the average households in 2011, which was the last year for which regional income data is available. The 2011 income level is adjusted for changes in exposure (see Section 5.2.1.2). Moreover, by assuming that the national household income distribution is applicable to a NUTS 2 region, the percentage of households that cannot afford insurance is estimated. Income growth is modelled by shifting the income distribution rightward while keeping a constant shape.

Kousky and Kunreuther (2013) propose that providing vouchers can overcome unaffordability of flood insurance. An individual receives a voucher if eq. (5.7) is equal to 0 with a value equal to the difference between the insurance premium and the affordability threshold up to the value of the insurance premium. For example, if the premium is €100 and there is a residual income (above the affordability threshold) of €60, the voucher should is valued at €40. This allows for affordability concerns to be eased while the deductible remains.

However, the voucher can act as an indirect premium subsidy, which stimulates development in flood-prone areas. Therefore, it should be phased out and only offered to current residents and not to new residents in flood-prone areas (Kousky and Kunreuther, 2013). In order to model these features and to move away from the composition of households, only households present in the starting year of the program are eligible for a voucher. Moreover, the percentage of the insurance premium that the voucher covers falls by 5 percentage points a year. Thus, after 20 years the voucher will no longer be offered. The cost of starting such a voucher scheme will be investigated at different points in time, namely for the years 2015 and 2040. The purpose is to illustrate how these costs may develop as a result of future socio-economic development and climate change.

5.2.2 Behavioural model of household flood risk adaptation investments

5.2.2.1 Decision rules

The behavioural model of household-level adaptation estimates how many households invest in the two flood risk reductions under conditions that are with financial incentives from insurers and also without these incentives. If financial incentives for mitigation are not offered, households will then base their decisions on their subjective beliefs about the benefits of dry and wet flood-proofing measures.

It is assumed that the decision-making process is based on subjective expected utility theory (Savage, 1954). It is assumed that policyholders take investment decisions on the basis of costs and benefits, while the perceived benefits of mitigation can diverge from actual benefits due to over- or underestimating flood risk. Accounting for such misperceptions of risks is important, because even though it is often found that a proportion of people has rational risk perceptions and behaves according to expected utility theory, others deviate from this theory (Hey and Orme, 1994; Harrison and Rustrom, 2009; Conte and Hey, 2013). Such deviations can result from probability weighting; this can be seen in Prospect Theory, for example. In addition, bounded rationality may explain why individuals are uninformed about the objective risk because of the presence of (intangible) costs of gathering information regarding low-probability risk (Kunreuther and Pauly, 2004). In this study, such deviations from rationality are accounted for by allowing decisions to be made on subjective risk beliefs, which may deviate from objective risk, as will be discussed in the calibration of risk perceptions in Section 5.2.2.2.

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Households can consider investing in each measure separately. Eq. (5.8) shows that the benefits of investing in a dry or wet flood-proofing measure ($\omega_{i,j,t}$) are different and are dependent on whether a financial incentive is present or whether the household must base their decision on their perceived benefits. The first element of eq. (5.8) is the case of financial incentives and the benefit is the premium discount, while the second element in the equation is the case where households base their investment decision on their perceived benefits. The perceived benefits are based on the household's share of the expected regional loss and the potential reduction in these losses. These benefits are converted into subjective benefits via φ_i. The variable φ_i is a random draw for each household from the overall φ distribution of risk perceptions; it is also a rescaling term and will account for the possible misperceptions of the flood probability and the expected flood loss, which is related to the effectiveness of the risk reduction. The purpose of φ_i is to act as a rescaling value, and φ_i can take values over $[\underline{\varphi}(\geq 0), \infty]$. For instance, if $\varphi_i = \underline{\varphi} = 0$, then $\omega_{i,j,t}^{subjective} = 0$ and the household sees no benefit from these measures. If $\varphi_i = 1$, the household's subjective risk reduction benefits equals the objective benefits. A value of $\varphi_i \lessgtr 1$ overestimates (>) or underestimates (<) the benefits of risk reduction.

$$Benefits = \begin{cases} \omega_{i,j,t}^{Incentive} = ER_{DRR}\bar{\pi}_{j,t} \\ \omega_{i,j,t}^{Subjective} = \varphi_i ER_{DRR} \frac{\int_0^{\bar{p}} pL(p)_{j,t}dp}{NH_{j,t}} \end{cases} \qquad (5.8)$$

Once the potential benefits in each period has been calculated, the household will make the cost-effectiveness calculation, eq. (5.10), using the higher value benefit, eq. (5.9). This can be interpreted in the following manner. If a household underestimates the benefits from risk reducing measures, the decision to invest in mitigation is determined by the premium discount. Households that have subjective benefits of mitigation that are larger than the premium discount base their decision to mitigate on their subjective risk reduction beliefs. In other words, these households overestimate the benefits of risk reduction; as a result, they can employ risk reducing measures even if these measures are not cost-effective. These households have an intrinsic motivation to implement risk reduction measures and are unlikely to change their behaviour due to external financial incentives.

$$\omega_{i,j,t}^* = \begin{cases} \omega_{i,j,t}^{Incentive} & if \ \omega_{i,j,t}^{Incentive} > \omega_{i,j,t}^{Subjective} \\ \omega_{i,j,t}^{Subjective} & if \ \omega_{i,j,t}^{Incentive} \leq \omega_{i,j,t}^{Subjective} \end{cases} \qquad (5.9)$$

Once the benefit of mitigation in a time period has been decided upon, the overall investment decision framework is presented in eq. (5.10). In eq. (5.10) a household will decide to invest in a particular risk reduction if the discounted benefits over 20 years are larger than the upfront investment costs, IC_{DRR}. Discrete time discounting is used where the discount rate is given by δ.

$$uptake = \begin{cases} Yes & if \ \sum_0^{20} \left(\frac{1}{1+\delta}\right)^t \omega_{i,j,t}^* - IC_{DRR} \geq 0 \ for \ DRR = 1,2 \\ No & if \ \sum_0^{20} \left(\frac{1}{1+\delta}\right)^t \omega_{i,j,t}^* - IC_{DRR} < 0 \ for \ DRR = 1,2 \end{cases} \qquad (5.10)$$

δ is fixed within nations and is 3.2% for France and 4.3% for Germany (Evans and Sezer, 2005). Households will only consider benefits over a 20 year period (e.g., Kreibich et al., 2011). This can either be viewed as the assumed lifespan of the measures or as myopia.

5.2.2.2 Calibrating the decision rule parameters

A distribution of individual flood risk perceptions is required to estimate φ_i. However, there is no previous research that has estimated the parameters of such a distribution, which is why it is calibrated using existing data. To model the risk perception distribution an appropriate shape for the distribution must be found. In order to select the distribution, a series of left bounded distributions were fitted to survey data of individual risk perceptions. Left bounded distributions are required because the lowest draw should be 0, which reflects individual believes that flood risk and benefits from flood risk mitigation are zero. Data collected in Botzen et al. (2010) and in Botzen et al. (2014) is used to find an appropriate shape. These surveys studied how perceptions of flood probabilities of households compare with objective flooding probabilities. It was found that this variable most closely follows a generalized Pareto distribution, as judged by Bayesian information criteria.

The calibration of the German risk distribution is based on the uptake rates of dry or wet flood-proofing provided in Kreibich et al. (2005) and uses the average risk faced and flood-proofing employment rate in the following NUTS 2 regions: Chemnitz, Dresden, Leipzig, and Sachsen-Anhalt in 2002.

The calibration of the French risk distribution is based on Poussin et al. (2014) for the average risk faced and flood-proofing employment rate in the following NUTS 2 regions: Champagne-Ardenne, Provence-Alpes-Côte d'Azur and Poitou-Charentes in 2011. The calibrated distribution is applied to other NUTS 2 regions in Germany and France by scaling the perceived risk according to the average flood risk per region. This implicitly assumes a representative or average household. Assuming the presence of a representative household implies that a single representative calibrated risk perception distribution is applied to flood-prone regions in France or Germany. The parameters of the calibrated distribution are then assumed to be fixed and applied to the separate NUTS 2 regions using the risk data for that specific region. Therefore, differing regional values of φ^* are calculated to indicate different levels of regional flood-proofing usage.

The PDF of the Generalised Pareto distribution is given by eq. (5.11) and the calibrated parameters in Table 5.3. The parameter θ can be interpreted as a threshold value. In the generalised Pareto distribution, where if k>0 then x can only take values such that $x \geq \theta$.

$$f(x|k,\sigma,\theta) = \left(\frac{1}{\sigma}\right)\left(1 + k\frac{x-\theta}{\sigma}\right)^{-\frac{1}{k}}$$ (5.11)

Table 5.3 Calibrated parameters of the Generalised Pareto distributions

	France			Germany					
	k	σ	θ	k	σ	θ	k	σ	θ
	Baseline						Bubeck et al. (2012)		
Wet flood-proofing	1.91	0.191	0.096	1.61	0.61	0	3.46	0.35	0.18
Dry flood-proofing	0.44	0.044	0.022	1.14	0.114	0.057	1.31	0.13	0.07

Notes: The risk perception distribution is calibrated using survey data from: [a] Poussin et al. (2014); [b] Kreibich et al. (2005); [c] Bubeck et al. (2013).

The parameters of the generalized Pareto distribution are estimated such that the outcomes of the assumed decision rules (Section 5.2.2.1) are consistent with the observed household wet or dry flood-proofing uptake rates. For this purpose, survey data is used from Kreibich et al. (2005) and Bubeck et al. (2013), who examine implementation of dry and wet flood-proofing measures by households in flood-prone regions in Germany; data

for France is taken from Poussin et al. (2014), who examines this for flood-prone regions in France. Such estimates of implementation of the dry and wet flood-proofing measures by households in flood-prone areas are more relevant than such estimates from a national sample, such as the ones provided by Osberghaus (2015) Germany. The reason for this is because only mitigation investments by flood-prone households are modelled in this study.

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

$$\varphi^* = \frac{IC_{DRR}}{ER_{DRR} \sum_0^{20}\left(\frac{1}{1+\delta}\right)^t \left(\frac{\int_{L(PT_j)}^{\infty} p(L_{j,t})\left(L_{j,t}\right)}{NH_{j,t}}\right)} \tag{5.12}$$

The next step is to calibrate the parameters of the distribution in a way where φ^* corresponds to the value of the target quantile. Each risk reduction measure has a separate risk perception distribution in each country. The uncertainty of these distributions are reflected by calculating three of such distribution based on the survey data given by Poussin et al. (2014), Bubeck et al. (2013) and Kreibich et al. (2005). These three estimates are interpreted as three different scenarios of risk perceptions; the resulting parameters can be found in Table 5.3. The calibrated distributions indicate that the majority of households underestimate the overall benefits from dry or wet flood-proofing measures. A minority overestimate such benefits, which is in line with the observation of many studies (e.g., Botzen et al., 2009b; Kunreuther and Michel-Kerjan, 2009).

5.3 Results

5.3.1 Risk-based flood insurance premiums

Table 5.4 summarises the estimated premiums. German insurance premiums increase on average by 77% over 2015–2040 from an average premium of €280 in 2015, while this is 48% for France over the same period from an average premium of €1,100. This large difference in flood insurance premiums is caused by a higher average flood risk per household in France compared with Germany. Other flood risk model studies (e.g., Dumas et al., 2013; Hattermann et al., 2014) produce similar flood risk estimates for these countries as compared with the work by Rojas et al. (2013). This can be explained by lower flood protection standards in many areas of France, which result in a higher annual average flood risk (Lehner et al., 2006). The estimated average flood risk is increasing across all regional pools; however, regional growth rates are quite different, resulting in a higher standard deviation (SD) over time. Moreover, the range of premiums in Germany is relatively wider than in France; the maximum premium in Germany is about 5 times as large as the minimum, while for France it is only 3 times. Risk in France appears to be somewhat more equally spread, while in Germany differences are more pronounced.

The expected premiums grow due to a combination of socio-economic development, population change, and climate change. Out of these three drivers, climate change has the smallest effect, but this effect depends on the scenario used. The hydrological model from Rojas et al. (2012) that underlies this chapter's risk predicts small changes for the areas investigated in the current chapter, due to the diverse magnitudes of regional climate change simulated by the climate models used in the hydrological analysis. Exposure growth has the largest effect as it increases flood risk by 2% per year on average across both Germany and France. This exposure growth especially increases average premiums per household in Germany where the number of households on average decline with -0.54% per year, while in France the number of households grows with 0.2% annually. In other words, the growth in exposed values per household is higher in Germany, which results in a stronger increase in average flood insurance premiums.

Schwarze et al. (2011) estimate a natural hazard insurance premium in Germany between €313-€376 per year with a deductible of 1% of the insured value or 10% of the damage suffered. That estimate is based on

what insurance companies would charge for insuring a model household that includes the risk element and the various cost loadings required to remain profitable. The mid-point estimate (€345) is about 20% larger than the average estimated premium presented in Table 5.4, which suggests that the estimated premium is close to the current actual natural hazard premium in Germany.[8]

It is difficult to compare the estimated premiums to current insurer practice for France due to the current disconnection of premiums with risk. The estimated premiums are on average 52 times larger in 2015 than the current premiums stated by The World Bank (2012). This large increase in premiums is due to two main reasons. First, the estimated premiums reflect the risk faced in this model, while this connection of premiums with risk is not present in the current French natural disaster insurance. Second, this chapter's estimated premiums reflect total flood risk that is spread (or averaged) over only households in floodplains, while the costs of current natural disaster premiums in France are spread over all households in France. Evidently, this solidary aspect of making all households pay for premium costs irrespective if they are flood-prone, which results in much lower premiums of the current natural disaster insurance in France.

Table 5.4 A summary of the estimated average insurance premiums (EUR/per year) for Germany and France in 2015 and 2040

	Germany		France	
	2015	2040	2015	2040
Average risk-based premium	€280	€490	€1100	€1600
SD	€110	€200	€370	€530
Minimum premium	€110	€190	€650	€940
Maximum premium	€530	€960	€1900	€3000

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[8] The slightly smaller estimated premium can be the result of a higher degree of risk-sharing across households in this chapter's scheme or because the current German insurance premium is based on coverage of multiple risks as German insurers do not always differentiate between riverine and flash floods. It is also possible that the proposed deductible is larger than the deductibles currently in place in Germany.

5.3.2   Household-level adaptation: investments in flood risk reductions
5.3.2.1   Adaptation investments in risk mitigation in the absence of financial incentives

Table 5.5 presents the effects of the estimated employment rates of wet and dry flood-proofing measures on the total expected annual damage for France. These estimates depend on the risk perception scenario. In this study, scenario 1 is taken as the baseline or the most likely scenario since that risk perception distribution is based on French data (Poussin et al., 2014). For this scenario, the French estimates indicate that without financial incentives risk is reduced by 10% in France in 2015 on average, which grows to 13% in 2040. Table 5.6 presents the effects of the estimated employment rates of wet and dry flood-proofing measures on the total expected annual damage for Germany. For Germany, risk perception distribution 2 is taken as the baseline scenario since it is based on the large survey dataset of Kreibich et al. (2005). For this scenario, the estimated employment rates result in an estimated 6% risk reduction in 2015 growing to 9% in 2040.

The higher risk faced in France results in more investment in risk reduction compared with Germany. However, risk grows faster in Germany than in France so the degree of risk reduced as a result of employment of risk reduction measures grows more rapidly in Germany. The growth in risk reduction is driven by the increased employment of different risk reduction measures in the two countries. For instance, the implementation rate of dry flood-proofing in France grows by an additional 23 percentage points compared to Germany over the 2015–2040 period. Wet flood-proofing grows by an additional 8 percentage points in Germany over the same period. Overall results slightly differ with respect to the risk perception scenario used. Results of the baseline scenarios (scenarios 1 and 2) are most similar when applied to either France or Germany and differing by only a few percentage points. Scenario 3 results in the highest risk reduction from flood-proofing based on risk perceptions. An explanation is that the calibration of scenario 3 is based on data from Bubeck et al. (2013), which includes respondents along the river Rhine who have repeatedly experienced flooding. As a result, those respondents have high risk perceptions and high levels of flood preparedness (Bubeck et al., 2012). It can be perceived that the estimated shares of households implementing flood risk reductions are low compared to recent estimates by Osberghaus (2015), who found that about 27% of households adopted flood risk

reductions. This difference can be explained in two ways. First, the sample populations differ. Second, the survey by Osberghaus (2015) took place after Germany has experienced more repeated flood events—such as major floods in 2002, 2006 and 2013—than respondents in this chapter's survey data from 2005; this may have induced the higher levels of flood preparedness reported in Osberghaus (2015).

5.3.2.2 Adaptation investments in risk mitigation with financial incentives through insurance

In this section, results are presented for the policy scenario in which households receive premium discounts when they mitigate flood risk. Flood-proofing is stimulated through this financial incentive, which as a best outcome can have the effect that all flood-prone households in a region implement the flood-proofing measure when the discount is sufficient to make this measure cost-effective.

In both countries, the financial incentives for investing in risk reductions measured correct for the low average individual flood risk perceptions. Financial incentives are very successful in France (see Table 5.5) as the estimated reduction in risk is 37% across the entire period modelled. This is because the financial incentive is large enough to make both measures cost-effective across all flood-prone regions. Depending on the flood risk perception scenario, the premium discounts for mitigation reduce flood risk more than the situation without such incentives by between 8-27 percentage points on average in 2015 and between 14-24 percentage points on average in 2040.

For Germany, the financial incentives for wet or dry flood-proofing results in reduced flood risk of 11% in 2015 and 21% in 2040 in the baseline risk perception scenario (see Table 5.6). In Germany, financial incentives are not large enough in 2015 to provide cost-effective wet flood-proofing incentives for all flood-prone households in a regional pool. By 2040, the premium discount provides flood-prone households in nine regions with sufficient incentives to make the wet flood-proofing measure cost-effective. Dry flood-proofing measures are cost-effective for flood-prone households in 16 regions in Germany in 2015; this increases to 36 regions by 2040. Depending on the flood risk perception scenario, the premium discounts for mitigation reduce flood risk more than the situation without such incentives

by between 4-10 percentage points on average in 2015 and between 8-15 percentage points on average in 2040[9].

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[9] The results assume that that all households behave according to the cost-benefit assessment of eq. 5.10. However, if the incentives are less effective, the additional risk reduction falls. Supposing that financial incentives increase employment rates of only 30% of households, a 1 percentage point risk reduction in Germany and 2 percentage points in France would occur under the preferred baseline scenario. This is 4 percentage points lower than the best case outcome.

Table 5.5 Estimates of the average flood risk reduction due to household flood-proofing measures within French NUTS 2 regions, with and without financial incentives, under three risk perception scenarios

	Risk perception scenario 1[a]			Risk perception scenario 2[b]			Risk perception scenario 3[c]		
	Without financial incentives	With financial incentives	Difference (percentage points)	Without financial incentives	With financial incentives	Difference (percentage points)	Without financial incentives	With financial incentives	Difference (percentage points)
2015									
Mean	10%	37%	27	14%	37%	18	19%	37%	18
SD	2%	0%		3%	0%		3%	0%	
Max	15%	37%	22	21%	37%	12	25%	37%	12
Min	7%	37%	30	11%	37%	22	15%	37%	22
2040									
Mean	13%	37%	24	18%	37%	19	23%	37%	14
SD	3%	0%		3%	0%		3%	0%	
Max	20%	37%	17	26%	37%	11	31%	37%	6
Min	9%	37%	28	13%	37%	24	18%	37%	19

Notes: The risk perception distribution is calibrated using survey data from: [a] Poussin et al. (2014); [b] Kreibich et al. (2005); [c] Bubeck et al. (2013).

Table 5.6 Estimates of the average flood risk reduction due to household flood-proofing measures within German NUTS 2 regions, with and without financial incentives, under three risk perception scenarios

	Risk perception scenario 1[a]			Risk perception scenario 2[b]			Risk perception scenario 3[c]		
	2015								
	Without financial incentives	With financial incentives	Difference (percentage points)	Without financial incentives	With financial incentives	Difference (percentage points)	Without financial incentives	With financial incentives	Difference (percentage points)
Mean	4%	14%	10	6%	11%	5	10%	14%	4
SD	1%	7%		1%	7%		2%	7%	
Max	6%	23%	17	9%	20%	11	14%	23%	9
Min	3%	6%	3	4%	4%	0	7%	7%	0
	2040								
Mean	6%	21%	15	9%	21%	12	13%	21%	8
SD	1%	9%		2%	8%		2%	7%	
Max	9%	37%	28	13%	37%	14	18%	37%	19
Min	4%	4%	0	5%	5%	0	9%	9%	0

Notes: The risk perception distribution is calibrated using survey data from: [a] Poussin et al. (2014); [b] Kreibich et al. (2005); [c] Bubeck et al. (2013).

5.3.3 Affordability of the risk-based priced insurance and insurance vouchers

The affordability of the risk-based premium is an issue for a non-negligible share of households. In Germany, the estimated premiums would be unaffordable across the 2015–2040 period for an average of 18% (SD = 5%) of flood-prone households within a regional pool. For France, this estimate is about 22% (SD = 3%) for 2015 and 2040. Affordability is less problematic for Germany because of the lower level of average flood risk. Nevertheless, in both countries the share of flood-prone households for whom the insurance is unaffordable is rather large, highlighting the need for a voucher scheme.

In both countries, the premiums grow over time; thus, delaying the introduction of the proposed scheme increases the vouchers costs. Table 5.7 also shows that the total Net Present Value (NPV) of offering an insurance voucher to the households in Germany in 2015 would cost €0.68 billion, which increases to €1.03 billion if the program starts in 2040. The number of households that would be eligible for the voucher falls over the period, but the premiums increase at a faster rate resulting in an overall increase. France faces substantially higher voucher costs that are about 4 times higher than Germany. These costs increase at a faster rate in France compared to Germany due to both an increase in the number of eligible households and premiums. However, while the voucher costs are large, the benefits from additional risk reduction in the future are larger than the voucher costs.[10] While the primary benefits of linking household risk reduction and insurance incentives is the additional risk reduction, the observation that the overall voucher costs are smaller than the overall benefits may ease social concerns.

Table 5.7 Costs in Net Present Value (NPV) of an insurance voucher scheme to maintain insurance affordability

	Germany		France	
	2015	2040	2015	2040
Average Voucher NPV cost per household	€2600	€4400	€9400	€14000
SD of the average voucher NPV	€990	€1800	€2800	€4100
Minimum value of the average voucher NPV	€1000	€1700	€5100	€7400
Maximum value of the average NPV	€4800	€8400	€16000	€24000
Total NPV of the vouchers	€0.68bn	€1.03bn	€1.95bn	€3.1bn
National voucher NPV / NPV damage reduced	1.22	0.67	0.4	0.45

5.3.4 Sensitivity analysis
5.3.4.1 The premium estimate

The first element of the sensitivity analysis is to test the sensitivity of the estimated insurance premiums to the uncertainty in the underlying risk estimates. This sensitivity test is conducted by estimating the 95% confidence interval around the estimated probability exceedance curves. On the

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[10] As long as the average measure implantation rate is increased by at least 40 percentage points, the ratio of voucher NPV and the NPV of risk reduced is smaller than 1.

whole, using both the upper and lower bound of the damage estimates results in the estimated premiums being 1% higher and 1% lower on average respectively; this applies for both France and Germany. Basing the analysis on the upper or lower bound of risk estimates does not substantially alter the results of the analysis. A second source of uncertainty for the estimation of the average premium is the number of households within a regional pool. This is investigated by constructing a 95% confidence interval around the number of households. The upper bound of the number of households alters premiums by +5% in Germany and +10% in France. For the lower bound, premiums are altered by -5% in Germany and -10% in France. Overall, this uncertainty in premiums has no noticeable impact on affordability (i.e. unaffordability still applies to 18% of households in Germany) or the overall investments in flood-proofing measures.

5.3.4.2   The effectiveness of risk reduction measures

Assuming a different level of effectiveness of the flood-proofing measures can alter the baseline implication level of flood-proofing measures in a situation without financial incentives. Under the baseline risk perception scenarios, the upper effectiveness bound results in an average risk reduction that is 3 percentage points higher in France; in Germany, the average risk reduction is 2 percentage points higher, with the number reaching to 11 percentage points by 2040. For the lower bound of the effectiveness of risk reduction, this average risk reduction is 4 percentage points lower in France; in Germany, it is roughly 2 percentage points lower, with the number reaching to 7 percentage points by 2040.

The uncertainty of the effectiveness of flood proofing also influences the strength of the financial incentives for risk reduction. Considering Germany first, the upper bound of the confidence interval for dry flood-proofing results increases the number of regions for which the incentive makes the measure cost-effective by 12 regions; for the lower bound, the number of regions is decreased by 9 regions instead. The 2040 results do not differ from the baseline for the upper bound estimate, but the number of regions with cost-effective dry flood-proofing incentives declines by 15 regions for the lower bound. The use of the upper or lower bound makes no difference for dry flood-proofing in France. Using the wet flood-proofing upper effectiveness bound in Germany increases the full employment rate by flood-prone households of this measure by 1 region in 2015 and by 5 regions in 2040. Using the lower effectiveness bound does not change the 2015 results for Germany in 2015, but it lowers the full use of dry flood-proofing by 5 regions in 2040. The upper-bound makes no difference to effectiveness of the financial incentives in France. The use of the lower bound in 2015 results in 4 fewer French regions taking the measure, but by 2040 the results no longer differ.

Overall conclusions regarding the effectiveness of stimulating investments in flood-proofing through financial incentives—compared with the situation without such investments—are robust to this source of uncertainty. This is especially the case for France where the average additional risk reduction with added financial incentives is within an additional 17 to 34 percentage points in 2040 depending on the assumed degree of effectiveness of flood-proofing. Thus, the flood-proofing benefits are substantial across the sensitivity range. This range is with 2-23 percentage points a bit wider for Germany. The level of risk in France is so sufficiently high that the uncertainty of the effectiveness of flood-proofing is largely unimportant. This could imply that there is a critical level of risk that once it is surpassed, only fundamental changes in assumed risk reduction benefits can cause reversals of a household's flood-preparedness decisions.

5.3.4.3   The costs of risk reduction measures

The baseline implication rate can alter if the risk perception distributions are calibrated with different investment costs. Calibration with the upper cost estimates results in an average risk reduction that is 1 percentage point lower in both Germany and France in 2040, while for 2015 results remain the same. Calibrating to the lower cost bound results in an average risk reduction that is approximately

the same in 2015 and 2 percentage points higher in 2014 for Germany, or 1 percentage point higher in France.

The results regarding the strength of the financial incentives offered are more sensitive to flood-proofing costs. In particular, wet flood-proofing is sensitive to the cost estimate used since the upper bound of the cost estimates implies that the financial incentives do not make wet-flood-proofing cost-effective for a single region in either France or Germany. Using the lower bound of cost estimates for wet flood-proofing does not change the results for France, while for Germany the number of regions for which the measure becomes cost-effective when financial incentives is offered increases to 36 in 2040.

Dry flood-proofing also has a wide range of cost estimates, but for France the range of dry flood-proofing costs has no overall effect on the effectiveness of financial incentives in stimulating flood-proofing. Germany, however, experiences noticeable differences since in 2015 the lower bound of the costs results in flood-prone households in 12 additional regions finding the measure cost-effective in in 2015.Using the upper bound results in households in only 2 regions finding dry flood-proofing cost-effective, which grows to 15 regions by 2040 for the upper bound of costs; for the lower bound, the number grows to 38 regions.

Overall, the sensitivity analysis of the costs of the flood-proofing measures mainly shows that cost uncertainty affects the relative attractiveness of employing one measure when compared with another. In particular, dry-proofing is more relatively attractive when the costs of wet-proofing approach the higher bound. Even with higher bound cost estimates, flood-proofing remains cost-effective for many households and financial incentives are effective in stimulating investments in such measures.

5.3.4.4 Time horizon of flood-proofing measures

Another important factor for implementing the flood-proofing measures is the time period over which households will consider the benefits in terms of saved flood damage from the measure. The above results have all been estimated on the basis of a 20 year time horizon. Expanding the time horizon to 40 years does not affect results for France, as in the work by Poussin et al. (2015). In Germany, a doubling of the time span of dry flood-proofing increases the number of regions by 7 in 2015 when insurance incentives for risk reduction are offered; these are all regions where this measure is found to be cost-effective. The change in time horizon has no influence on the adoption of the measure wet flood-proofing in Germany. Overall results are thus robust to assumptions about the time horizon over which damage savings from risk reduction are considered by individuals.

5.4 Discussion

5.4.1 Premiums, flood risk adaptation, and insurance vouchers under the proposed insurance scheme in Germany

The estimated insurance premium of the proposed public-private flood insurance is €280 on average for Germany in 2015 (see Section 5.3.1), which can be placed in context by a comparison with current premiums. Schwarze et al. (2011) estimate flood insurance premiums that are larger than this chapter's estimated premiums, which may be due to lower deductibles in practice than assumed in this chapter's model or this chapter's greater degree of risk pooling. Creating a large pool of both high and low risk households who must buy insurance can correct for adverse selection, which is a current concern in the German insurance market (Schwarze and Wagner, 2007; Seifert et al., 2013).

The proposed scheme is very effective at promoting adaptation via the employment of dry flood-proofing. In particular, in 2015 the financial incentive is large enough to provide cost-effective incentives in 16 regions to employ this measure, while this increases to 35 regions by 2040. Moreover, the use of wet flood-proofing is promoted by the financial incentives, albeit to a smaller

extent. In 2040, flood-prone households in 7 regions find this measure cost-effective based on the premium discounts. These 7 regions are more at risk than the regions for which this measure is not cost-effective; therefore, this measure is employed where it is most efficient. The difference in employment rates between the two flood risk reduction measures is mainly the result of investment costs. While the premium discount is larger for households that invest in wet flood-proofing, the investment costs of this measure are also much higher than for dry flood-proofing.

The average premium under the proposed flood insurance scheme may be lower than the current insurance combined with the stronger incentives for risk reduction; this observation suggests that the proposed scheme creates a positive situation for households and insurers overall. However, despite these advantages, it may be desirable to introduce the voucher scheme to ensure a smooth transition to the scheme with a stronger link between risk reduction and insurance premiums. This is because the proposed insurance is estimated to be unaffordable for an average of 18% of households per region, which is a large proportion. Moreover, the average estimates could be masking large premium increases for certain households, as the SD of this chapter's estimates indicates.

The desirability of the proposed insurance scheme may be judged according to the risk reduction it achieves and the costs of the voucher system. Introducing the risk-based premiums and premium discounts for mitigation in 2015 is estimated to reduce the expected annual flood damage to residential areas by an average of an additional 5 percentage points across regions compared to the baseline investments in risk reduction. In 2040, the reduction in the regional average level of expected annual damage is increased by an additional 12 percentage points. In 2015, the NPV cost of the voucher system is 122% of additional damage prevented through risk-based premiums. However, by 2040 the NPV of the vouchers are 67% of the value of the additional damage prevented. Therefore, it appears that the benefits of the financial incentives for risk reduction outweigh the costs of the voucher scheme over time. In conclusion, the proposed insurance scheme is especially beneficial when flood risks increase in the future because of climate and socio-economic change.

5.4.2 Premiums, flood risk adaptation, and insurance vouchers under the proposed insurance scheme in France

The estimated risk-based flood insurance premium for France is on average €1100 in 2015 (Section 5.3.1). It is difficult to place this estimate in context with current premiums due to the weak link with risk currently in French insurance premiums. However, the premiums estimated are approximately 52 times larger than the current premiums that are more affordable. An advantage of the proposed scheme is that it is very effective at promoting household flood risk adaptation. Introducing the financial incentives in 2015 is estimated to reduce the expected annual flood damage to residential areas by an average of 27 additional percentage points across regions compared to the baseline investments in risk reduction. In 2040, the regional average level of expected annual damage is reduced by an additional 24 percentage points. This is because the financial incentives offered by the premium discounts over twenty years are sufficient to render the investigated risk reductions cost-effective for the investigated regions.

The higher premium of this chapter's proposed insurance scheme hampers the affordability of flood insurance for flood-prone households in France. The percentage of households for which the risk-based premiums are unaffordable is approximately 22%. Therefore, even though the risk-based premiums encourage risk reduction, a voucher system is desirable for overcoming affordability problems caused by the proposed insurance scheme. In 2015, the NPV cost of the voucher system is 40% of the value of the additional damage prevented through financial incentives; in 2014, this was at 45%. Therefore, it appears that the benefits of the financial incentives for risk reduction outweigh the costs of the voucher scheme already in 2015.

5.4.3 A comparison of changes in flood risk over time and household-level adaptation between Germany and France

The main driver of changes in flood insurance premiums, and flood risk overall, over time in both Germany and France is the growing level of exposure under the SERS A1 climate and socio-economic projections. Assuming that the flood risk growth rate can be decomposed into two equally weighted components, the exposure component over the 2015–2040 period is 60 times larger than the hazard component in absolute size for Germany and 82 times as large in France. For both countries, this contributes substantially more to the final insurance premium estimates than changes in climate or population. The second most important driver for insurance premiums is the changes in the number of households, which affects the potential size of the risk-pool. The effect of population dynamics differs between the countries. In Germany, the number of households is estimated to fall, causing an upward pressure on average household insurance premiums for given exposure growth, while in France the increasing number of households limits the effects of increasing exposure on the average insurance premium.[11]

Climate change plays a relatively smaller role in the development of flood insurance premiums, which has been observed in other studies (e.g., Paudel et al., 2015). Rojas et al. (2013) predict a slight fall in flood damage in France and Germany based on the climate change scenario used here in the mid-21st century, and a more rapid increase in the late 21st century. Therefore, the main drivers of the trends in average insurance premiums to be concerned about in the short to medium term are exposure growth and population dynamics. However, unlike climate change, these do not represent fundamental changes in the natural hazard (i.e. the likelihood or severity of the flood event) and may be easier to cope with, for example, by expanding reinsurance coverage (e.g., Dlugolecki, 2008; CII, 2009). If the increase in flood risk and premiums is the result of greater wealth, then the ability of policyholders to pay higher flood insurance premiums has also improved. Climate change, however, would have implied higher premiums resulting from factors that are external from the policyholder, which are unrelated to an improved ability to pay for these premiums.

The changing flood risk levels over time have a large influence on household investments in flood risk reduction measures in both countries. In the absence of insurance incentives, these investments grow less in France compared to Germany. This is because the average flood risk grows more slowly combined with a greater degree of underestimation regarding the flood risk faced in France compared to Germany due to the calibrated shape of the risk perception distribution. The importance of changing risk levels regarding the effectiveness of financial incentives for risk reduction differs between France and Germany. France has relatively high level of flood risk, which has the effect that once underestimation of flood risk by individuals has been corrected for, both of the investigated risk reductions are cost-effective. As a result, the increasing trend in average flood risk has little effect. This result is different for Germany where average levels of risk in 2015 are lower than in France and the upward trend in flood risk increases the insurance incentives for investing in risk reductions. In both countries, the financial incentives from the risk-based flood insurance premiums result in a substantial reduction in expected annual flood damage, suggesting that these insurance incentives are an effective way to stimulate adaptation to changing flood risk. This finding suggests that as flood risk increases in the future, the benefits of strengthening the connection between risk and risk reduction may outweigh the costs of correcting for affordability concerns.

5.4.4 Practical considerations for insurance related financial incentives for risk reduction

Surminski et al. (2015) notes that there is not a strong link between policyholder level risk reduction and premiums in European natural disaster insurance markets. Moreover, Thieken et al. (2006) found this was the case for German flood insurance in 2002. A possible obstacle for strengthening the link

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[11] Due to the larger pool over which to share losses.

between household-level risk reduction and premiums is that such a link entails transaction costs. Transaction costs occur because of the need to individualise premiums at a detailed level or because of monitoring and enforcement of the implementation of risk reduction measures. Filatova (2015) states that the cross-subsidisation of premiums across policyholders can result in lower transaction costs. Enforcement is also needed for compulsory insurance. This can be problematic: In the U.S.A, even though flood insurance is compulsory for homeowners with a federally backed mortgage in the 1/100 year flood zone, the penetration rate is below 50% in these areas (Dixion et al., 2006; Czajkowski et al., 2012). This problem may arise because it is the responsibility of the homeowner to buy flood insurance. In France, the compulsory natural hazard insurance is provided by the insurers when a standard household insurance policy is sold, which customers cannot refuse. This has been successful and resulted in almost universal coverage.

There are examples of insurers providing policyholders financial incentives for flood risk mitigation. One such instance is noted by Surminski et al. (2015), who explain that a cover holder of Lloyds of London provides a premium reduction to insured households in the Netherlands of 5% if certain flood-proofing measures are employed, such as Dry flood-proofing. The National Flood Insurance Program (NFIP) in the U.S. has several schemes in place to provide incentives for policyholders to reduce or more actively manage the flood risk that they face. At the individual policyholder level, there is the severe repetitive loss program. This program is focused on households that regularly make large insurance claims. These households are offered grants to engage in risk reduction measures, such as elevation, and will increase premiums by 150% if the proposed risk reduction measures are not carried out (Mathewson et al., 2011). The premium offered to these policyholders can further increase by 150% if large claims are made at later dates. Moreover, the NFIP can offer premium discounts to households who have elevated their building. These examples show that a link between risk reduction and insurance premiums can be made.

5.5 Conclusion

Several studies have argued that risk-based flood insurance can incentivize policyholders to adapt to changing flood risk, although the effectiveness of such incentives has hardly been researched. For example, calls have been made to improve the design of flood insurance in Europe where flood risk is expected to increase as a result of climate and socio-economic change. However, despite the interest in flood insurance as a key mechanism in flood risk management, different stakeholders have different and potentially conflicting roles in mind for insurance. Governments and policyholders tend to value affordability and widespread coverage, while the insurance industry often favours risk-based pricing and the possible incentives for flood risk management. With those concerns in mind, this chapter aims to examine whether these roles can be fulfilled by introducing a compulsory public–private flood insurance system in France and Germany. Recently, it has been proposed to introduce such a scheme in Germany. Compulsory natural disaster insurance has existed in France since 1982, and it has been suggested that this insurance can be linked to incentives for risk reduction, as is studied here.

This study examines the potential trade-off between risk reduction and affordability in a model of risk-based public–private flood insurance, including household flood preparedness decisions. In particular, this model estimates regional risk-based flood insurance premiums and household flood preparedness in situations both with and without premium discounts for mitigation; this study also examines affordability issues with charging risk-based rates. The development of premiums and flood risk preparedness is modelled to examine adaptation to changing flood risk. Three main conclusions can be drawn from the results of this model.

The first is that risk-based flood insurance premiums can substantially differ from current premiums and that these differences are highly dependent on the country and market. Current private market

flood insurance premiums in Germany are relatively close to this chapter's premium estimates for the compulsory insurance system. The estimated risk-based premiums are about 20% lower, which suggests that for Germany, a movement towards a compulsory insurance scheme or a greater degree of risk pooling may result in lower flood insurance premiums on average. By contrast, the current compulsory natural disaster insurance premiums in France are not risk-based, and a movement towards risk-based premiums would cause a large increase in premiums for the country. It is estimated that premiums could increase by a factor of 52 in 2015.

The second conclusion is that providing incentives through risk-based insurance premiums is effective in promoting flood risk adaptation by policyholders. The reason is that the premium discounts for mitigation correct for underestimation of flood risk by individuals. In France, these financial incentives would promote every household on average to employ both of the investigated flood risk reductions. The insurance incentives are slightly weaker in Germany where current flood risk levels are lower, but the incentives become more effective over time when flood risk increases. For example, nearly all households located in floodplains are estimated to invest in dry flood-proofing by 2040, while those in high risk areas will be incentivised to employ wet flood-proofing as well. The results show that the insurance incentives encourage adaptation to changing flood risks, which limits the overall predicted increase in future flood risk. By 2040, these incentives are expected to reduce the annual expected flood damage by 12% in Germany and 24% in France.

The third conclusion is that risk-based pricing hampers the affordability of flood insurance; this can be addressed by a temporary voucher scheme. The risk-based insurance would be unaffordable for about 1 in 5 floodplain households. This can imply that a voucher scheme to smoothen the transition towards the proposed scheme can be rather expensive. As an illustration, the voucher costs in 2015 are €0.68 billion in Germany and €1.95 billion in France. Over time, the damage reduction incentivized by the risk-based premiums outweighs these voucher costs. Moreover, the costs of providing the vouchers relative to the benefits of additional mitigation fall over time in both countries.

Although this chapter's behaviour model accounts for possible misperceptions of flood risk, it is assumed that households base decisions on flood-preparedness by trading off costs and benefits of flood-proofing measures. This could be seen as a limitation of this chapter's approach when households make decisions on other grounds. Allowing for alternative decision-making frameworks can be a fruitful area for future research. In addition, there are several uncertainties regarding the applied input data and modelling approach. The importance of these uncertainties was investigated in a sensitivity analysis, which showed that the results are overall robust to this chapter's estimated confidence intervals regarding various assumptions about the following areas: (a) investment time horizons of households; (b) costs of risk reduction measures; (c) the effectiveness of the risk reduction measures; and (d) the regional flood risk estimates. However, there are still remaining caveats, which are open for future research. In particular, the calibrated flood risk perception distribution was assumed to be fixed over time, and differences in risk perceptions between regions were assumed to be only caused by differences in objective risk. Future research could examine temporal and spatially differentiated distributions of flood risk perceptions, which depend on other factors than only objective risk. For instance, time periods with long gaps between floods will likely contribute to reduced flood risk awareness, while periods immediately after a flood can result in perceptions that imply overestimation of objective risk. Another caveat is that there are few independent empirical studies about the employment of flood risk reduction measures and their effectiveness, which implies that the evidence base for these estimates is small. Future research could focus on establishing an improved evidence base for estimates of flood risk reduction measures that are in place in different regions and how effective these are in limiting flood damage.