Analysis

Future Public Sector Flood Risk and Risk Sharing Arrangements: An Assessment for Austria

Christian Unterberger\textsuperscript{a,b,c,}\textsuperscript{*}, Paul Hudson\textsuperscript{d}, W.J. Wouter Botzen\textsuperscript{e,f,g}, Katharina Schroer\textsuperscript{a,b}, Karl W. Steininger\textsuperscript{a,h}

\textsuperscript{a} Wegener Center for Climate and Global Change, University of Graz, Austria
\textsuperscript{b} FWF-DK Climate Change, University of Graz, Austria
\textsuperscript{c} Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland
\textsuperscript{d} Institute of Earth and Environmental Science, University of Potsdam, Germany
\textsuperscript{e} Institute for Environmental Studies, VU University, Amsterdam, the Netherlands
\textsuperscript{f} Utrecht University School of Economics, Utrecht University, the Netherlands
\textsuperscript{g} Risk Management and Decision Processes Centre, The Wharton School, University of Pennsylvania, USA
\textsuperscript{h} Department of Economics, University of Graz, Austria

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ABSTRACT

Climate change, along with socio-economic development, will increase the economic impacts of floods. While the factors that influence flood risk to private property have been extensively studied, the risk that natural disasters pose to public infrastructure and the resulting implications on public sector budgets, have received less attention. We address this gap by developing a two-staged model framework, which first assesses the flood risk to public infrastructure in Austria. Combining exposure and vulnerability information at the building level with inundation maps, we project an increase in riverine flood damage, which progressively burdens public budgets. Second, the risk estimates are integrated into an insurance model, which analyzes three different compensation arrangements in terms of the monetary burden they place on future governments’ budgets and the respective volatility of payments. Formalized insurance compensation arrangements offer incentives for risk reduction measures, which lower the burden on public budgets by reducing the vulnerability of buildings that are exposed to flooding. They also significantly reduce the volatility of payments and thereby improve the predictability of flood damage expenditures. These features indicate that more formalized insurance arrangements are an improvement over the purely public compensation arrangement currently in place in Austria.

1. Introduction

Floods account for a major share of natural hazard losses experienced in the European Union between 1980 and 2016 (European Environment Agency, 2017). Socioeconomic development combined with ongoing climate change will further increase flood risks, due to worsening flood conditions and more people and assets being placed in harm’s way (Alfieri et al., 2018; Rojas et al., 2013; Winsemius et al., 2016).

For governments, the projected increase in flood damages carries the risk of significantly burdening public budgets (Unterberger, 2018). In the aftermath of floods, governments must restore public infrastructure and often provide compensation to people and affected businesses for non-insured losses. For example, the German federal government created a special ad-hoc fund of €7.1 billion to provide support to those affected by the 2002 flood event. The role of governments as emergency risk managers exposes the public sector to significant risk. The responsibility to respond to the consequences of floods creates a large public contingent liability, which must be managed. This liability increases if the state is the only actor to bear this expenditure. Importantly, floods strike regardless of the economic circumstances or governments’ fiscal position. Therefore, governments should consider implementing mechanisms that protect their budgets from the impacts of floods, including strategies that ensure the adequate provision of funds for post disaster relief and reconstruction and incentives that limit flood damages (Cevik and Huang, 2018).

Insurance has emerged as an important player in flood risk management (Botzen and van den Bergh, 2008; Schwarze et al., 2011; Steininger et al., 2005; Surminski et al., 2015a, 2015b). Insurance coverage guarantees contractually specify ex-post compensation, while
The advantage of the two-staged model framework is its transferability to other countries and hazard classes. The flood risk model could easily employ inundation maps from other regions. Given that the relationship between the magnitude of the hazard and the damage it causes (as illustrated by the stage damage curves) can be established, provided that hazard maps and exposure data are available, the risk model can be applied to other hazard types. The advantage of the insurance model in that regard is its direct application of the estimates and spatial resolution of the risk model. Thus, it allows for the comparison of different compensation arrangements irrespective of hazard types, spatial scales, and geographic location.

The results indicate that a combination of risk transfer to private insurance companies, incentivizing cost efficient damage mitigation measures at the building level and collaboration between the public and the private sector represent an improvement over current practices. This is because governments gain more financial certainty, in addition to potentially lower flood losses due to the incentivized risk reduction. These two features reduce the overall pressure placed on public budgets in terms of reduced monetary burden and increased certainty of financial arrangements. While the pure monetary burden grows under insurance-based systems, the benefit of insurance is that the financial uncertainty caused by flood losses decreases since losses can be budgeted for in advance. Therefore, these results offer further support to the growing momentum toward increasing multi-sectorial partnerships in flood risk management (European Commission, 2017; Flood Re, 2018; Golnaraghi et al., 2017; Hochrainer-Stigler and Lorant, 2018; Insurance Europe, 2018; Surminski et al., 2015a, 2015b; The Geneva Association, 2018).

2. Methods: Flood Risk and Insurance Model

2.1. Flood Risk Model

The monetary loss $L$ caused by a given flood is a function of inundation depth $H$, the value of elements that can be damaged $E$, and their susceptibility to being damaged $V$ (Crichton, 2008). Flood risk, or the expected annual damage (EAD) is the probability-weighted sum of losses from all possible flood events.

$$ L = f(H, E, V) $$

Flood hazard information is obtained from the GLOFRIS model cascade (Ward et al., 2017) at a resolution of approximately 1 × 1 km². The current flood hazard is modeled by using meteorological data from the EU-WATCH project (Weedon et al., 2011). For the projections until 2080, meteorological fields from the ISIMIP data are applied to the GLOFRIS model (Frielier et al., 2016). These meteorological data are derived from five different global climate models (GCMs), which are run for one representative concentration pathway (RCP 8.5). The GLOFRIS model focuses on riverine floods rather than pluvial flooding, burst water mains, etc. The model has been successfully validated in a range of contexts (Ward et al., 2017, 2013; Winsenmius et al., 2013).

For the current climate and future projections, flood inundation maps for the following return periods are used: 1/2; 1/5; 1/10; 1/25; 1/50; 1/100; 1/250; 1/500; 1/1000. Flood protection, such as dikes and increased retention basins, lowers risk by preventing certain floods from occurring. Flood protection measures are included in the model by excluding damage from flood events with return periods that are higher than or equal to the protection standard of the measure, which means that the damage for that flood event is set equal to 0. As an illustration, if flood protection measures for up to 30-year events are assumed, then only events that happen less frequently than 1 in 30 years cause damage. Currently 88% of the areas that exhibit significant risk of

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1 The GCMs are: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, Nor-ESM1-M.
flooded, given particular inundation depths. The applied stage damage curves and values at risk are based on de Moel and Aerts (2011) and de Moel et al. (2014) and are explained in the Supplementary material (S1). To reduce the vulnerability of buildings, flood-proofing measures at the building level can be applied, which change the relevant stage damage curve. We focus on dry flood-proofing measures as compared to other measures dry flood-proofing is cheaper and easier to install (Aerts et al., 2013). Moreover, dry flood-proofing does not require a large scale intrusive retrofitting of public buildings which are actively providing needed public services. Dry flood-proofing is assumed to be effective until an inundation depth of 1 m is reached, after which the measure fails (de Moel et al., 2014). The benefits of dry flood-proofing can be seen through the change in the EAD. The investment and maintenance costs associated with dry flood-proofing per building type are further described in the Supplementary material (S2). Finally, vulnerability is assumed to be static unless a property manager is actively incentivized to alter his or her building’s vulnerability. This is because there is currently limited information on how the autonomous behavior of stakeholders alters vulnerability or riverine flood inundation patterns (Aerts et al., 2018).

With the flood return periods and modeled damages, exceedance probability loss curves and the EAD can be derived (Ward et al., 2011). The overall EAD is disaggregated according to Austria’s 99 political districts. It is assumed that damage to buildings that fall within the classification of education, health, culture, miscellaneous, sport fields and parks fall within the domain of the regional governments of the individual political districts, whereas the federal government is responsible for damage to military and railway infrastructure.

Fig. 2 provides a summary overview of the input variables and model chain used to derive the EAD.

### 2.2. Budgetary Burden and Insurance Model

The pressure on government budgets at both federal and political district level can be measured as the expected expenditure on insurance premiums plus the uncompensated reconstruction costs. The smaller this amount is the less pressure is placed on budgets. The budget pressure is shown in Eq. (2), in which \( \pi \) is the cost of gaining access to

\[ \pi = \text{cost of gaining access to} \]

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Additionally, we note that the potential for the dry flood-proofing measures to fail shows how it is still useful to maintain flood insurance coverage.
financing mechanisms, FR shows the expected flood repair costs, which is equal to the EAD, while the government can receive financial support, H, or indemnity payments, I, net of any deductible, D.

\[ \text{Burden} = \pi + FR - H - (I - D) \] (2)

In estimating the burden that flood risk places on government budgets, the following three different insurance schemes are analyzed. First, we consider the compensation system currently in place in Austria, where flood risk is borne by the public sector. In the second scheme, flood risk is transferred to a private insurer. It is assumed that the governments purchase the offered insurance policy, which provides suitable coverage. The advantage of insurance is that it provides more certainty regarding annual expenses, as compensation is no longer financed in an ad-hoc manner after a flood. Moreover, it is assumed that there is a clearly defined riverine flood insurance policy, which can be an extension of current insurance policies covering a set of more frequent risks, i.e. fire. Generally, insurance premiums exceed the expected value of risk due to loading factors (shown in Eqs. (5) and (6)), which occur due to transaction costs, profit motivations, business costs, uncertainty surcharges, etc. Moreover, it should be considered that impacts can be correlated since several floods can occur in a single year and a large number of claims can be made in a small area. Private insurers deal with this possibility of extremely high losses by purchasing insurance coverage from reinsurers. Private reinsurers achieve a greater degree of spatiotemporal diversification compared to primary insurers, but still charge a premium surcharge for covering extreme risks due to risk aversion. In contrast, a reinsurer financed by the public sector can handle extreme damage through borrowing or taxation.

Therefore, in the third scheme, we examine a public-private insurance mechanism in which the federal government acts as a risk neutral reinsurer. The main advantage of such a public-private arrangement is a reduction in the reliance on risk-averse private reinsurers. Alternatively, a public sector reinsurer can act - akin to reprofusing the role of the European Union Solidarity Fund as proposed by Hochrainer-Stigler et al. (2010) - as a part of a public reinsurance network for public infrastructure. We simplify the motives of individual private insurers by noting the general interest in increasing collaboration between the insurance industry and the public sector in covering flood risk (European Commission, 2017; Flood Re, 2018; Golnaraghi et al., 2017; Hochrainer-Stigler and Lorant, 2018; Surminski et al., 2015a, 2015b; The Geneva Association, 2018).

2.2.1. Current Compensation System

Under the current compensation system, the budgetary burden on the federal government’s budget is \( \text{Federal}_{PS} \) for a given protection standards \( PS \) at time \( t \) (Eq. (3)). The \( \text{FR} \) element for the federal government is the sum of the EAD to federally owned infrastructure and the share \( \tau \) of the expected compensation payments to the regional governments \( i \sum_{i=1}^{99} \text{FR}_{\text{Regional},PS} \). The prime purpose of the disaster fund is not to provide compensation and as such the remaining elements, \( \pi \), \( H \), \( (I - D) \) are set equal to 0.

The budgetary burden for the political districts (\( \text{Regional}_{PS} \) in Eq. (4)) maintains the assumption that the \( \pi \) and \( D \) elements are set equal to 0, as the compensation is effectively free, complete, and not pre-financed. However, it is now assumed that the \( H \) element is equal to \( (1 - \tau)\text{FR}_{\text{Regional},PS} \), where \( \tau \) is equal to 0.5, hence political districts only have to cover half of their EAD, based on the current practice (Austrian Ministry of Finance, 2012).

\[ \text{Federal}_{PS} = \text{FR}_{\text{Federal},PS} + \tau \sum_{i=1}^{99} \text{FR}_{\text{Regional},PS} \] (3)

\[ \text{Regional}_{PS} = (1 - \tau)\text{FR}_{\text{Regional},PS} \] (4)

2.2.2. Risk Transfer to Private Insurer

When the risk is transferred to a private insurer, the \( \pi \) element of the

Fig. 2. Schematic overview of input data and model chain used to derive the expected annual damage. Adapted from de Moe et al. (2014).
budgetary burden is the premium that insurers request from each governmental body.

These premiums are calculated as \( n_{\text{federal}, \text{PS}} \) and \( n_{\text{regional}, \text{PS}} \) in Eqs. (5) and (6) for the federal and regional governments, respectively.

\[
\begin{align*}
n_{\text{federal}, \text{PS}} &= (1 + \lambda)((EAD_{\text{federal}, \text{PS}} - D_f) + \sigma_D^{\text{federal}, \text{CM}}) \\
n_{\text{regional}, \text{PS}} &= (1 + \lambda)((EAD_{\text{regional}, \text{PS}} - D_r) + \sigma_D^{\text{regional}, \text{CM}})
\end{align*}
\]

(5)

(6)

The core element of the premium is the EAD plus a surcharge to represent the volatility in annual losses which reflects risk aversion by reinsurers \( c \). This surcharge is calculated following Paudel et al. (2013), whereby it is the product of a risk aversion coefficient \( c \), set equal to 0.55 as in Paudel et al. (2013), and the sum of the standard deviation of losses \( \sigma_D^{\text{CM}} \) for the estimated exceedance curve and the standard deviation of EADs across climate models \( \sigma_D^{\text{CM}} \). On top of this core premium, insurers charge a further surcharge \( \lambda \) to cover administrative costs and to generate profit. Data from the OECD insurance statistics database shows that between 1996 and 2016, the ratio of gross operating costs to gross premiums in the non-life insurance sector was ~0.2. On top of this ratio we add a profit and risk aversion factor of 0.1, resulting in a total loading factor of 0.3, which matches Hudson et al. (2016). As a simplifying assumption we model the insurance industry as a single representative firm instead of multiple heterogeneous firms in a competitive market where each must decide which risks to insure in order to maximize its profitability. Future research could examine insurer behavior of multiple heterogeneous firms.

A deductible is present, as the use of deductibles are important to reduce the pressure on government budgets remains the same, except for the additional one-time payment necessary to implement dry flood-proofing. However, the property assigned to the federal government is usually not suitable for dry flood-proofing and as such the federal burden remains unchanged.

A regional government decides to employ a dry flood-proofing measure (DFP in Eq. (9)) if the net present value of the reduction in premiums, over the dry flood-proofing’s 20-year lifespan (with negligible maintenance costs), is larger than the upfront cost of employing the measure (see Eq. (9)). A discount rate \( r \) of 3.5% is used, which is the European Union’s recommended rate for Central European projects (Pálinkó and Szabó, 2012).

\[
DFP^{\text{PS}, \text{b}} = \begin{cases} 0 & \text{if } \sum_{i=0}^{20} \left( \frac{1}{1 + r} \right)^i < \cos \lambda, \text{b} \\ & \left( 1 + \lambda \right)(EAD_{\text{federal}, \text{PS}} + \sigma_D^{\text{federal}, \text{CM}}) \\ & \left( 1 + \lambda \right)(EAD_{\text{regional}, \text{PS}} + \sigma_D^{\text{regional}, \text{CM}}) \\ \end{cases}
\]

(9)

The decision to employ dry flood-proofing is done at the building class level \( b \), which means a regional government decides if it will flood-proof some combination of building classes. While these calculations could also be done at the building level, we focus on the aggregate building class level because a building level analysis is computationally too demanding in a country level study.

2.2.3. Public-Private Insurance Mechanism

Several studies have argued that reinsurance premiums can be quite volatile and high relative to the expected value of the reinsured loss (Hofman and Brukoff, 2006; Kunreuther and Pauly, 2005; Paudel et al., 2015). Therefore, we introduce a public-private insurance mechanism in which the federal government, or a network of governments, act as a risk neutral reinsurer for regional governments. Hence the \( c \) loading is equal to zero because a public sector reinsurer is less risk averse and less profit driven.

Under this arrangement: the budgetary burden for the federal government consists of a risk neutral premium to finance its own expected losses for the \( \pi \) element; the \( FR \) element consists of the repair costs for the federal government and the proportion of regional government losses it provides reinsurance for; the \( I \) element is the indemnity payment received net of the insurance deductible; the \( H \) element is, again, set equal to zero.

Additionally, the burden for the regional governments is different. The \( \pi \) for the regional governments is presented as \( n_{\text{Regional}, \text{PS}} \), which consists of the total premium charged for both the risk averse private and risk neutral public reinsurance coverage, with and without disaster risk reduction incentives. We assume that the federal government provides quota-style reinsurance whereby the reinsurer compensates a fixed proportion of losses (assumed to be 15% following Hudson et al. (2016)). We assume that the federal government acts on a not-for-profit basis and therefore, only a loading factor to meet the administrative costs of providing such a service (\( \lambda = 0.2 \)) is included.

2.3. Volatility of Payments

The mentioned compensation arrangements offer varying levels of financial certainty and predictability for the government actors. This is because formal insurance coverage provides a greater degree of financial certainty, as an uncertain loss is exchanged for a fixed loss in the form of the premium.

The more certain and predictable an expenditure on flood recovery is, the easier it is to be a fixed element of the public budget process. The less certain budgetary allocations are, the less prepared the policymaker is for financing flood recovery expenditures. Therefore, uncertainty can be seen to be placing a greater burden on government budgets as the balance of funds must be found at the appropriate date in an ad-hoc manner, regardless of the government’s current financial situation.

To evaluate this element of the various compensation arrangements, the volatility of payments \( \text{VoP} \) is calculated in Eq. (10) for the federal government and Eq. (11) for the average regional government.
We assume that protection standards against 30-year events are uniformly in place (FLOPRO30 in Fig. 3). The risk model based on the MIROC-ESM projections calculates an increase in EAD by 343%, while with the NorESM1-M projections an increase of 12% is obtained. The multi-model mean across the five climate models increases by 113%. Including the protection standards envisaged by the Austrian national flood risk management plan, i.e., uniform protection standards up to 100-year return periods (FLOPRO50 and FLOPRO100), clearly alleviates the increase in EAD between the reference period and 2080. The risk reducing effects of structural protection standards can be seen when a scenario without any flood protection in place is considered, i.e., NOPRO in Fig. 3. Here, the increase of EAD until 2080 ranges between 497% and 40%, again dependent on the GCM the flood risk model is based on. Again, the MIROC-ESM model projections lead to the highest damage projections and the NorESM1-M model projections suggest a lower increase. The differences across the models directly result from the projected inundation depths. While the MIROC-ESM-CHEM model projects a rather wet future for Austria with high inundation depths, the NorESM1-M model projects drier conditions with reduced inundation depths.

Applying dry flood-proofing measures to all public buildings, with the exception of transport and military infrastructure, located within 100-year flood plains, reduces the EAD to public infrastructure by 25% on average. The share in public flood risk represented by public buildings alone can be reduced by 70% on average. Fig. 4(a)–(c) indicates that considerable reductions can be achieved irrespective of the considered climate model and flood protection standards in place.

Breaking down the EADs to the political district level shows that around 60% of regional governments are affected by flood risk. This is shown in Fig. S2 in the Supplementary material (S3).
current Disaster Fund. However, again, some of this can be mitigated through the stimulated risk reduction.

3.3. Volatility of Payments

The metric for the volatility of payments is presented in Table 4 and shows the potential development of the volatility of payments relative to the status quo. The volatility of payments increases over time. However, this increase in volatility can be mitigated by increasing the formalized nature of the compensation arrangements. This is because under the private insurance markets, the value is the smallest, as a large amount of risk is transferred to the private insurance markets. A development toward a public-private structure results in a higher volatility of payments for the federal government, although it is smaller than under an informal compensation arrangement.

3.4. Overall Improvement

The results in Table 5 highlight the compensation arrangements that score highest for a given weighting scheme across the importance of the overall level of premium payments and their annual volatility. Only the results for 2020 are presented, as later periods are functionally identical.

The public-private as well as the private insurance arrangement both with an active link to risk reduction incentives are determined to make a suitable trade-off depending on which outcome is focused upon. The stronger the focus is on lowering the budgetary burden, the more likely the public-private structure is to score highest. A stronger focus on the volatility of payments results in the private insurance arrangement being more likely to score highest. This pattern occurs because under a private insurance arrangement, the government, across levels
of governance, completely passes the volatility in losses to the private sector. While in the public-private arrangement, the government must retain some of this volatility in losses to act as the public reinsurer. However, the public-private arrangement allows a greater role for less risk averse insurers to support the private sector, thereby allowing the direct budgetary burden to fall by reducing the premiums charged as compared to the private insurance arrangements.

Overall, the results of Table 5 indicate the benefits of moving toward a more strongly formalized insurance, in particular, a compensation arrangement with stronger incentives for policyholder risk reduction. The multi-criteria analysis highlights that the increased certainty is the key benefit.

4. Discussion

4.1. Discussion of Model Uncertainties

The results of the insurance model are based on the EAD calculations, which are derived by the flood risk model. Therein, various models and input data are combined: inundation maps from climate scenarios, building level exposure data, stage damage curves, and maximum damage values. Eventually, uncertainties in each of these input parameters have to be considered when interpreting the results.

First, the range in the projections presented in Fig. 3 is attributable to the differences in the climate models that the GLOFIRS model is forced with. These models only show low consistency regarding the future change in flood hazard in Austria (Winsemius et al., 2016). While the MIROC-ESM-CHEM GCM projects a considerable increase in flood hazard, the NorESM1-M GCM projects only minor changes. Therefore, we face a high degree of uncertainty regarding the future flood hazard in Austria (Bloschel et al., 2011). Second, the GLOFIRIS framework only considers riverine floods for large rivers. Hence, damage caused by small rivers, attributable to pluvial processes, are not represented (Winsemius et al., 2013). The inclusion of such rivers would likely lead to an increase in the EAD. The third, used exposure data does not include all relevant infrastructure categories. While the damaging process for railways is understood rather well (Kellermann et al., 2015), the same does not apply to roads. Currently, no generic structural damage function is available in the scientific literature for the latter (Thieken et al., 2008), thus flood risk posed by road infrastructure is not included in the analysis. According to Rednast-Friedl et al. (2015), the current expected annual precipitation related damage to the Austrian road

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**Table 1**

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**Table 2**

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**Table 5**

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**Panel B: Risk reduction incentive**

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network amounts to €18 million, based on reported repair costs between 1981 and 2010. This damage is estimated to increase to €38 million for the period 2036–2065 (Bednar-Friedl et al., 2015). Compared to our risk estimates, this number for mid-century damage is small; hence omitting flood risk to road networks only slightly affects the presented estimates for future flood risk. Fourth, the variety of structural and content features across and within building classes makes it difficult to represent all damage categories individually (de Moel and Aerts, 2011; Merz and Thieken, 2009). The actual vulnerability of public infrastructure may therefore differ from the one implied by the assumed stage damage curves and associated maximum damage values (Aerts et al., 2018; Koks et al., 2014). However, at least for the railway infrastructure, the recent study by Kellermann et al. (2015) compared the damage as calculated by means of applied stage damage curves with actual flood damage to the Austrian railway system and found comparable results.

Additionally, there is no accurate information regarding flood protection levels across Austria (Schinko et al., 2017). As shown in Fig. 3, the total EAD depends on the flood protection standards assumed to be in place. We capture a large part of this uncertainty by assuming three minimum uniform protection standards across the country that are in line with the evolution of protection standards scheduled in the Austrian national flood risk management plan, which is a movement from FLOPRO30 toward FLOPRO100. In reality, however, some regions are protected well above the 1 in a 100 year benchmark, e.g. the city of Vienna.

Moreover, there is a degree of uncertainty over the costs of dry flood-proofing in terms of applying values compiled in the U.S. to those compiled in Europe. To account for that we used an international construction price index to correct for construction cost differences between the U.S. and Austria (Consultants Compass International, 2009). We further investigate how sensitive our results are to this uncertainty in costs by modeling the benefit-cost ratio of the dry flood-proofing measures relative to investment costs (see S2). This shows how much larger the upfront investment costs of the dry flood-proofing measures could be and still be cost-effective. The ratios are large across all building classes and protection standards. This indicates that the investment costs would have to be substantially higher to alter the investment decision, which gives confidence in our results.

4.2. Discussion of Main Results

Worldwide, the cost of natural disasters has been steadily increasing and is projected to further increase in the future (Alfieri et al., 2016; Barthel and Neumayer, 2012; Swiss Re Institute, 2017). As a consequence, governments’ liabilities for disaster losses will accumulate (see Section 3, see also Kousky and Kunreuther (2017)). We have shown that flood damage to public infrastructure represents an additional burden to the Austrian public budget. By 2040, it will range between €127 million and €496 million, depending on the protection standards in place (see Table 1). In 2015 the endowment of the Austrian disaster fund amounted to €290 million. Schinko et al. (2017) estimate that by 2030 it will increase to €320 million and by 2050 it will stand at €370 million. Looking at the outcome under the highest level of assumed flood protection (FLOPRO100), the fund could easily cover the additional costs. For lower protection standards, however, the fund’s resources become scarce. It is important to remember that our analysis only considers the EAD to public buildings and infrastructure. Private flood risk is not accounted for in the analysis, nor is the fund’s role to be the developer and maintainer of disaster prevention infrastructure. Pretenthaler et al. (2015) analyze flood risk to Austrian private property and conclude that by 2030 the EAD amounts to €280 million and until 2050 a further increase to €430 million is projected. Combining these estimates with the ones we presented in Table 1 highlights that the fund’s resources will be insufficient by 2030 (at the latest) irrespective of the protection standards assumed to be in place. Schinko et al. (2017) present similar conclusions. Moreover, we note that our estimated flood risk for public property is in line with those for private property, which matches the roughly equal split of observed flood losses between the public and private sectors (Sinabell and Url, 2006).

Contrasting the increase in EAD with the economic growth resulting from the assumed socioeconomic development reveals that until 2080 the share of flood related losses remains constant (MIROC-ESM model projections) or even declines slightly (all other projections incl. the multi-model mean), respectively. This observation, however, must not be interpreted as economic growth being an appropriate solution for the problems that flood risk can cause. First, Hsiang and Jina (2014) show that natural disasters have a long lasting negative growth effect. Second, even if the share of risk relative to real GDP declines, this does not mean that overall risk is sufficiently managed by the public sector. An increase in flood risk is particularly relevant in times of demographic changes and poses significant challenges for public sector health and pension systems.

A switch from the current ad-hoc governmental relief system toward an insurance-based approach would significantly lower the overall burden on the government, particularly if risk reduction incentives are provided (see Table 5). There is the potential for differing levels of government and private sector interaction depending on what is prioritized in terms of the monetary burden or the volatility of payments.

Given the projected increase in both the monetary burden and the potential volatility of payments, governments need to encourage investments in cost-effective risk reduction measures in the private as well as in the public domain. Risk-based insurance premiums could encourage investments in cost-effective risk reduction and thereby reduce the losses from natural hazards. This movement, however, is likely to require collaboration between insurers and governmental actors. This is because the development of fully risk reflective premiums at the individual property level may be expensive for a single actor, while collective action may reduce these costs. For the private sector this has already been proposed (Hudson et al., 2016; Michel-Kerjan and Kunreuther, 2011). Additionally, in the public sector, economic incentives can help to increase adaptation efforts of local governments.

We have demonstrated that there is a strong potential benefit from
an insurance design that incentivizes the implementation of additional building level flood risk reduction measures, and thereby reduces the burden from floods on both the regional and the federal governments' budgets. At the same time, the formalized insurance coverage helps to achieve more financial certainty for public budgets than the current arrangement does (Kousky and Kuneureh, 2017).

5. Conclusion

The large number of recent extreme weather events and the occasionally devastating damage they caused underscore the imperative of reducing the economic as well as societal risks of natural disasters. It is important to improve preparation for these disasters and to adapt to the changing risks. This includes, among other things, building more wisely and adjusting incentives to the effect that those who make decisions regarding infrastructure development also bear the risk in case disasters strike and cause damage. Doing so not only reduces the ad-hoc burden on public budgets, but also makes contingent liabilities explicit.

By means of a two-staged model framework we show how the switch from a risk transfer mechanism based on ad-hoc compensation toward a formal insurance arrangement increases the certainty of what governments must pay to finance flood recovery costs. Additionally, the proposed compensation arrangement provides incentives for risk reduction measures at the political district level, while simultaneously charging premiums to the federal as well as regional governments that accurately reflect their respective levels of flood risk. This allows to better budget flood losses ex-ante, and thereby reduces the need for ad-hoc ex-post funding. Overall, this leads to a higher degree of preparedness and higher resilience of public budgets as well as public infrastructure.

Generally, the design of natural disaster insurance systems can be considered as a public policy choice (Surminski, 2018). Therefore, a range of stakeholders need to be included in this decision process so that the systems put in place suitably reflect the needs of those involved in integrated (flood) risk management (Bubeck et al., 2016). Recently, a range of different points of views and debates between the insurance industry, academics, and various levels of governance were published on natural disaster insurance, which mainly focused on insurance for private agents (European Commission, 2017; Flood Re, 2018; Golnaraghi et al., 2017; Hochrainer-Stigler and Lorant, 2018; Insurance Europe, 2018; Surminski et al., 2015a, 2015b; The Geneva Association, 2018). Our results can stimulate a wider discussion between relevant stakeholders, and future research, on how to better manage the threat posed by natural disasters to the public sector, which has so far received less attention. Moreover, our results highlight the potential benefits of further public measures to limit flood risk, while further maintaining measures to support flood losses when the public infrastructure measures fail.

The results of this study have the following three main implications for future research. First, a better understanding of the disaster preparedness of public buildings and infrastructure can improve flood risk estimates. Second, while this paper focuses on direct flood damage, there are also indirect economic impacts from flood events, such as business interruption, which may have implications for the fiscal position of governments that future research can examine. Third, governments' assets are exposed to more than just riverine flooding, and the introduced modeling framework could be applied or extended to other extreme weather events.

Declarations of Interest

None.

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Appendix A. Supplementary Data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2018.09.019.

References

Flood Re, 2018. Incentivising Household Action on Flooding and Options for Using