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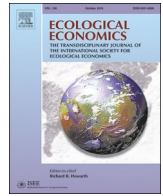
Analysis

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

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A B S T R A C T

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

contract designs can be used to incentivize ex-ante risk reduction (Botzen et al., 2009; Kunreuther, 1996; Surminski and Hudson, 2017). Several studies have shown that mitigation measures at the building level can effectively reduce the damage of natural disasters (Hudson et al., 2014; Kreibich et al., 2005; Poussin et al., 2015). Therefore, insurance contracts that offer risk-based premiums and reward the installment of mitigation measures with a discount are a possible approach to deal with increasing flood losses (Hudson et al., 2017; Michel-Kerjan and Kunreuther, 2011). Moreover, such actions can aid and support other policies aimed at stimulating risk reduction through say building code alterations or regulations by providing positive rewards for these actions. Risk-based insurance premiums charge policyholders a premium in line with the total flood risk they face. Therefore, those at higher risk will tend to pay more for an insurance policy, while those who reduce their risk, pay less. This allows insurance to act as a price signal of risk, which can stimulate adaptation to changing flood risks.

Most of the literature focuses on private household flood insurance (Botzen and van den Bergh, 2008; Hudson et al., 2016; Osberghaus, 2015). However, flood risk to public infrastructure and the insurance implications have received less attention. The impacts of floods on public infrastructure can have more profound ramifications than on private property. Any delay in restoring public infrastructure causes indirect effects since many people rely on and require the services of public infrastructure in the fields of education, health, transportation, and culture. Additionally, the value of public infrastructure can exceed that of individual private property, since schools and hospitals are often large facilities and equipped with high-tech installations (Aerts et al., 2013). In order to address the gap in the literature, this article seeks to analyze the future development of riverine flood risk faced by the public sector in Austria in terms of exposed public infrastructure and the potential implications that different financial risk sharing arrangements can have on the total financial burden on public budgets.

Austria provides an interesting case study due to its high income and its capacity to implement adaptation strategies, and whose existing public sector risk management strategy is increasingly challenged to improve its effectiveness (Prettenthaler et al., 2015; Steininger et al., 2015). In Austria, flood risk is currently primarily borne by the Austrian disaster fund (*Katastrophenfonds*), financed by 1.1% of the federal share on income taxes, taxes on capital yield, and corporate taxes (Holub and Fuchs, 2009). The fund can hold reserves of up to €30 million from unspent resources; surpluses beyond that are redistributed back into the general budget (Austrian Ministry of Finance, 1996). If needed, additional funds can be appropriated from the federal budget (Gruber, 2008). The fund's primary role is to implement, and conduct maintenance of, large-scale disaster prevention measures. These investments account for ~70% of the fund's expenditure (Austrian Ministry of Finance, 2018). The remainder can be used to compensate disaster related damage. The damage to public infrastructure in municipalities tends to be compensated at a rate of ~50% (Austrian Ministry of Finance, 2012). The remainder is borne by local government budgets.

We develop a two-staged model framework to study the development of flood risk to public infrastructure and to assess the burden it implies on public budgets. At the first stage, a risk model assesses and projects the flood risk to public infrastructure in Austria. At the second stage, an insurance model is applied to analyze three different compensation arrangements for covering the projected increase in flood damage. In essence, we compare an informal insurance system with more formalized systems. Austria's disaster fund is considered informal as differing shares of losses will be compensated in different years. In a formal insurance policy, clear rules determine compensation. Two main benefits of insurance are studied: the potentially increased financial certainty and the potential for additional flood risk adaptation. The compensation mechanisms are evaluated by a multi-criteria analysis that assesses the future monetary burden in conjunction with the volatility of payments under each arrangement, while also accounting for a range of different adaptation priorities.

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.

$$L = f(H, E, V) \tag{1}$$

Flood hazard information is obtained from the GLOFRIS model cascade (Ward et al., 2017) at a resolution of approximately $1 \times 1\,km^2$. 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 (Frieler et al., 2016). These meteorological data are derived from five different global climate models[1] (GCMs), which are run for one representative concentration pathway (RCP 8.5). The GLORFIS 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; Winsemius 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.
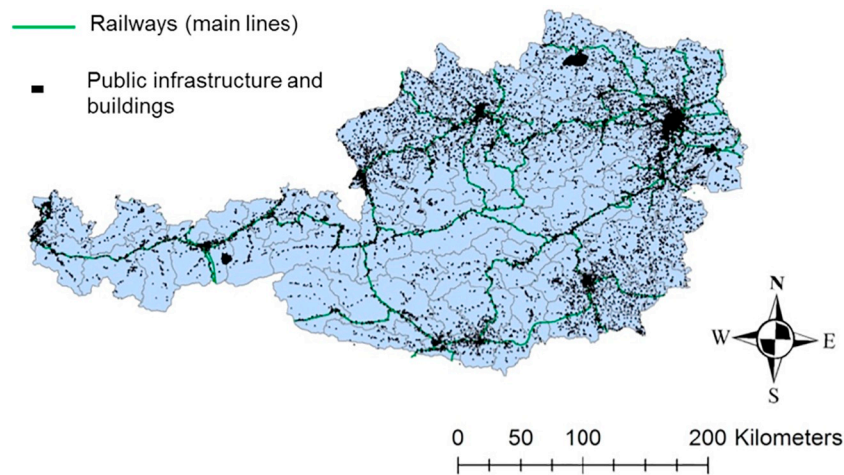
Fig. 1. Public buildings and infrastructure in Austria. Green lines represent the main railway connections. Black dots show public buildings and infrastructure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

flooding in Austria are protected against frequent flood events with a return period of above 1 in 30 years (The Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2016). According to the current Austrian national flood risk management plan, protection standards will be continuously increased until protection against floods with a 100 year return period is achieved (The Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2016). Within this strategy, three different nationwide flood protection standards are assumed: protection up to 30, 50, and 100 year return periods (denoted as FLOPRO30, FLOPRO50, and FLOPRO100). It is assumed that within a flood protection scenario, the level of protection remains fixed at that level over time. To highlight the risk reducing effects that protection standards have, the results when no protections standards are in place are also modeled (NOPRO). It is assumed that the state maintains the protection levels by accounting for changes in the hazard. As a simplifying assumption we focus on hard infrastructure, such as dikes. While there are a range of actions that could prevent, or limit, the extent of floods such as nature-based solutions, for our purposes it is not important how a particular reduction in hazard is achieved. Also note that our analysis does not focus on the optimal choice of the collective flood protection level, but on the design of risk transfer mechanisms once a given flood protection standard has been decided upon.

The flood hazard information is combined with object-based exposure information on public infrastructure. For each building, openstreetmap.org provides information regarding building type, i.e. kindergarten, school, hospital, etc. This information enables a categorization of six public building classes: education, health, culture, miscellaneous, military, and sport fields and parks. Additionally, the main lines of the Austrian railway system are included in the analysis (Fig. 1).

To factor in the feedback between climate change and socio-economic factors, shared socioeconomic pathways (SSPs) are used. The value of the exposed infrastructure is assumed to increase at the same rate as real GDP under the given SSP. Following Winsemius et al. (2016), RCP 8.5 is combined with SSP5, i.e., a scenario with high mitigation and low adaptation challenges. This scenario combination represents a high end climate scenario for the development of flood risk, which has been used in other studies (Alfieri et al., 2015; Winsemius et al., 2016). Alfieri et al. (2015) argue that with the current rate of global warming and the challenges of limiting global warming to 2 °C increase by the end of the century, policymakers require assessments of high end scenarios in order to better understand the potential climate change impacts and plan accordingly following the precautionary principle.

The vulnerability of the elements exposed to flooding is represented by stage damage curves. Stage damage curves indicate what fraction of the maximum value is at risk (measured in €/m^2) if a building is 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).[2] 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 π is the cost of gaining access to

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[2] 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.
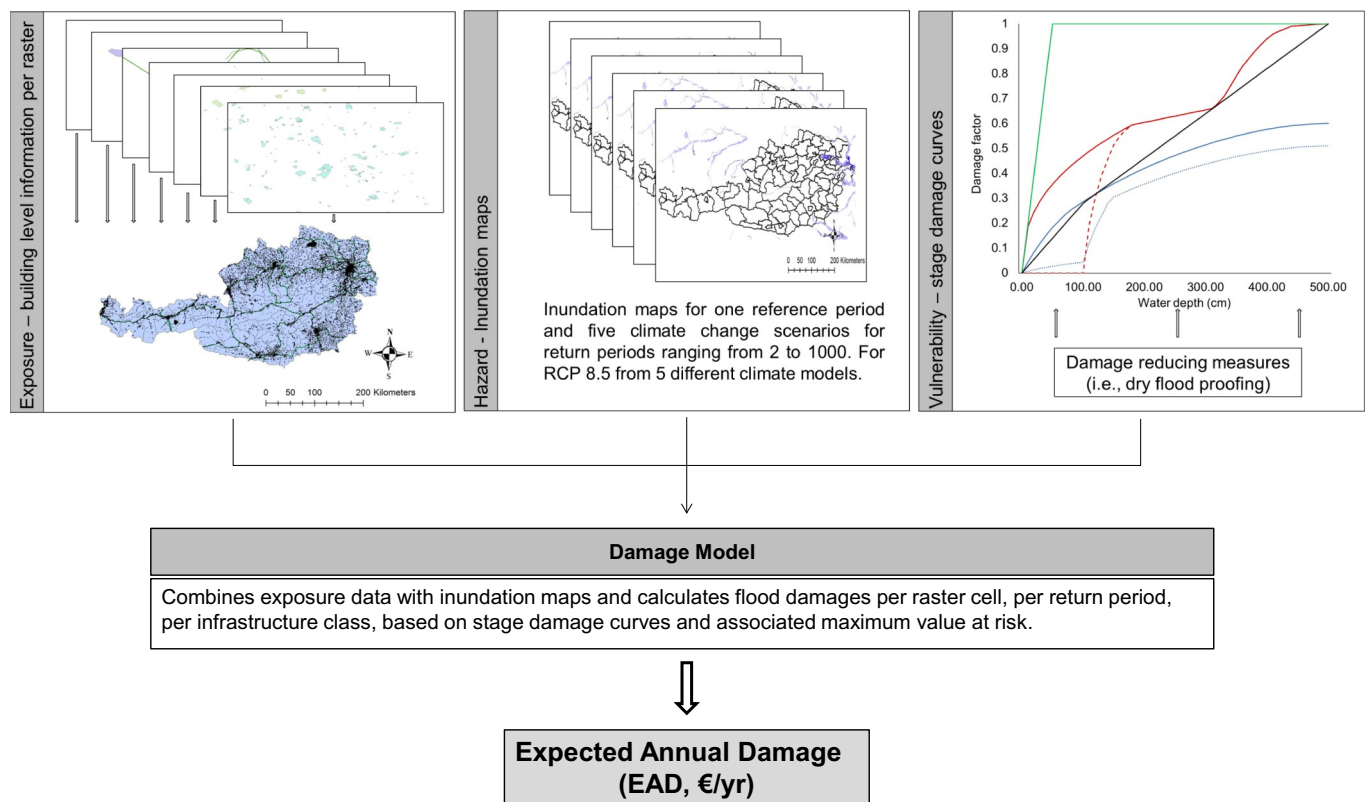
Fig. 2. Schematic overview of input data and model chain used to derive the expected annual damage.
Adapted from de Moel et al. (2014).

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*.

$$Burden = \pi + FR - H - (I - D) \tag{2}$$

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

refocusing 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 $Federal_t^{PS}$ for a given protection standards *PS* at time *t* (Eq. (3)). The *FR* element for the federal government is the sum of the EAD to federally owned infrastructure and the share τ of the expected compensation payments to the regional governments i ($\sum_{i=1}^{i=99} FR_{i,t}^{regional,PS}$). The prime purpose of the disaster fund is not to provide compensation and as such the remaining elements π, H, $(I - D)$ are set equal to 0.

The budgetary burden for the political districts ($Regional_{i,t}^{PS}$ in Eq. (4)) maintains the assumption that the π, and *D* elements are set equal to 0, as the compensation is effectively free, complete, and not prefinanced. However, it is now assumed that the *H* element is equal to $(1 - \tau)FR_{i,t}^{regional,PS}$, where τ 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).

$$Federal_t^{PS} = FR_i^{federal,PS} + \tau \sum_{i=1}^{i=99} FR_{i,t}^{regional,PS} \tag{3}$$

$$Regional_{i,t}^{PS} = (1 - \tau)FR_{i,t}^{regional,PS} \tag{4}$$

2.2.2. Risk Transfer to Private Insurer

When the risk is transferred to a private insurer, the π element of the

budgetary burden is the premium that insurers request from each governmental body.

These premiums are calculated as $\pi_t^{federal,\,PS}$ and $\pi_{i,\,t}^{regional,\,PS}$ in Eqs. (5) and (6) for the federal and regional governments, respectively.

$$\pi_t^{federal,PS} = (1 + \lambda)((EAD_t^{federal,PS} - D_t) + c(\sigma_{federal,t}^{L} + \sigma_{federal,t}^{CM})) \tag{5}$$

$$\pi_{i,t}^{regional,PS} = (1 + \lambda)((EAD_{i,t}^{PS} - D_{i,t}) + c(\sigma_{i,t}^{L} + \sigma_{i,t}^{CM})) \tag{6}$$

The core element of the premiums 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 $\sigma_{i,t}^{L}$ for the estimated exceedance curve and the standard deviation of EADs across climate models $\sigma_{i,t}^{CM}$. On top of the core premium, insurers charge a further surcharge λ 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 elements of insurance contracts (Paudel et al., 2015). Following the results of Paudel et al. (2015) and Hudson et al. (2016) we set the deductible at 15% of the loss suffered. In this scheme no other source for financing reconstruction is possible. The burden simplifies to Eqs. (7) and (8).

$$Federal_t^{PS} = \pi_t^{federal,PS} + D_t FR_t^{federal,PS} \tag{7}$$

$$Regional_{i,t}^{PS} = \pi_{i,t}^{regional,PS} + D_{i,t} FR_{i,t}^{regional,PS} \tag{8}$$

Formal insurance mechanisms can also provide incentives for risk reduction through premium discounts. It has been argued that this link is not standard practice in Europe, due to transaction costs (Surminski et al., 2015a, 2015b). However, transaction costs could be reduced if flood coverage is bundled into pre-existing insurance policies, or a certification process of risk reduction measures is employed. This could be similar to how the National Flood Insurance Program uses property level elevation certificates in order to provide discounts to policyholders with elevated buildings (Aerts et al., 2013).

Therefore, we also analyze the potential effects of successful disaster risk reduction measures on flood risk (superscript *DRR* in Eq. (9)). We assume that all regional government buildings can employ dry floodproofing and will receive premium discounts if dry flood-proofing is employed, because the EAD is now lower. Other than this alteration, 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[3] 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

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[3] Doll et al. (2014) conclude that the most relevant rail infrastructure adaptation measure is the regular inspection of embankments and vegetation control. This is not readily generalizable due to local specificities. Military areas are extensive areas with a mixture of unidentifiable uses, which is therefore infeasible to protect with dry flood-proofing.

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).

$$DFP_{i,t,b}^{PS} = \begin{cases} 0 & if \quad \sum_0^{20} \left(\frac{1}{1 + r}\right)^t (1 + \lambda)(EAD_{i,t,b}^{PS} + c(\sigma_{i,t}^{L} + \sigma_{i,t}^{CM}) \\ & \qquad - EAD_{i,t,b}^{PS,DRR}) < cost_{i,t,b} \\ 1 & if \quad \sum_0^{20} \left(\frac{1}{1 + r}\right)^t (1 + \lambda)(EAD_{i,t,b}^{PS} + c(\sigma_{i,t}^{L} + \sigma_{i,t}^{CM}) \\ & \qquad - EAD_{i,t,b}^{PS,DRR}) \geq cost_{i,t,b} \end{cases} \tag{9}$$

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 π 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 π for the regional governments is presented as $\pi_t^{regional,\,PS,\,PP}$, 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 *VoP* is calculated in Eq. (10) for the federal government and Eq. (11) for the average regional government.

$$VoP_t^{Federal} = \frac{\varpi_1(\sigma_{federal,t}^L + \sigma_{federal,t}^{CM}) + \varpi_2 \overline{(\sigma_{i,t}^L + \sigma_{i,t}^{CM})}}{(\sigma_{federal,2020}^L + \sigma_{federal,2020}^{CM}) + 0.5\overline{(\sigma_{i,2020}^L + \sigma_{i,2020}^{CM})}} \tag{10}$$

$$VoP_t^{regional} = \frac{\varpi_2 \overline{(\sigma_{i,t}^L + \sigma_{i,t}^{CM})}}{0.5\overline{(\sigma_{i,2020}^L + \sigma_{i,2020}^{CM})}} \tag{11}$$

In Eq. (10), ϖ_1 represents the share of federal losses that a given level of government is accountable for, while ϖ_2 represents the share of average regional government losses that the federal government finances. The denominator remains constant and represents the initial volatility of payments for the Disaster Fund in 2020. The numerator will change across the various structures. For example, in the case of the Disaster Fund, $\varpi_1 = 1$ and $\varpi_2 = 0.5$, while in the case of a purely private market $\varpi_1 = 0.15$ due to the supposed deductible and $\varpi_2 = 0$ due to the transfer of this responsibility to the private market. Eq. (11) presents a similar metric for the average regional government, which does not bear a share of the federal losses.

2.4. Overall Improvement

Both the budgetary pressure placed on governments and the potential changes in volatility of payments present potential areas of improvement or deterioration depending on the structure of the compensation. Therefore, in order to judge the overall potential benefits of each market structure, a multi-criteria analysis is used. This approach is shown in Eqs. (12) and (13).

In Eq. (12), an overall multi-criteria score $MCS_{t,s}^w$ for compensation arrangement s at time t for weighting scheme w is the weighted sum of the score regarding the budgetary burden ($S_{t,s}^{BB}$ with weight ω_1) and the volatility of payments ($S_{t,s}^V$ with weight ω_2) at time t for compensation arrangement s. The individual score for the two criteria is standardized in Eq. (13), such that the best performing compensation arrangement receives a final score of one (and the worst a score of zero). The monetary burden is displayed as an example in Eq. (13).

The values for $S_{t,s}^{BB}$ are taken to be the total average monetary burden across possible protection standards at time t. The values for $S_{t,s}^V$ are taken to be the average volatility of payments across the federal and regional governments.

$$MCS_{t,s}^w = \omega_1 S_{t,s}^{BB} + \omega_2 S_{t,s}^V \tag{12}$$

$$S_{t,s}^{BB} = 1 - \frac{S_{t,s}^{BB} - S_{t,}^{BB,min}}{S_{t,}^{BB,max} - S_{t,}^{BB,min}} \tag{13}$$

The possible compensation arrangements are: Disaster Fund, Private Insurance (no disaster risk reduction incentive), Public-Private Insurance (no disaster risk reduction incentive), Private Insurance (with disaster risk reduction incentive), and Public-Private Insurance (with disaster risk reduction incentive). In the absence of specific weights for the relative importance of the two scores, five different schemes are used to represent various policymaker preferences.

3. Results

3.1. Expected Annual Flood Damage

Fig. 3 reveals that until 2080 the EAD to public infrastructure increases across all projections. In particular, the MIROC-ESM-CHEM and GFDL-ESM2M GCMs predict an increase in flood damage, whereas the HadGEM2-ES and NorESM1-M GCMs predict dryer conditions. Generally, the projected EAD increases are driven by a combination of climate change and socio-economic development. While inundation patterns do vary across climate models and time, the majority of the increase in risk originates from the assumed pattern of socio-economic development.

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).

3.2. Burden on Public Budgets

3.2.1. Current Compensation System

Table 1 displays the annual expected monetary burden on public budgets under the current situation, i.e., the Disaster Fund. Under this arrangement the budgetary burden placed on the federal government is substantially larger than that for regional governments. The stakeholders in the regional governments do not have strong incentives for improving their risk management activities. Therefore, the budgetary pressure grows with the overall risk.

3.2.2. Risk Transfer to Private Insurer

Table 2 highlights the burden on public budgets if the risk is transferred to private sector insurers and reinsurers. The pressures on budgets are the insurance premium and the expected size of the deductible. Therefore, the monetary burden is larger than in the current compensation system. This is due to the fact that the stakeholders are each paying more than their EAD in terms of the total insurance premium and deductible. However, the presence of insurance incentives for risk reduction has a noticeable impact on the total monetary burden, causing it to fall by ~50% for regional governments.

3.2.3. Public-Private Insurance Mechanism

Table 3 presents the same general results as Table 2 with the exception that there is public-private collaboration between a federally based reinsurer and private insurance. The most noticeable difference is that the budgetary burden for the federal government is lower than under the other arrangements. This is because the federal government formally accepts a smaller proportion of the risk faced by political districts, for which it is compensated. This is in addition to paying a risk neutral premium to itself to pre-finance the expected flood losses. This is a different process to the current Fund's arrangement, because in effect, the compensation role of the Fund is placed in a separate body that is dedicated to pre-financing such losses. The regional governments remain worse off than when compensation is not provided by the
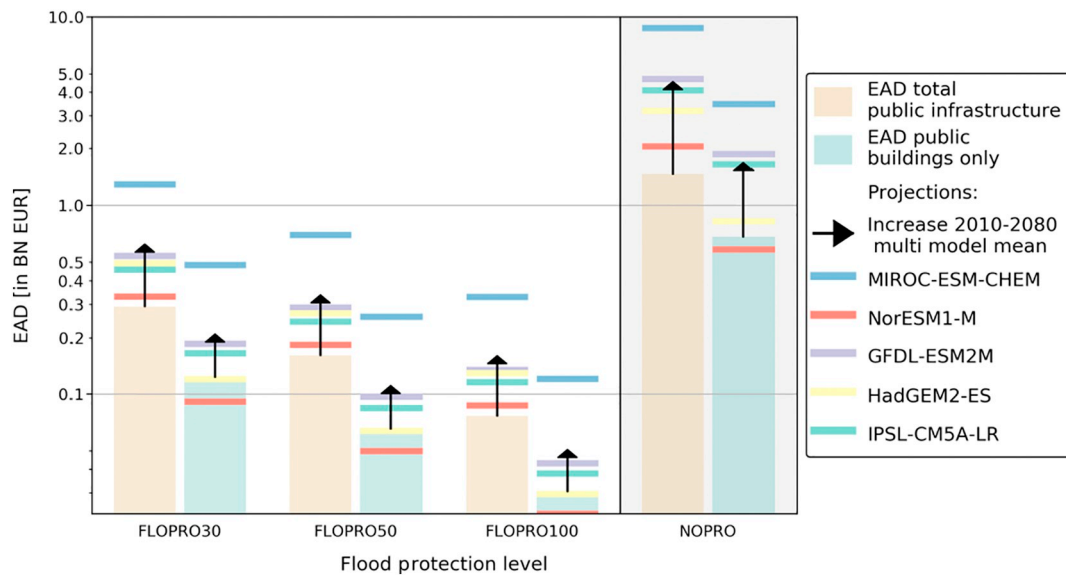
Fig. 3. Expected Annual Damage (EAD, in billion Euros) for the public infrastructure in Austria (incl. railways, parks, and military areas, beige) and for public buildings only (green) for the reference period and projected increase in 2080. The projection of EADs is presented for each of the 5 climate models considered as well as the resulting multi model mean. EADs are shown for different nationwide protection standards (x axis). FLOPRO30 corresponds to uniform protections standards against 30 year events, whereas FLOPRO50 and FLOPRO100 correspond to flood protection against 50 year and 100 year events, respectively. NOPRO indicates a scenario without any flood protection. Note that the y axis is drawn with logarithmic scale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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
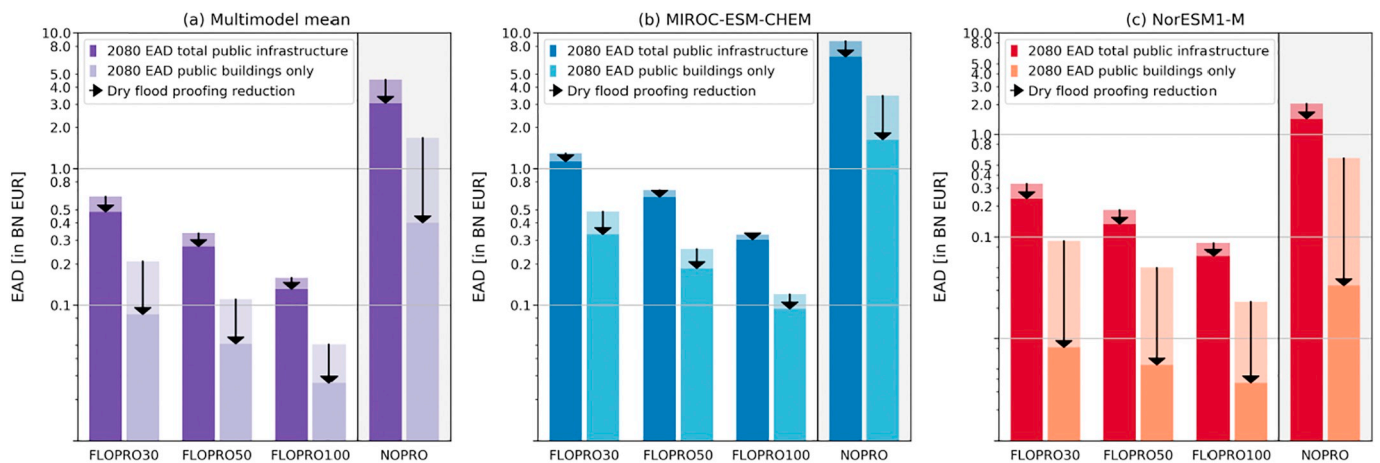
Fig. 4. Expected Annual Damage (EAD, in billion Euros) under the RCP 8.5 scenario for the public infrastructure in Austria (incl. railways, parks, and military areas) and for public buildings only. Arrows indicate the potential reduction through dry flood-proofing measures under different flood protection standards (x axis). FLOPRO30 corresponds to uniform protections standards against 30 year events, whereas FLOPRO50 and FLOPRO100 correspond to flood protection against 50 year and 100 year events, respectively. NOPRO indicates a scenario without any flood protection. Results are shown for the multi model mean (a), the model with the wettest (b) and the driest (c) projections. Note that the y axis is drawn with logarithmic scale.

Table 1

Total expected annual budgetary burden on public budgets (in million Euros) when losses are financed by a Disaster fund.

	2020	2040	2060
FLOPRO30			
Federal government	353	412	471
Regional government	76	84	91
Total budgetary burden	429	496	562
FLOPRO50			
Federal government	193	224	256
Regional government	40	44	48
Total budgetary burden	233	268	304
FLOPRO100			
Federal government	92	107	121
Regional government	19	20	22
Total budgetary burden	111	127	143

Table 2

Total expected annual budgetary burden on public budgets under private insurance mechanisms (in million Euros). Panel A shows the budgetary burden without links to risk reduction. Panel B includes risk reduction measures.

	Panel A: No risk reduction incentive			Panel B: Risk reduction incentive		
	2020	2040	2060	2020	2040	2060
FLOPRO30						
Federal government	348	412	476	348	412	476
Regional government	196	215	235	93	99	104
Total budgetary burden	544	627	711	441	511	580
FLOPRO50						
Federal government	191	226	260	191	226	260
Regional government	105	115	125	57	60	63
Total budgetary burden	296	341	385	248	286	323
FLOPRO100						
Federal government	92	108	125	92	108	125
Regional government	49	54	59	29	31	33
Total budgetary burden	141	162	184	121	139	158

Table 3

Total expected annual budgetary burden on public budgets under public-private insurance mechanisms (in million Euros). Panel A shows the budgetary burden without links to risk reduction. Panel B includes risk reduction measures.

	Panel A: No risk reduction incentive			Panel B: Risk reduction incentive		
	2020	2040	2060	2020	2040	2060
FLOPRO30						
Federal government	325	384	444	325	384	444
Regional government	192	212	231	91	97	102
Total budgetary burden	517	596	675	416	481	546
FLOPRO50						
Federal government	178	210	242	178	210	242
Regional government	103	113	123	55	58	62
Total budgetary burden	281	323	365	233	268	304
FLOPRO100						
Federal government	86	101	116	86	101	116
Regional government	48	53	57	28	30	32
Total budgetary burden	134	154	173	114	131	148

Table 4

The values associated with the Volatility of Payments metric, on average across the various protection standard scenarios, relative to the current status-quo arrangement. The case without incentives for risk reduction is shown in Panel A and the case with incentives for risk reduction in Panel B.

	Panel A: No risk reduction incentive			Panel B: Risk reduction incentive		
	2020	2040	2060	2020	2040	2060
Federal government						
Disaster Fund	1	1.2	1.39			
Private Insurance	0.12	0.15	0.18	0.12	0.15	0.18
Public-Private Insurance	0.88	1.07	1.25	0.87	1.05	1.23
Regional governments (on average)						
Disaster Fund	1	1.09	1.18			
Private Insurance	0.3	0.33	0.36	0.25	0.26	0.26
Public-Private Insurance	0.3	0.33	0.36	0.25	0.26	0.26

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 (Blöschl et al., 2011). Second, the GLOFRIS 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. Third, the 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 Bednar-Friedl et al. (2015), the current expected annual precipitation related damage to the Austrian road

Table 5
The multi-criteria analysis weighting factors and the highest scoring structure out of those studied. The possible compensation arrangements are: Disaster Fund, Private Insurance (no risk reduction incentive), Public-Private Insurance (no risk reduction incentive), Private Insurance (with risk reduction incentive), and Public-Private Insurance (with risk reduction incentive).

	Evaluation elements		Highest scoring structure
	Premium burden (ω_1)	Volatility of payments (ω_2)	
Weighting 1	1	0	Public-Private Insurance (with risk reduction incentive)
Weighting 2	0.75	0.25	Public-Private Insurance (with risk reduction incentive)
Weighting 3	0.5	0.5	Private Insurance (with risk reduction incentive)
Weighting 4	0.25	0.75	Private Insurance (with risk reduction incentive)
Weighting 5	0	1	Private Insurance (with risk reduction incentive)

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 complied 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. Prettenthaler 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 Kunreuther, 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.

Acknowledgements

This work was funded by the Austrian Science Fund (FWF) under

Appendix A. Supplementary Data

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

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