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Inequality in Flood Insurance Arrangements to Finance Flood Recovery under Climate Change.

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Abstract

Austria faces a substantial flood insurance and adaptation protection gap. As a result, after a damaging flood, households and governments need to redirect funding to cover uninsured damages. Households may not be able to afford expensive recovery costs, and governments may need to redirect funds and reduce spending on planned objectives, or increase debt. The resulting indirect impacts caused by slow recovery, increased debt, or redirected government spending, may be prevented by reducing flood risk and/or increasing coverage by insurance. Reducing the flood insurance protection gap in Austria, as in many other countries, can be done by various means, which differ in how flood risk is born and spread amongst the population. This study's objective is to assess these different flood insurance systems that policymakers have at their disposal in terms of their distributional impacts. Potential insurance systems are assessed on whether they are able to provide financial protection for all citizens. This assessment is done by using a partial equilibrium model of the flood insurance sector and by applying spatially detailed data on household income. Results show that improvements in flood protection have short-term benefits to reduce the protection gap, but this strategy becomes less effective due to climate change. Enabling the development of a private flood insurance market is beneficial for higher income households to reduce the financial consequences of a flood, but for lower income households, high costs prove to be a substantial barrier to insurance uptake. Government involvement in the provision of flood insurance is beneficial for ensuring equality regarding the ability to insure against flooding, preventing increasing inequality in flood vulnerability. The Austrian government should maintain insurance uptake requirements and ensure a degree of risk-sharing. A limited degree of risk-reflective pricing is beneficial to stimulate adaptation.

1 Introduction

In Austria, more than 27% of the population is exposed to flooding (Rentschler et al., 2022). Climate- and socioeconomic change will likely exacerbate this figure in the future (Winsemius et al., 2016). Households may need to evacuate when faced with the immediate threat of a flood, and are afterwards met with expensive costs to repair their belongings. Reducing flood risk and impacts to tolerable levels requires a combination of measures, including large-scale flood protection infrastructure (e.g., dykes) (Ward et al., 2017), household-level flood-proofing measures (e.g., flood barriers and flood resistant building materials) (Aerts, 2018), and insurance to financially cover remaining risk (von Peter et al., 2024). These adaptation strategies, however, each have their challenges and limitations, resulting in an adaptation gap (Aerts et al., 2024). There are indications that the adaptation gap is particularly large for low-income households (Sayers et al., 2018), and that, because of this, flood impacts are partly driven by income inequality (Lindersson et al., 2023). This study examines the extent of the adaptation gap for different household income levels in Austria, and assesses policy strategies to reduce the adaptation gap more equitably.

Concerning flood risk reduction through flood protection infrastructure, we examine how the distribution of uncovered flood risk develops if the Austrian authorities invest in raising flood defenses. Austrian flood risk management (FRM) aims to uphold such defenses to withstand at least a 100-year flood in all built areas, except in specific areas where this is deemed impossible (Unterberger et al., 2019). In practice, however, in many areas flood protection standards are below this objective (Bundesministerium für Landwirtschaft, 2021).

Raising flood protection infrastructure may be obstructed by high costs. Also because such investments would not provide full protection against floods, additional measures are necessary to reduce the impacts of flood events. Firstly, households exposed to floods may adapt by, for example, flood-proofing their homes or, with severe flood risk, relocating to saver areas. Secondly, it is important to have a well-organized flood damage compensation mechanism, which provides sufficient compensation for those experiencing flood damage to recover and continue with their lives or businesses. Low insurance coverage obstructs and slows down the recovery process after a flood, which has implications for the well-being of those directly affected (Luechinger & Raschky, 2009; von Möllendorff & Hirschfeld, 2016), but also creates long-lasting economic impacts, even outside of the flooded area (Rousová et al., 2021; von Peter et al., 2024).

In Austria, as in many other countries, there is a substantial flood insurance protection gap (Le Den et al., 2017). A public disaster relief fund (Katastrophenfonds) is established to cover a part of the damages caused by floods and other natural disasters. Although no legislation obliges the fund to cover residential damages, in practice the fund covers damages above €1000 up to 20-50% of damages (Hanger et al., 2018). However, in cases of exceptional distress the fund has been applied to cover 100% of residential damages. It is the household's responsibility to cover any residual flood risk, either through self-insurance or by purchasing coverage from private insurers. Insurers in Austria, however, maintain strict limits on covered flood risk, and refusing coverage in high-risk areas is not uncommon. According to Insurance Europe the limit on flood coverage is usually around €10.000, and the uptake of flood coverage amongst households is between 10 and 25%[1]. The combination of incomplete compensation from the Austrian disaster fund, low insurance uptake, and

[1] https://sustainability.insuranceeurope.eu/interactive-downloads/2747/property-catastrophe-insurance-austria/Property+catastrophe%20insurance%20-%20Austria.pdf

restricted coverage levels, leads to a considerable flood insurance protection gap.

It is often suggested that to increase resilience against floods, the flood insurance protection gap needs to be substantially reduced (Knittel et al., 2023; Raschky et al., 2013-02; Reiter et al., 2022; Rousová et al., 2021). There are many ways to approach this objective, and an effective strategy may require a combination of measures. Flood risk management (FRM) may aim to reduce flood risk, for example, by improving flood protection infrastructure, or stimulating household-level flood adaptation (Kundzewicz et al., 2018). Since it is likely infeasible (or undesirable) to fully prevent flood damage, some form of insurance will need to be established to cover remaining flood risk. Increasing the insurance penetration rate in Austria will require certain policy changes. The existence of a disaster fund that covers an uncertain amount of flood risk makes it unattractive for households to buy flood insurance coverage (Raschky et al., 2013-02). Because of low demand for flood coverage, the market for private flood insurance is small. An issue that contributes to keeping this market small is the enhanced presence of adverse selection due to the (partial) public flood compensation (Raschky et al., 2013-02). Additional insurance coverage (on top of the uncertain coverage of the public fund) is attractive for the most at-risk households. As a result of lower-risk households foregoing flood coverage, the ability of insurers to pool risk and charge relatively affordable premiums is limited, further discouraging households from buying flood coverage.

An improvement to the current policy of public compensation for flood damage is to either expand the coverage of the public fund, or to commit to a lower amount of coverage by the fund. If coverage through the public fund is low or non-existent, there should be higher demand for flood coverage, stimulating the development of a private flood insurance market. In practice, however, it is often politically unfeasible to deny compensation after a flood or other disasters, a phenomenon coined the Samaritan's dilemma by Buchanan, 1975. Modern welfare states are to some degree implicitly obligated to provide relief after destructive disasters. As a result, an insurance protection gap calls for aid to uninsured households after a flood, which, in turn, crowds out demand for private insurance, causing a higher future flood insurance protection gap (Browne & Hoyt, 2000). The option of unconditional government aid after a disaster is made especially attractive for many by the costs of insurance coverage. Besides the actuarial costs of covering flood risk, which may be especially high in floodplains, insurers charge various forms of premium-markups. Moreover, due to their limited risk-pooling capacity, insurers generally transfer risk associated with the most extreme (unlikely) events to reinsurance firms. Because the reinsurance market is dominated by only several global firms, market power enables these firms to charge premiums several times the actuarial fair rate (Froot, 2001).

Both costs of insurance and the potential of receiving public funding if uninsured, makes it difficult for a private insurance market to develop. What makes the position for private flood insurance even more precarious when 'competing' with public funding, is the underestimation of flood risk by individuals. Human psychology tends to be biased when assessing the risk of infrequent events (Kunreuther, 2021), which include many natural disasters such as floods. In general, it is found that the impacts of potential floods are often underestimated (Mol et al., 2020), which means that an actuarially fair flood insurance premium (or a slightly more expensive premium due to markups) is and unattractive investment for many individuals.

To overcome these barriers that challenge flood insurance markets, several studies advocate for mandatory flood coverage (Osberghaus & Reif, 2021; Reiter et al., 2022). By using legislative means to close the insurance protection gap, governments are spared potentially unforeseen costs after a disaster, which have negative macroeconomic impacts (Knittel et al., 2023), and households receive more certainty concerning the insurance coverage of flood impacts. Although many European nations apply some form of flood insurance purchase requirements (Le Den et al., 2017), in some countries there is political restraint, such as in Germany, where a bill to instate mandatory flood insurance was rejected based on consumer freedom principles (Schwarze & Wagner, 2007).

Besides regulating the coverage of flood insurance, governments may choose to pursue a policy with regards to insurance pricing. In a privatized flood insurance market, with limited barriers to market entry, competition amongst insurers will lead to the lowest overall costs paid for flood coverage. In a fully competitive market, insurers will try to obtain a competitive advantage by optimizing their risk models. The insurer that charges premiums most accurately is able to attract low-risk households with low premiums, while high-risk households may choose relatively cheap coverage from an insurer that uses coarser flood risk assessment methods. Over time, operations of the insurer that applies coarser risk models will become unfeasible, as it is left with mainly high-risk households. A fully competitive insurance system will thus evolve towards risk-based premiums.

A distinct issue with insurance premiums that accurately reflect flood risk is that flood insurance can become unaffordable in areas at high risk of flooding (Hudson et al., 2016; Tesselaar et al., 2020). Flood insurance coverage could, therefore, be unattainable for lower-income households in risky areas, or become so due to increasing flood risk as a result of climate change. Low-income households may be especially vulnerable to flood impacts due to limited means to finance the recovery of damaged property. While there are opposing perspectives as to whether this is a societal or an individual problem (Thaler & Hartmann, 2016), many welfare-states consider the inability of households to insure, or otherwise adapt to flood risk, a societal problem that demands supportive public policy. Essentially, the Austrian Katastrophenfonds is a disaster finance system founded on a solidarity principle, where all Austrians contribute to financing the recovery of those unfortunately impacted by a flood. If solidarity ethics are prioritized over principles of individual responsibility, Austria may choose to enhance coverage of the disaster fund. Several European countries, including Spain, France, and Belgium, choose such an approach, where the risk born by those residing in floodplains is shared equally within society.

A notorious concept in the insurance industry is moral hazard, which states that insurance coverage reduces the incentive an individual may have to limit risk. Insurance pricing strategies, such as deductibles or premium discounts for the application of DRR-measures, may be applied to combat moral hazard. A risk-based premium strategy is considered effective to communicate the risk faced by individual policyholders and provide a financial incentive to mitigate risk, for example, by avoiding settling in high-risk areas (Tesselaar et al., 2023). Advanced risk-based pricing strategies may include premium discounts based on the application of property-level DRR-measures. Solidarity-based, flat premium structures, are criticized for failing to curb moral hazard, and discourage households from adapting to (increasing) flood risk (Surminski & Eldridge, 2017). From a societal perspective, an insurance system with a flat premium structure may cause higher future flood costs compared to one with risk-based premiums (Hudson et al., 2019).

As is apparent from the literature discussed above, there are benefits and downsides associated with policy choices of FRM and flood insurance. A topic that receives less attention, but is nonetheless important to consider when designing policy to enhance flood resilience, is the potential inequality concerning the ability of different societal groups to adapt to flood risk. We touched upon the issue of unaffordability of flood insurance, which, in an insurance system with voluntary coverage, would cause a larger insurance protection gap for low-income households compared to higher-income segments (Ma et al., 2021). The issue of unaffordability also applies to the ability of households to reduce flood risk through DRR-effort. The risk is that, on average, a society may perform well to reduce or limit flood risk, while, in fact, certain population groups are systematically falling behind in coping with flood risk. Impacts of future floods may, then, be particularly high for these societal groups, who are also vulnerable to fall into a poverty trap because of this (Cappelli et al., 2021). Certain policy choices concerning FRM and flood insurance may limit these inequalities. Therefore, this study shows an important additional aspect for policymakers to consider.

For this study, we are particularly interested to explore how flooding impacts households in different income groups, and how policy changes concerning the organization of flood insurance and FRM may affect the distributional impacts of floods. We systematically compare the effect of several policy-changes on the impact of floods on household finances. Assessed policy changes include the introduction of a public reinsurer, which should increase the willingness of insurers to cover flood risk in Austria; increasing coverage by the public Catastrophe Fund; an insurance system with capped risk-based premiums; and a status-quo insurance system, but where flood protection standards (i.e., dykes) are improved. For each of these policy-scenarios, we apply a spatially explicit partial equilibrium model (Hudson et al., 2019; Tesselaar et al., 2023) to assess insurance premiums, and uptake of insurance coverage and DRR-measures by households. Using high-definition data on household income, we assess to what extent income is a barrier to insurance coverage and DRR-uptake, and how such barriers may be reduced by insurance or FRM policy change.

The next section describes the model setup and the data used in the simulation exercise. This is followed by a presentation and discussion of results. The article ends with a concluding section.

2 Simulation method

For this research, we are interested to simulate flood insurance premiums in Austria, under various types of insurance systems, and under current and future climate and socio-economic conditions. After projecting premiums, we aim to assess the budgetary impact of flood insurance coverage for different income groups in Austria. This section first explains how flood risk is simulated, then how premiums are assessed, and finally how the impact of premiums on household finances is determined.

2.1 Flood risk assessment

Austria faces a wide range of disasters, but riverine flooding is one of the most prominent threats (Leitner et al., 2020). The mountainous geography causes rivers to be responsive to rainfall, which, particularly in combination with snow melt, causes peak water levels in the river systems that flow through the Austrian valleys. To simulate the risk posed by riverine flooding in Austria, we apply the global flood risk model GLOFRIS (Ward et al., 2017; Winsemius et al., 2016). This model applies a conventional approach to assessing natural disaster risk, which is to combine the elements hazard, exposure, and vulnerability.

Flood hazard refers to the biophysical aspect of flood risk, and simulates to what extent land is inundated by river runoff that is associated with certain probabilistic meteorological events occurring in a river's catchment. Considered events are expressed as return periods, and encompass 2, 5, 10, 25, 50, 100, 250, 500, and 1000-year return periods. For each of these return-periods, the hydrological model PCR-GLOBWB and the hydrodynamic model DynRout are applied to simulate whether water levels exceed embankments, and if so, to what extent land is inundated. For present-day flood hazard, these models are forced with time-series data on various meteorological conditions from 1960-1999, obtained from the EU-WATCH dataset (Weedon et al., 2011). For future flood hazard, the models are forced using meteorological data generated by global circulation models (GCMs), which apply representative concentration pathways (RCPs) to account for global warming. For this study we apply the GCM HadGEM, developed by the UK's Meteorological Office, and force this using RCP4.5 (a middle-of-the-road scenario regarding greenhouse gas emissions) and RCP8.5 (a scenario representing a high level of global warming). The assessment of flood hazard by GLOFRIS is done on a 30' by 30' (arcseconds) spatial scale (approximately 1x1km). Finally, the application of GLOFRIS is limited to rivers above Strahler order 6, which means that flood risk is not simulated for smaller rivers. This is because smaller rivers are subject to somewhat different biophysical processes, are more sensitive to local rainfall, and floods in these rivers are considered more "flashy" in nature (Winsemius et al., 2016).

The resulting flood inundation maps per return period are overlain with a spatial dataset showing the urban area per flooded grid cell. For this purpose, the HYDE database is used (Klein Goldewijk et al., 2011), which shows the fraction of each grid cell (5' x 5') that is made up of urban land cover. Using GDP-normalized estimates from the Damagescanner model (Jongman et al., 2012), an economic value is given to the urban area exposed to flooding. Future flood exposure is estimated using the 2UP-model (van Huijstee et al., 2018), which applies a local interpretation of population growth estimates, such as those derived from the Shared Socio-economic Pathways (SSPs). In essence, the 2UP-model applies a spatial suitability map of urban growth based on various factors that may attract or repel households from settling in a certain location. In this study, we apply two socio-economic scenarios; SSPs 2 and 5, which represent average and high population growth respectively. Finally, in order to assess the value of damage caused by a certain level of flood inundation GLOFRIS applies flood depth-damage curves (Moel et al., 2016).

At this point, we are able to estimate flood damages caused by specific probabilistic meteorological events. In order to estimate flood insurance premiums, we must approximate an expected annual value based on the various return periods assessed in the previous steps. To do this, we can use the flood return periods and associated damages to draw a flood probability-impact curve for each grid cell. The Annual Expected flood Damage (EAD) is then the integral of this curve. However, before this can be done, we must take into account that in many areas flood protection infrastructure is in place to prevent floods up to a certain water level. To do this, we apply flood protection standards as estimated on a regional level (Bundesländer) by Scussolini et al., 2016. In the flood probability-impact curve, this means that water levels with return periods below the regional flood protection standard do not cause any damage.

Besides flood protection infrastructure, which is applied on regional scale, households themselves are able to reduce the vulnerability of their homes to flooding. To do so, households may install DRR measures, such as dry- or wet flood-proofing measures. Dry flood-proofing refers to measures that prevent flood water from entering a property, which includes flood-barriers, but also raising a property above potential flood-levels. Wet flood-proofing refers to measures that limit the damage once water has entered a property, including water-proof building materials and a specialized flood-proof basement. Hudson et al., 2014 generalize the flood risk reduction as a result of dry- and wet-proofing measures to be 12.8% and 24.6% respectively. We account for household-level DRR in our assessment by simulating demand for these measures by households, which is impacted by costs, income, and reduced flood risk. The exact procedure of this simulation is described in Section 2.3.

2.2 Estimating insurance premiums

For this research, we study the implications of three flood insurance policy choices on household finances. These policy choices are stylized versions of insurance systems as seen in practice in several European countries. These stylized insurance systems are not designed to accurately represent insurance operations and premium-setting rules, but are rather intended to study societal implications of certain fundamental political choices with regards to insurance pricing and coverage. The first system we define is one where coverage is provided by private insurance firms. As explained earlier, competition amongst private insurers will develop towards premiums that are risk-based, meaning they are to some degree differentiated based on the flood risk of individual policyholders. Insurance coverage from private insurers can be both optional or mandatory for households. Contrary to risk-based insurance is a system where flood risk is shared equally amongst Austria's households. For Austria, in practice, this would mean an expansion of coverage by the current Catastrophe Fund. Finally, since there are distinct advantages and downsides to both systems mentioned so far, there is a system that attempts to seek a middle ground, reducing the negative impacts of both systems. Such a system is characterized as a Public-Private-Partnership (PPP). How premiums are calculated in each of these systems is formulated in detail in Hudson et al., 2019, and is described more intuitively below.

2.2.1 Private insurance

All flood insurance systems aim to spread the covered risk over time and space. However, the extent to which this spreading of risk is done may differ under different systems. As mentioned previously, for private insurers active on a competitive insurance market, there is a competitive advantage to more accurately estimate risk-profiles and price coverage accordingly, which for flood insurance mainly means the location of a covered property with respect to potential flooded land. This study assesses flood risk on a $1km^2$-level, which allows us to estimate risk-based premiums on this geographical scale. Essentially, the premium for the coverage of risk is then the EAD divided by the number of households residing within that $1km^2$. However, insurers charge various additional markups on top of the coverage of EAD. Firstly, because insurers are averse to uncertainty, they charge a markup based on the volatility of risk. In our simulation, this markup is a risk aversion premium multiplied by the volatility, which is based on the difference between assessed damages associated with the considered return periods. Additionally, insurers generally transfer risk of the most extreme events to a reinsurer. In our simulation, a private insurer will transfer 15% of its covered risk to a reinsurer in a stop-loss contract type, which is based on a review of European flood insurance contracts in Paudel, 2012. The reinsurer charges a premium estimated using a similar method as the insurer, with the only difference being the profit markup. Because the reinsurance market is characterized by limited competition, reinsurers are able to charge substantial profit margins, which is 50% of the covered risk in our analysis. Due to competition, insurers are not able to charge a profit markup, but do charge a markup for administrative costs, which is 2% of covered risk in our simulation.

2.2.2 Public insurance

A public insurance system is one where flood damages are compensated by the government, who generally charge "flat rate" premiums, insensitive to the risk of individual policyholders. With the focus of this study being on Austria, this system could be seen as an expansion of the current public Catastrophe fund to covering 100% of flood risk. Under this insurance policy scenario, premiums are set by spreading risk amongst all Austrian households. Therefore, unlike the risk-based premium, which only applies to the population at risk of flooding, flat-rate premiums have to be paid by all households residing in Austria.

2.2.3 Public-private insurance

The final insurance system that we simulate is one where premiums are "limited risk-based". In this insurance system, coverage is provided by private insurers, who calculate premiums based on individual risk, but the government (involved as a reinsurer) maintains a premium cap. This type of system is based on the UK's flood reinsurance program, "Flood Re", which lets insurers that cover high-risk households charge subsidized premiums and pool the excess risk in a reinsurance pool that involves all British insurers covering flood risk, as well as the government. Through the reinsurance pool, all insurers contribute to covering the excess risk by charging an additional markup on coverage for low-risk households. Because this system requires a cross-subsidization between low- and high-risk households, which is obstructed by adverse selection when flood coverage is voluntary, it functions best when flood coverage is mandatory. In our simulation, the premium cap is set to 1.5% of Austrian median income (based on how the premium cap is set by the UK's Flood Re), which is €565 in 2010. This means that households that for households residing in high-risk zones, the premium amount above €565 is transferred and shared by households facing lower or no flood risk.

2.3 Insurance and DRR-uptake

Estimating the impact of insurance policy changes on the insurance protection gap also requires insight into the uptake of insurance (when optional) and DRR-measures. Although factors that influence the decisions to take flood insurance and apply DRR-measures are diverse and to some extent chaotic, some of these factors are found to occur systematically. We can simulate these systematic factors to approximate the uptake of insurance and DRR-measures.

Simulating consumer choices regarding insurance- and DRR-uptake has been developed and applied in the Dynamic Integrated Flood Insurance model (Hudson et al., 2016, 2019; Tesselaar et al., 2022, 2023). These choices are simulated in the model framework by applying subjective expected utility (SEU) theory (Savage, 1972). In the choice model, households exposed to floods consider SEU-values for several options related to insurance- and DRR-uptake, and choose the option with the highest SEU-value subject to the condition that it is affordable. To assess affordability, we apply household-level income data obtained from Statistics Austria, which we have access to on a 1x1km-scale. If the insurance premium and/or DRR-investment exceeds a household's poverty-adjusted disposable income, insurance coverage and/or DRR is considered unaffordable and unavailable for the household, if optional. Poverty-adjusted disposable income represents income after essential payments have been made to stay alive, and is generated by subtracting income by the at-risk-of-poverty line. The at-risk-of-poverty line varies depending on household composition, and because our income data is based on individual income taxes, we need to make an assumption about the amount of income earners per household. For this, we assume that 75% of income earners that earn less than the Austrian minimum monthly wage does so voluntarily because they share income with someone earning above this threshold. We adjust our household-income data accordingly by randomly selecting 75% of individuals earning below the minimum monthly wage and placing them together in a household with a higher income earner. This method produces realistic statistics on at-risk-of-poverty, which is 13% of households in our dataset and 17% according to Statistics Austria in 2023 for the whole of Austria.

If affordable, households face the decision to purchase insurance coverage, and invest in wet- and dry-flood-proofing measures. In our simulation, these decisions are based on the value of SEU of each choice, which are given in Equation 1. For each simulated household the SEU of purchasing insurance, investing in DRR, and not doing either of these, is estimated. Importantly, households can choose to both purchase insurance and invest in DRR, the combination of which generates financial benefits in the form of a reduced insurance premium.

$$
\begin{aligned}
\text{SEU(base)}_{j,i,t} =& \beta_j p_i U(W_{j,t} - \gamma_j L_{i,t}) + (1 - \beta_j p_i) U(W_{j,t}) \\
\text{SEU(insurance)}_{j,i,t} =& \beta_j p_i U(W_{j,t} - \pi_{i,t} - \alpha\gamma_j L_{i,t}) + (1 - \beta_j p_i) U(W_{j,t} - \pi_{i,t}) \\
\text{SEU(DRR)}_{j,i,t} =& \beta_j p_i U(W_{j,t} - C - (1-\delta)\gamma_j L_{i,t}) + (1 - \beta_j p_i) U(W_{j,t} - C)
\end{aligned} \tag{1}
$$

Each option in Equation 1 evaluates SEU by combining two possible outcomes; either a flood occurs with probability p_i, or there is no flooding. The subscript i denotes on which 1x1km grid-cell the simulated household is located. Because this is subjective expected utility, what counts in the decision-making process is the perceived flood probability, which we assume is based on the local flood protection standard, taken from Scussolini et al., 2016.

With flood probability p_i the household faces flood losses $L_{i,t}$, where the subscript t indicates the year being assessed (2010 or 2080). $L_{i,t}$ is the result of applying the flood probability p_i to the flood probability-impact curve (see Section 2.1). Expected utility is simulated over the impact of flooding on overall wealth, meaning we subtract the flood losses $L_{i,t}$ from a household's overall available financial means $W_{j,t}$, which is determined as a fixed proportion of household income[2]. Both the wealth impact of flooding, as well as the state where no flood occurs (and wealth remains complete), are transformed using a logarithmic utility function U, which is characterized by constant relative risk aversion, and is considered suitable to simulate human decision-making under risk (Wakker, 2008).

So far, our description of SEU(base) may be considered to represent a rather rational individual. To account for systematic biases concerning the perception of low-probability high-impact risks, such as flooding, we transform the flood probability p_i and impact $L_{j,i,t}$ parameters based on empirical findings (Mol et al., 2020). More specifically, for each household β_j is drawn randomly from a normal distribution with $\mu = 1.2$ and $\sigma = 0.2$, representing a general tendency to overestimate flood probabilities. On the contrary, flood impacts are generally underestimated in our simulation, with γ_j being drawn randomly from a distribution with $\mu = 0.7$ and $\sigma = 0.2$.

SEU(insurance) in Equation 1 introduces insurance coverage and costs to the choice framework. $\pi_{i,t}$ captures the household's insurance premium, as explained in Section 2.2. α represents the insurance deductible, which is the share of flood losses that need to be covered by the insureds themselves. It is important to note that insurance premiums need to be paid irrespective of whether a flood occurs. The SEU(DRR) estimation adds the DRR-investment cost C and the effectiveness of the measure to reduce flood risk (δ). Our simulation considers two types of measures; wet- and dry flood-proofing, for which we apply standardized costs of €16.000 and €23.000 respectively, based on estimations in (Aerts, 2018), and for which we maintain risk-reduction rates of 12.8% and 24.6%, based on findings in Hudson et al., 2014.

[2]as proposed by Eurostat (Ahamdanech Zarco, 2010). The wealth ratio for Austria is estimated at 1.86.

2.4 Impacts on household finances

The aim of this study is to assess the distributional impacts of flood risk, flood adaptation options, and insurance policy. This objective is pursued by simulating to what extent insurance premiums and adaptation costs are a barrier to the ability of households to reduce damage or recovery costs after a flood, and, ultimately, what the impact of a flood is on a household's wealth, taking into account the application of risk-reduction measures and insurance coverage. This is done for each simulated household located in a floodplain, but the model output is aggregated to three income groups, which are classified by dividing the income distribution into three equally sized groups. The low-income group (Q1) is made up of all households below the 33^{rd} percentile of the income distribution, which is €25317. For the middle- (Q2) and high-income (Q3) groups this threshold is respectively €35468 and €48239. The final assessment done in this study is to estimate the impact of a 100-year flood event as a share of household wealth. For this purpose, a household's wealth is approximated as a fixed proportion of its annual income, as proposed by Eurostat (Ahamdanech Zarco, 2010).

3 Results and discussion

Using GLOFRIS the total EAD in Austria is estimated at €161.5 million in 2010, which is projected to become €498 million by 2080 under RCP4.5-SSP2. Assuming the Austrian Catastrophe Fund covers 30% of this risk (€48.5 million in 2010 and €149.5 million in 2080), and Austrian insurers cover 5% (€8 million in 2010 and €25 million in 2080), the annual insurance protection gap is €105 million in 2010 and €324 million in 2080. Expressing the insurance protection gap in terms of EAD is useful for policymakers to prepare for potential additional disaster relief, however, it is an insignificant amount when compared to a single rare event. For example, the 2024 floods in Austria, as a result of storm Boris, is estimated to have caused €700 million in damages to households (Friesenbichler et al., 2024).

The Austrian insurance protection gap can be reduced by means of an insurance policy reform. In the following we assess the implications of such reforms on insurance premiums, on household finances, on the development of future flood risk, and on reducing the insurance protection gap for different income groups.

Figure 1 presents several plots showing modeled flood insurance premiums in Austria for 2010 and 2080. Panel A shows boxplots of risk-based flood insurance premiums in all of Austria for 2010 (blue), and 2080 under RCP4.5-SSP2 (red) and RCP8.5-SSP5 (green). Besides risk-based premiums under current flood protection standards, the plot also shows the development of premiums when flood protection standards are raised following dedications made by Austrian FRM. In 2010, under current protection standards, half of all risk-based insurance premiums are in between €1050 and €9050 annually. However, in extreme cases premiums may reach as much as €20.000. Panel C shows the spatial distribution of risk-based flood insurance premiums in 2010. It can be seen that premiums are particularly high in several areas surrounding the Danube, as well as several sporadic areas in the south of the country. It is important to note that these insurance premiums represent a hypothetical situation where premiums reflect risk on a detailed local scale. In reality, premiums are often lower due to lower levels of risk coverage, higher degrees of premium cross-subsidization, premium and coverage regulation, and pooling of different types of risk by insurers (Seifert-Dähnn, 2018). Nonetheless, if regulation allows it, a competitive privatized insurance system will advance towards premiums that increasingly reflect risk of individual policyholders (Lamond & Penning-Rowsell, 2014). For properties in particularly high risk-areas, an actuarially sound flood insurance premium, then, may be as high as several percentages of the property value (OECD, 2016).

In Panel A we can see that premiums rise towards 2080 under both scenarios, but to a larger extent under RCP8.5-SSP5. Improving protection standards has substantial impacts on reducing premiums in 2010, for which it almost halves the median premium. However, this strategy becomes less effective over time, as increasing flood risk reduces the effectiveness of current protection standards.

Panel B of Figure 1 presents the size of premiums under flat-rate and partially risk-based flood insurance systems. Flat-rate premiums are homogeneous for all Austrian households, which is why this data is shown as a single point. Under partially risk-based premiums, almost all (76%) of the areas at risk of flooding are projected to reach the premium-cap of 1.8% of median income. Since this is insufficient variation to construct a boxplot, also this data is displayed as a single point. Under flat-rate flood insurance, the premium is €130 in 2010, rising up to €385 and €440 in 2080 under RCP4.5-SSP2 and RCP8.5-SSP5 respectively. An important note here is that, whereas risk-based flood insurance only applies and is only paid for by households at risk of riverine flooding, which are 420.000 households in 2010 and 591.000 in 2080 under RCP8.5-SSP5, flat-rate insurance spreads flood risk equally amongst Austrian households, meaning the premium needs to be paid by all 4.1 million households in Austria. Under partially risk-based insurance, most households at risk of flooding pay a capped premium, where the excess risk (the amount above this premium cap) is shared amongst households with lower or no risk. In 2010, where the premium cap is €565 (paid for by 320.000 households), the excess flood risk means an €8 annual premium for households with lower or no flood risk.

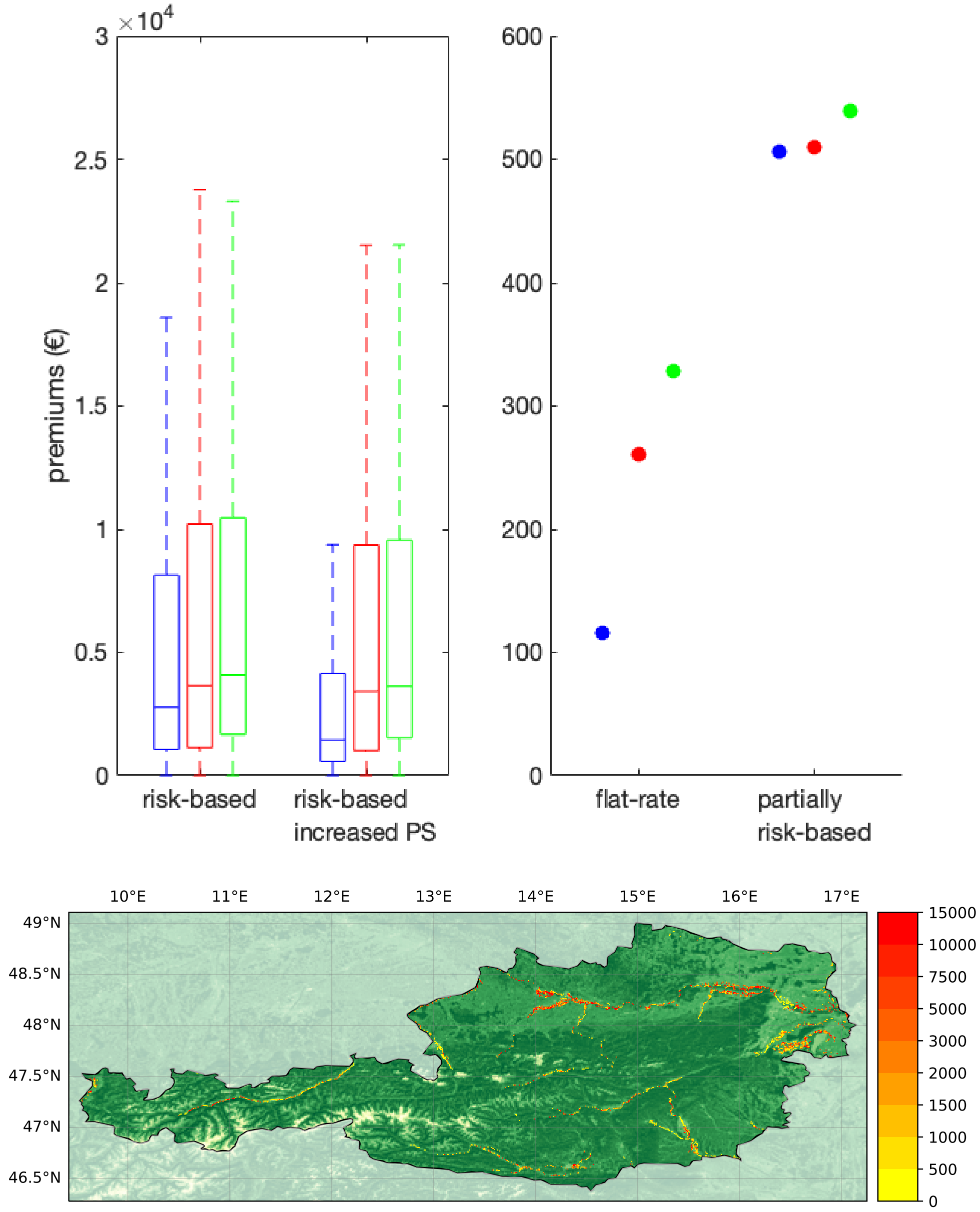

Figure 1: (Modeled flood insurance premiums. (top): Aggregated for all of Austria, shown separately for the four insurance and FRM scenarios, and for 2010 (blue), 2080 under RCP4.5-SSP2 (red), and 2080 RCP8.5-SSP5 (green). (bottom): The spatial distribution of premiums in Austria in 2010 for the risk-based insurance scenario.

An important issue caused by increasingly risk-based flood insurance is that premiums exceed the willingness of households to pay for coverage, or become unaffordable. Although premiums reflect the risk of policyholders, meaning that risk-averse households would purchase insurance to spread wealth if price loading is sufficiently low, households tend to underestimate low-probability high-impact risks, such as flood risk (Kunreuther, 2021). High premiums mean that the difference between households' subjective risk and premiums is potentially larger, causing more households to forego insurance coverage. For those that do want flood coverage, or when insurance is mandatory, unaffordability of premiums may be an obstacle. Unaffordability is a normative concept, meaning its assessment can be contextual and subjective (Hudson, 2018). An often applied method is to assess the ratio of overall housing costs to household income. For example, based on US-legislature, a housing affordability assessment by Dixon et al., 2017 considers housing 'burdensome' if expenses on rent or mortgage, property taxes, and insurance, exceeds 40% of household income. In an extensive survey of New York City they find this definition applies to 22% of the studied population under the current insurance premium-setting strategy, whereas this may increase to 33% when more accurate risk-based premiums are applied. The EU maintains a similar benchmark of 40% for assessing the 'housing cost overburden rate'.

Figure 2 presents the share of household income spent on flood coverage, aggregated to each of the three income groups for the Austrian population living in floodplains, for each of the assessed insurance policy scenarios in Figure 1, and for the baseline and future flood conditions. Under risk-based insurance, the share of income spent on flood insurance coverage in 2010 is less than 13% for half the floodplain population in the lowest income group. For the other half of this income group, premiums as a share of income reaches as high as 150%, meaning the premium is higher than income. Keeping the insurance system unchanged, premiums as a share of income rise steadily towards 2080, with higher impacts under RCP8.5-SSP5 than RCP4.5-SSP2. Most outcomes in Figure 2 follow a similar pattern of outcomes as the size of premiums in Figure 1. A minor irregularity can be observed for partially risk-based premiums, where future premiums under RCP4.5-SSP2 make up a slightly smaller share of income than under baseline levels of flood risk. The reason for this is that RCP4.5-SSP2 increases the area at risk of flooding compared to the baseline, but many of the new areas at risk face relatively low flood risk. Therefore, relatively fewer areas that reach the premium cap, meaning the average premium for those located in floodplains is slightly lower.

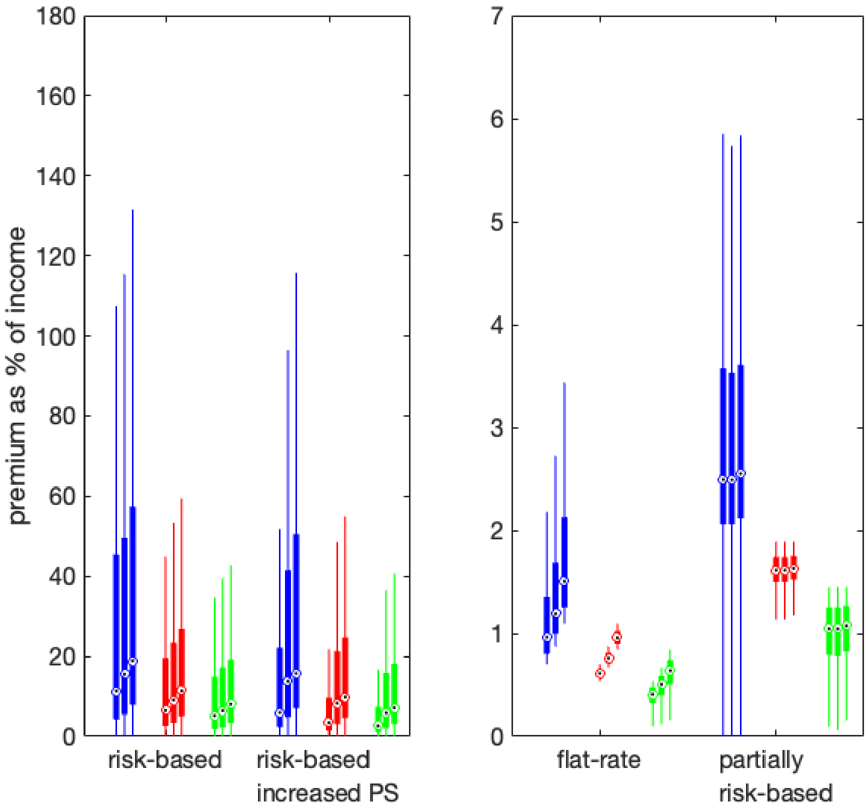

Figure 2: Percentage of household income spent on flood insurance in 2010, on average for three income groups, under four insurance scenarios. Blue boxplots refer to low-income households, red boxplots to middle-income households, and green boxplots to high-income households.

The flood insurance premium as a share of household income gives an indication of the budgetary impact of flood coverage for households. However, if we want to know for how many households flood insurance may be too expensive, forcing them into poverty or to forego insurance coverage, we may consider the risk-of-poverty threshold. The EU sets this threshold at 60% of national median equivalised disposable income, which for Austria is a monthly income of €1392 (in 2023) for single-person households and €2924 for 4-person households (EAPN, 2024). Flood insurance may be deemed unaffordable when a household's income is below this threshold (depending on household composition) or falls below it as a result of paying the premium. In Figure 3 we present the number of households for whom insurance is deemed unaffordable considering these criteria, for each income group, for the four proposed insurance/FRM scenarios, and for the baseline and two future flood scenarios. A striking result in this figure is that the baseline level of unaffordability is relatively insensitive the insurance/FRM scenarios compared to premiums as a share of income shown in Figure 2. From the floodplain households in the baseline scenario, not considering flood insurance costs, approximately 16% are deemed to live in a state of poverty or are at-risk of poverty, which is slightly lower than the Austrian national at-risk-of-poverty rate (17.7%)[3].

Under risk-based flood insurance, premiums are expected to be unaffordable for 34% of the population at risk of flooding, 23% of which is made up of the lowest income group. Under flood insurance with flat-rate and capped premium systems, uaffordability is virtually nonexistent for middle- and higher income groups, whereas it is problematic for 16% of the lowest income group. However, considering that almost 16% of households are at-risk-of-poverty without insurance costs, unaffordability induced by these premiums is negligible. Future unaffordability increases across all insurance systems and income groups under RCP8.5-SSP5. Under RCP4.5-SSP2 we can observe slightly lower increases in the population for whom insurance is unaffordable, except for high-income households under risk-based insurance, where unaffordability slightly declines compared to the baseline scenario. Although premiums as a share of income does rise for this income group (as seen in Figure 2), the amount of households in this income group exposed to floods in 2080 under this scenario slightly declines after 2010. Another noteworthy observation in Figure 3 is that increasing protection standards does seem effective to somewhat reduce unaffordability across all income groups under baseline flood conditions. For low-income households, unaffordability reduces from 23% to 20% of the population at risk of floods. However, considering future flood conditions, it can be seen that increasing flood protection standards to guarantee a minimum protection against 1/100-year flood events is insufficient to substantially reduce future unaffordfability. Limiting the impacts of climate change on household budgets and insurance unaffordability may require more substantial improvements in protection standards, or changes in insurance arrangements towards more risk-sharing.

[3]https://www.statistik.at/en/statistics/population-and-society/income-and-living-conditions/poverty

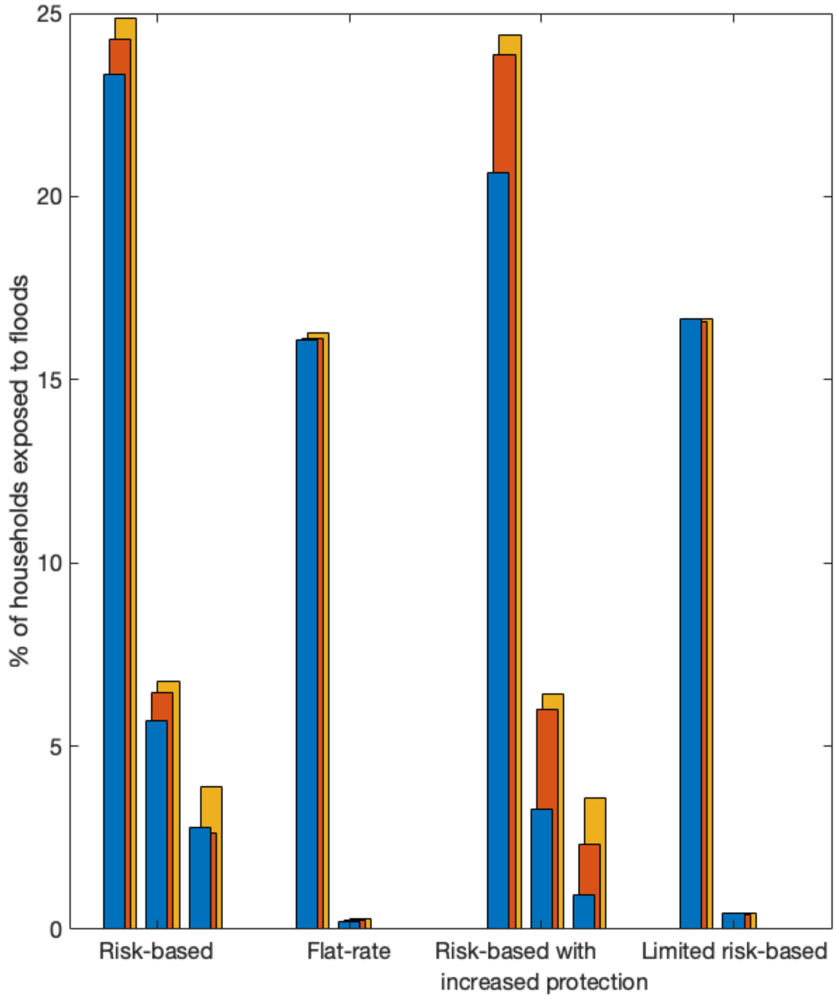

Figure 3: The amount of households in Austria for whom flood insurance is deemed unaffordable, following the risk-of-poverty threshold. Amounts are shown separately for each income group (left = low-income, middle = middle-income, right = high-income), for 2010 (blue), for 2080 under RCP4.5 (orange), and 2080 under RCP8.5 (yellow), and for four different insurance systems.

The most important advantage of risk-based premiums is that it signals risk, which may stimulate risk-reduction effort by policyholders. Households may thus reduce their risk-based flood premium by installing risk reduction measures if they are located in a flood zone, or entirely avoid high premiums by settling or relocating away from these areas. For example, dwellings in flood zones may be made more flood resistant by installing flood barriers or applying a flood resistant building-foundation. Following Aerts, 2018, who systematically reviewed the costs and effectiveness of such measures, dry-proofing (including flood barriers) reduces flood risk by about 13%, while wet-proofing (a flood resistant foundation) reduces approximately 25% of flood risk. Installing such measures may, thus, substantially reduce premiums, if premiums reflect household-level risk with sufficient accuracy. Whether households are inclined to invest in these DRR-measures is limited due to high upfront costs and the discounting of future benefits, but also due to the tendency of individuals to underestimate flood impacts (Mol et al., 2020), which may reduce the perceived need for these measures (Bubeck et al., 2012). Using a household decision-model based on subjective expected utility (SEU) theory, we assess the extent to which flood risk may be mitigated by households' investments in flood-proofing. Moreover, our simulation allows us to assess this household-level DRR under financial incentives created by the different insurance systems.

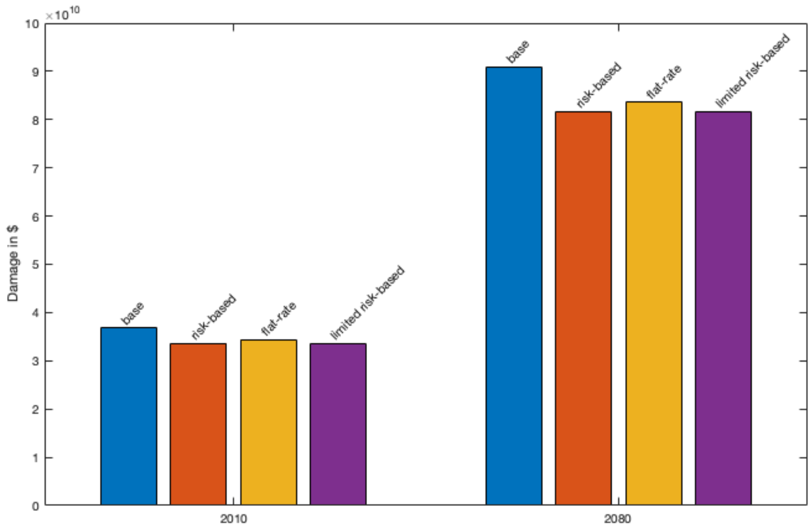

Figure 4: Projected damage caused by a 100-year flood in all Austrian floodplains simultaneously. Flood impacts are shown for 2010 and 2080, considering modeled flood adaptation by households under different insurance incentive structures.

Figure 4 shows the damage if all Austrian floodplains were to face a 100-year flood simultaneously, as well as to what extent these damages may be mitigated by households' application of DRR-measures. Increasing flood protection to 100-year standards, as was shown in earlier plots, would completely diminish damages in the scenario shown in this figure. If current protection standards are maintained, it can be seen that flood impacts more than double towards 2080, considering the high-end scenario RCP8.5-SSP5. The option to reduce risk by applying adaptation measures results in reduced flood impacts of close to 8% under a system with flat-rate premiums, which does not give financial incentives for risk-reduction effort. Risk-based, or limited risk-based, premiums do apply such financial incentives through premium discounts, and show a reduction in flood impacts of close to 10% in our projections. Limited effectiveness of risk-based premiums to stimulate risk-reduction effort may be caused by low insurance uptake when coverage is optional. Also, the DRR-investment cost on top of paying a risk-based premium is unaffordable for certain households that are able and willing to purchase flood insurance. Under limited risk-based premiums, the financial incentive to apply DRR-measures is reduced by the premium cap, which, for households that pay the capped premium, makes it financially ineffectual to invest in DRR. However, raising the premium cap will increase the DRR-investments under this system. The size of this premium cap is, therefore, a political deliberation between solidarity and efficiency objectives.

Results presented in Figure 4 align with empirical literature on DRR-investments by households and the effect of disaster compensation mechanisms on this. Firstly, there are considerable perceived obstacles to investing in flood preparedness, including both DRR and insurance uptake. Besides financial costs, literature finds that the underestimation of risk and lacking coping appraisals of individuals are barriers to flood preparedness (Bubeck et al., 2012). Mol et al., 2020 also find that the investment in flood preparedness by households is unconnected to insurance coverage. Whereas moral hazard is an important concept in the insurance industry, there is no evidence that flood insurance coverage discourages investing in DRR. Due to the absence of moral hazard, the potential effect that financial incentives through premium discounts may have on DRR-investments is lower in our theoretical model. There is, however, no clear empirical evidence of the effect of premium discounts on DRR-effort (Kousky, 2019), which is largely because such flood insurance policies are in practice hardly applied. Important barriers to the application of premium discounts for DRR-uptake include the short-term nature of insurance contracts, the lack of robust evidence of the risk-reduction potential of many DRR-measures, and high administrative costs in maintaining building-specific insurance contracts (Surminski & Eldridge, 2017). Novel object-based flood risk simulations show potential to increase the accuracy and reduce the costs of flood risk assessments of individual properties, also considering specific DRR-measures (Englhardt et al., 2019). Moreover, a building-level climate- or flood-risk label could be developed to take into account the installation of DRR-measures (Meyer & Hartmann, 2023), which would reduce the administrative costs of insurers to account for these measures in premium-setting.

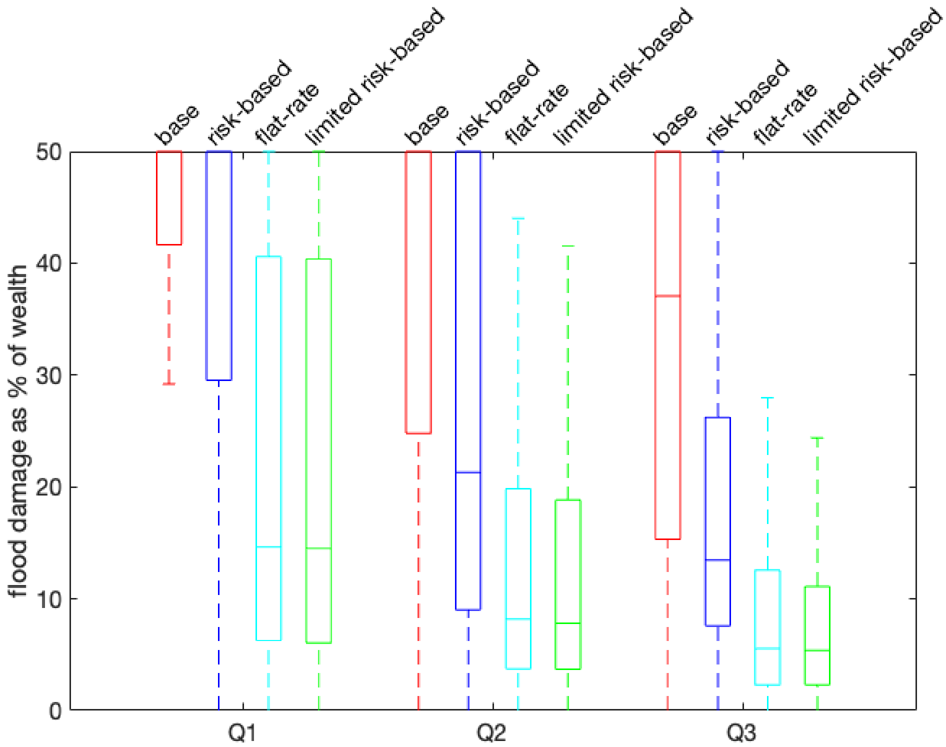

Figure 5: Boxplots of projected uninsured flood damage in 2010 as a share of household wealth caused by a 100-year flood in all Austrian floodplains simultaneously. Results are shown for three income groups (Q1 = low-income, Q3 = high-income) and different insurance strategies. The red plots show a scenario where there is no option to insure and invest in DRR measures. The blue plots show a scenario where households have the option to insure against risk-based premiums and invest in DRR measures. The yellow and green plots show scenarios of public and public-private insurance, where insurance is mandatory, and DRR optional.

An important barrier to household-level flood adaptation and insurance uptake is high insurance premiums or upfront investment costs. Inevitably, income has a considerable impact on the decision of households to invest in DRR. In Figure 5 we explore how income in our simulation impacts the extent to which households are able to reduce their flood risk or cover flood risk through insurance. Without the option of adaptation or insurance coverage (red boxplots), damage caused by a 100-year flood will comprise almost all of the wealth owned by low income households (Q1). For middle- (Q2) and high-income households (Q3) the impact of such floods is also high, but notably lower. When we introduce the option to purchase insurance and apply DRR-measures (blue boxplots), it can be seen that uninsured risk reduces for all income segments, but more notably with higher income. With insurance and adaptation options, the median uninsured flood impact is still 100% of wealth for low-income households, whereas this reduces from 100% to 43% for middle-, and from 74% to 30% for high-income households. The cyan and green boxplots show uncovered flood damage as a share of household wealth under public and public-private insurance structures respectively.

Because insurance uptake is mandatory in these insurance systems, household income does not affect insurance uptake. For this reason, uncovered risk is substantially reduced for all income segments. The reduction in flood impact as a share of household wealth is highest for middle-income households under the public-private insurance scenario with limited risk-based premiums (green boxplots), where median uncovered impacts decline from 100% to 15% of wealth. This is because the middle-income segment is mostly able to afford DRR-measures, and the risk-reduction as a share of wealth is higher for this income segment compared to the high-income group. The trend observed in Figure 5 becomes critically problematic when assessing future climate change impacts. In Figure 6, in Appendix 5, it can be seen that flood impacts as a share of household wealth increases for all, but much more severely for low-income households, who are also substantially more restricted to reduce the financial impacts of floods.

The results presented in Figure 5 imply that the insurance and adaptation protection gaps are more acute for lower income groups in Austrian society. A change from the current system, where additional coverage besides the 20-50% of damage covered by the Catastrophe Fund is hardly available, to an insurance system where private insurers increase their coverage against risk-based premiums, would predominantly benefit higher income groups and leave the insurance and adaptation protection gaps for lower-income households to a large extent unchanged. Such developments may exacerbate wealth inequalities, as low-income households face higher flood impacts and have a lower capacity to recover from these impacts Sayers et al., 2018. Ultimately, this development may lead to a spatial concentration of low-income households in high-risk areas, attracted by lower property prices, or unable to relocate to safer areas (Tate et al., 2021). Fortunately, there are multiple measures that can be taken to prevent such an outcome. A higher degree of cross-subsidization of flood premiums between low- and high-risk households, preferably with insurance uptake requirements for all households in Austria, will increase the accessibility of insurance coverage for low-income households. To maintain financial incentives for households to adapt to flood risk, the degree of risk-sharing may be limited. In addition to cross-subsidization of premiums, the adaptation gap for low-income households can be reduced by means of subsidies or low-interest loans for the flood-proofing of properties, as proposed by Kunreuther, 2021. Lastly, in areas where flood vulnerability is particularly high, improved flood protection infrastructure may be prioritized, as suggested by Sayers et al., 2018 and Tate et al., 2021.

4 Conclusion

This study addresses the challenge of how to reduce the Austrian flood insurance protection gap in an equitable way. In Austria, a public disaster compensation fund provides incomplete funding of damage to residential buildings after a flood. Although households are encouraged to obtain insurance coverage for the risk not covered by this fund, the degree of risk privately insured is meager. As a result of this coverage gap, floods become an increasing liability for the Austrian government, who is often implicitly obliged to provide additional compensation, outside of the Catastrophe Fund's budget. Increasing flood risk due to climate- and socio-economic change will exacerbate these issues. Although Austria is the focus of this study, it is important to note that a high insurance coverage gap for natural disaster risk is deemed problematic in many countries (Bellia et al., 2023), making this a case-study for a more broadly observed issue.

For this study, we are particularly interested to explore how flooding impacts households in different income groups, and how policy changes concerning the organization of flood insurance and FRM may affect the distributional impacts of floods. We systematically compare the effect of several policy-changes on the impact of floods on household finances, where households are aggregated into income groups. Policy changes include the introduction of a public reinsurer, which should increase the willingness of insurers to cover flood risk in Austria; increasing coverage by the public Catastrophe Fund; an insurance system with capped risk-based premiums; and a status-quo insurance situation, but where flood protection standards (i.e., dykes) are improved. For each of these policy-scenarios, we simulate the decision of households to purchase insurance (if voluntary) and apply DRR-measures, using a subjective expected utility decision-model. Household income is an important driver of the uptake of these choices, data for which is obtained on household-level.

This study finds that the design of flood insurance markets notably impacts inequality in the ability to adapt to increasing flood risk. If the development of a private flood insurance market is pursued, with fully risk-based pricing, high premiums in areas facing considerable flood risk will make insurance coverage inaccessible for many, but particularly for low-income households residing there. Increasing flood protection standards to withstand a 100-year flood everywhere in Austria more than halves the risk-based premium in our baseline analysis (2010), but the effectiveness of this strategy to limit the costs for high-risk households diminishes for analyses that consider future flood risk under climate change. The most effective strategy to limit the financial burden of floods on households is to design an insurance system with mandatory coverage and a degree of risk-sharing amongst policyholders. This can be realized through an expansion of the Austrian Catastrophe Fund, which covers damages and is capitalized by income, corporate taxes, and capital yields (Hanger et al., 2018). Alternatively, the Austrian government may instate a premium cap and enforce a degree of premium cross-subsidization, which may be done through a government-backed (re)insurance pool such as the Flood Re program in the UK.

There are, however, important implications associated with risk-sharing. Most notable is the argument that it reduces the incentive for policyholders to adapt to high flood risk, such as by applying DRR-measures or avoiding settling in floodplains. In our analysis, however, we find that the premium incentive may be insufficiently effective at reducing risk to justify high inequalities in the ability of households to purchase insurance and adaptation measures. Unaffordability issues may outweigh the benefits of reduced risk under fully risk-based insurance pricing. Limited risk-based pricing, with a cap on insurance premiums, performs better at balancing the objectives of maintaining affordability, stimulating DRR-effort, and minimizing inequality concerning the ability of households to cope with the financial impacts of floods.

This study applies detailed information on household income to assess the financial barriers to insurance and DRR uptake. Although affordability is an important condition for the uptake of these measures and, therefore, flood coping capacities, it is not the only factor.

Research finds a wide range of socioeconomic indicators of flood coping capacities, including indicators for flood preparedness (Bubeck et al., 2012). An assessment of future flood insurance and adaptation gaps that integrates a more diverse range of relevant socioeconomic characteristics is an interesting consideration for future research.

5 Appendix

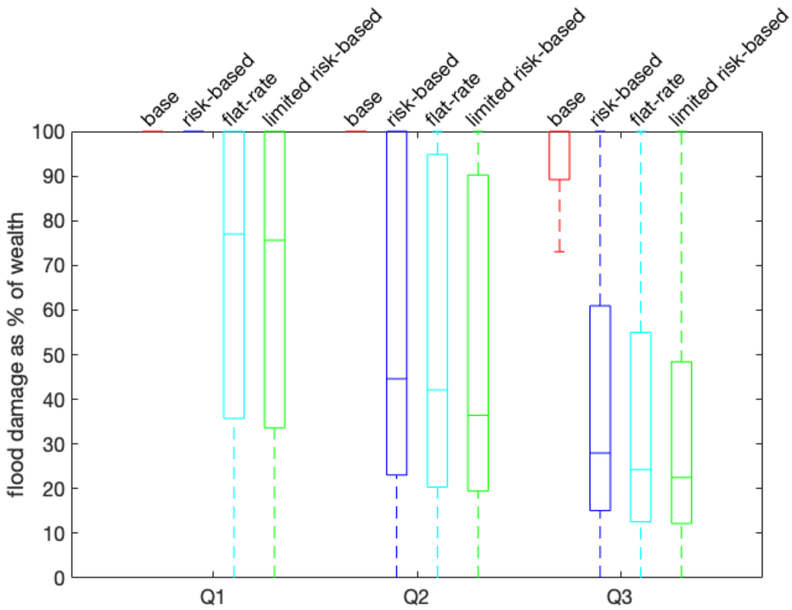

Figure 6: Boxplots of projected uninsured flood damage in 2080 as a share of household wealth caused by a 100-year flood in all Austrian floodplains simultaneously. Results are shown for three income groups and different insurance strategies. The red plots show a scenario where there is no option to insure and invest in DRR measures. The blue plots show a scenario where households have the option to insure against risk-based premiums and invest in DRR measures. The yellow and green plots show scenarios of public and public-private insurance, where insurance is mandatory, and DRR optional.

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