



Adaptive risk management strategies for governments under future climate and socioeconomic change: An application to riverine flood risk at the global level

Stefan Hochrainer-Stigler^{a,*}, Thomas Schinko^a, Andries Hof^b, Philip J. Ward^c

^a IIASA - International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria

^b PBL Netherlands Environmental Assessment Agency, Netherlands

^c Institute for Environmental Studies, Vrije Universiteit Amsterdam, Netherlands

ARTICLE INFO

Keywords:

Fiscal risk
Adaptive risk management
Risk layering
Global fund
Capitalization regimes
Flooding

ABSTRACT

Climate-related disaster risks pose a threat to sustainable development today and in the future. Major global agendas, such as the Sendai Framework for Disaster Risk Reduction and the Sustainable Development Goals, address ways of developing effective management strategies for tackling such risks. Risk management is increasingly focusing on low probability but high impact events, next to the more traditional attention on expected losses. We focus on urban riverine flood risk across 200 countries for today, 2030, and 2080, and develop a risk-threshold approach for identifying whether a country is exposed to risk of extreme events and, if so, when and how much. Furthermore, we apply a risk-layer approach to delineate the kinds of risk reduction or financing instruments that may be needed to manage emerging risks at the national level. Based on these country-level results, we analyze the macroeconomic consequences of setting up a global fund as one international option for coping with floods today and in the future. An additional macroeconomic analysis of different funding schemes for capitalizing the global fund provides insights into linking national risk management efforts with global efforts to manage risks. The global fund could be capitalized according to different equality principles. Our results provide an argument for an equity-based capitalization principle rather than a risk-based one, as the former makes damages at the local level a global responsibility.

1. Introduction

Global climate change is already impacting countries across the world and, with global Greenhouse Gas (GHG) emissions still on the rise, climate-related impacts are expected to increase further in the future (IPCC, 2012). Climate-related disasters in particular, such as riverine flooding, can potentially lead to large impacts on societies (Winsemius et al., 2016; Alfieri et al., 2017; Ward et al., 2017; Dottori et al., 2018). Ways of developing effective adaptation policies against such risks are addressed in major global agendas such as the Sendai Framework for Disaster Risk Reduction and the Sustainable Development Goals (UNDRR, 2015; UNDP, 2015). To assist these efforts, there are recent calls suggesting to particularly focus on low-probability but high-impact events (NCC Editorial, 2016), which can cause dramatic socio-economic consequences both in the short as well as the long term on various scale, e.g. from the household up to the country and global level (Nordhaus,

2011; Weitzman, 2013; Hinkel et al., 2015; Gaupp et al., 2020). Corresponding risk-based modeling approaches are consequently needed that focus on the tails of the (loss) distribution. For example, Abadie et al. (2017) and Galarraga et al. (2018) introduced a risk threshold, based on high-risk tail measures, which they used to set up adaptive risk management strategies against extremes. In this paper, we build and extend on these recent efforts and develop a more nuanced methodological framework for adaptive risk management under climate and global change. We apply this methodology to riverine flood risk at the country level, focusing on governments as one of the primary risk bearers (IPCC, 2012). Based on these results, we analyze the macroeconomic consequences of setting up a global fund to cope with these floods for today and in the future (Hochrainer-Stigler et al., 2014). Our model development and application allow us to answer three important and interrelated questions: (i) how to determine financial needs to address the impacts of extreme events, such as riverine floods, at the

* Corresponding author.

E-mail addresses: hochrain@iiasa.ac.at (S. Hochrainer-Stigler), schinko@iiasa.ac.at (T. Schinko), Andries.Hof@pbl.nl (A. Hof), philip.ward@vu.nl (P.J. Ward).

<https://doi.org/10.1016/j.envsci.2021.08.010>

Received 3 December 2020; Received in revised form 28 July 2021; Accepted 9 August 2021

1462-9011/© 2021 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

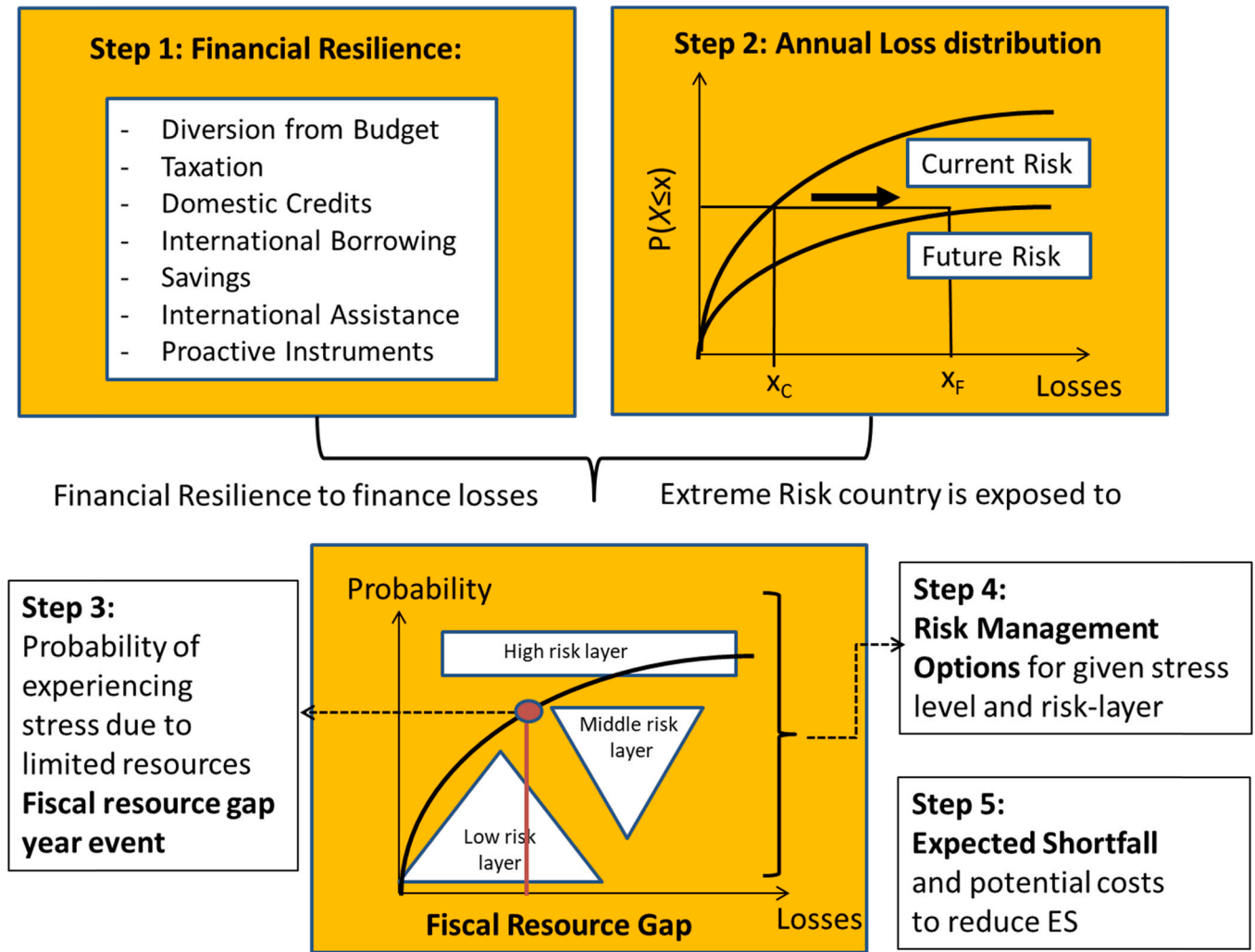


Fig. 1. Methodological approach. Source: Authors

country level; (ii) the amount of capitalization needed for a possible global fund (according to our suggested risk-based method for determining financial needs); and last but not least (iii) what the macroeconomic effects of different rules to determine countries' contribution to this fund would be.

In more detail, recently suggested adaptive risk management approaches that particularly focus on low probability but high impact events (so-called tail risks), determine the risk threshold at which a risk bearer is assumed to behave risk averse in a rather arbitrary manner, e.g. risks that would lead to more than 1% of GDP loss are assumed to be too high for a risk bearer to cope with and therefore should be managed (Abadie et al., 2017). We expand such approaches by explicitly incorporating individual coping resources to determine a so-called fiscal gap year event (i.e., the probability of an event that consumes all governmental resources available for coping with such an event) (Hochrainer-Stigler et al., 2015). The risk measure applied in our analysis is the Expected Shortfall (ES), a now prominent risk measure, which is defined as the expected value when the loss is greater than a given probability level (Abadie et al., 2017). The first novelty of our approach is that the fiscal gap year event allows information to be derived about expected losses that the risk bearer cannot cope with, rather than expected losses involving risks that the risk bearer could adequately address with the resources at hand. Consequently, we can provide a more nuanced and tailor-made risk threshold for each risk bearer.

Such information can further be used to formulate an adaptive risk

management strategy, that is, to address at what point in time further adaptation is needed due to increased risk from, say, climate or global changes. Current advances being made in this field usually do not focus on different types of management options for adaptation. We aim to include this aspect by applying a so-called risk-layer approach, where events are grouped into different risk layers according to their frequency. The risk-layering approach has been proposed as a sophisticated way of conceptualizing the relationship between risk and the appropriateness of disaster risk management investment options, such as risk reduction or risk financing (Linnerooth-Bayer and Hochrainer-Stigler, 2015). We calculate the ES for different risk layers and we use this information to derive respective costs of reducing them, for today and in the future. Hence, the second novelty of our approach is that adaptive management strategies for different risk layers, different time horizons, and respective costs can be assessed simultaneously.

Finally, our approach allows for the projection of funding needs, capitalization requirements, and financing strategies related to extreme events. This information can be used, for instance, to set up a global fund to assist countries in coping with current and future events. While all countries would be able to contribute to this fund, their relative contributions could be based on normative criteria, such as their capacity to pay or the contribution they make to climate change. Alternatively, instead of contributions being related to equity criteria such as these, they could also be predicated on a purely risk-based funding scheme. Here, we analyze how equity-based contributions would differ from risk-

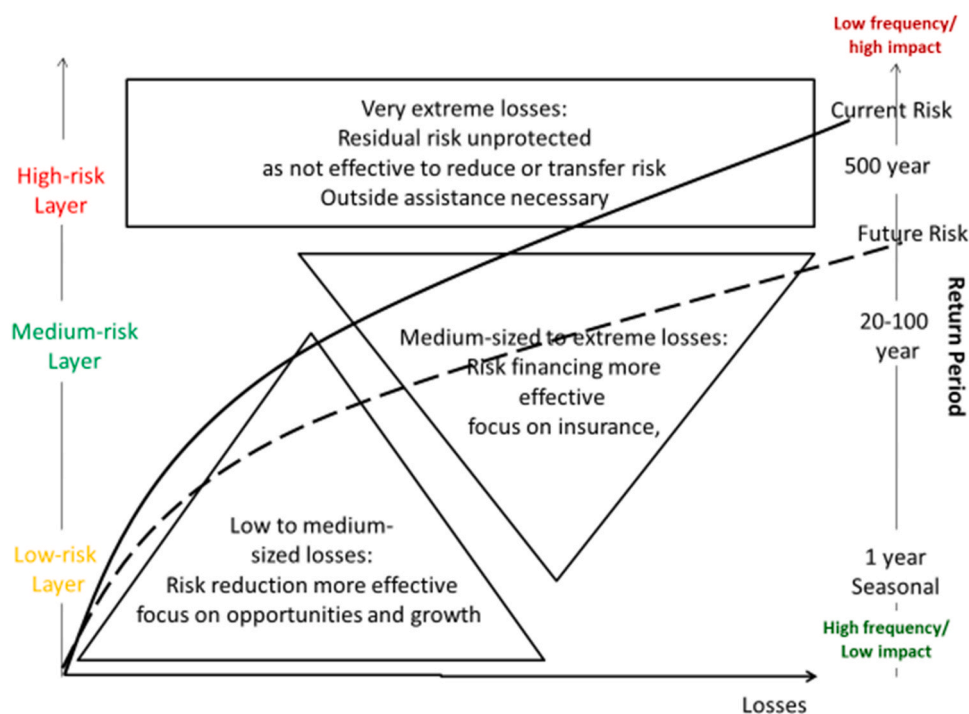


Fig. 2. The layering approach for risk reduction and risk financing using a loss distribution. Source: Adapted from Mechler et al. (2014).

based contributions in terms of global and regional macroeconomic outcomes, using a simple economic growth model embedded in an integrated assessment model. To the authors' best knowledge, the approach presented here is the first to combine a truly (i.e., fully probabilistic) risk-based method with an integrated assessment/economic growth model, and this factor represents our third novel contribution. We apply our approach to riverine flood risk at the country level for today, the near term (2030), and the far future (2080), and we focus on the government as key risk bearer and decision maker regarding current and future adaptation (IPCC, 2012).

Our paper is organized as follows. In Section 2 we present our methodology in detail and discuss its relevance in comparison to other approaches and the advantages of an integrated perspective. Section 3 presents the data and scenarios used in our analysis. Section 4 presents an application on country-level flood risk and the consequences of setting up a global fund. Section 5 discusses results in a broader context, and Section 6 provides steps forward and an outlook for the future.

2. Methodology

The point of departure for our methodology are the papers by Abadie et al. (2017) and Galarraga et al. (2018), both of which suggested using a risk threshold approach for delineating adaptation strategies. These and similar approaches treat the question of whether risks will overwhelm the coping capacity of a given risk bearer in a rather ad hoc manner, providing a type of generic threshold for decision makers' risk aversion. For example, Abadie et al. (2017) used losses as a percentage of local GDP as an indicator, and assumed that 1% or 2% of relative losses (depending on the case at hand) will mark the point of risk aversion for the risk bearer. We expand this approach and use context-specific coping capacities to determine the high-risk threshold at which, once reached, the risk bearer will behave in a risk-averse manner (e.g., will wish to decrease this risk). Our focus in this paper is on the country level, and especially on the public sector and corresponding fiscal risk. We apply our method to riverine flood risk, but it can also be applied to other extreme events, provided that some modest data requirements are met,

as discussed below.

Our methodological approach is visualized in Fig. 1. The first step consists of calculating available fiscal resources to finance losses from extremes, based on the CatSim methodology (Hochrainer-Stigler et al., 2015). This includes various measures, such as budget diversion or international borrowing. Details as to how resources for each of these measures can be estimated are given in Hochrainer-Stigler et al. (2014); for example, if a government runs a budget deficit greater than 5%, no budget diversion capability is assumed; otherwise a maximum of 10% of total revenue can be diverted to finance losses. Here, we use a recent update of fiscal resource numbers for our calculations based on Markanday et al. (2020) (see Supplementary I). For example, for Afghanistan the maximum fiscal resources available to finance losses are about USD 80 million, while for Albania they are an estimated USD 358 million.

In the second step, the risk that a country is exposed needs to be estimated. Risk in our approach is represented in the form of loss distributions (depicted in step 2 in Fig. 1). A loss distribution indicates the probability that a given loss, say, x , is not exceeded, namely, $P(X \leq x)$. Loss distributions for extreme events are commonly assessed within catastrophe modeling approaches, which is a resource-intensive task and even more complicated if future dynamics, such as climate change and socioeconomic developments, have to be incorporated into it which is the case in our work. For this study, we use riverine flood risk estimates from Winsemius et al. (2016) and Ward et al. (2017), which have been compared with past observed losses, and used to project future changes in risk under different climate and socioeconomic scenarios. Risk is represented there through probabilistic estimates of direct urban damages (in USD 2010 purchasing power parities) on the country level for all countries in the world. However, the loss estimates there do not incorporate protection levels. We therefore additionally rely on country-specific flood protection levels stated in the FLOPROS database of Scussolini et al. (2016). We have assumed that flood protection levels indicate the probability level at which losses will start to emerge. For example, for flood protection levels of a 50-year return period, we assume that no losses occur for all events that happen below the 50-year

return period. This is in line with other studies dealing with extreme events at such large scales (see Jongman et al., 2014; Ward et al., 2017; Willner et al., 2018). To take future changes and (model) uncertainties into account, we used riverine flood risk estimates based on two different global climate models (GCMs), IPSL and MIROC (for a detailed explanation, see Winsemius et al., 2016 and Section 3). In addition, we used two Regional Concentration Pathways (RCPs) for our analysis: RCP2.6 and RCP4.5. For all calculations, we have assumed the middle-of-the-road socioeconomic developments of one of the Shared Socioeconomic Pathways (SSPs): SSP2. As the loss distributions are in total damages, we assume that it will be the responsibility of the government to finance 50% of these losses (for a discussion, see Hochrainer-Stigler et al., 2014 and Section 3). Fig. 1 step 2 indicates the change in country level risk by a shift in the loss distribution to the right (e.g., for the same probability level the losses increase from x_C to x_F .) For Afghanistan, a 100-year event (i.e., an event that happens on average every 100 years, or with 0.01% probability) would cause losses of around USD 229 million today (i.e., x_C) and would increase to USD 19 billion (i.e., x_F) in the future (2080).

The available loss distributions give the correspondence between the probability of an event occurring and the related losses. Losses have to be financed using available resources. At some point the losses are so large that they can no longer be financed. Step 3 (Fig. 1) identifies these events and their corresponding probability of occurrence by combining the loss distributions with the fiscal resilience estimates. The first event where it is no longer possible to finance all the losses is called the fiscal resource gap and this can be used as an indicator for risk aversion (Mechler and Hochrainer-Stigler, 2014). The probability of this event happening can be estimated from the loss distribution, again using the return period concept (e.g., a 50-year return period means that such an event happens on average every 50 years). We use the country-specific fiscal resource gap events instead of the generic and ad hoc risk threshold levels suggested in past research. The advantage of such an approach is that it takes into account the large differences in risk aversion levels among countries for assessing fiscal resilience.

In step 4, the fiscal gap information is used to identify a portfolio of different risk management options and related costs for different risk layers. For our purposes, we distinguish between three generic options: risk reduction, risk financing, and assistance, corresponding with three risk layers (Fig. 2): low, middle, and high.

The risk options and risk layers are based on Linnerooth-Bayer and Hochrainer-Stigler (2015). For the low risk layer, we include events up to the 100-year return period (i.e., the *low-risk layer* is here defined to include all loss events between the 1- and 100-year event). For this layer, risk reduction is likely to be cost-effective, as the events happen relatively frequently. For the *middle-risk layer* (up to 500-year return period; i.e., all events between the 100- and 500-year event), we assume that risk reduction options are too expensive, so that risk financing instruments are used instead. Finally, as shown in the uppermost layer of Fig. 2, for the *high-risk layer* (i.e., all events larger than the 500-year return event), we assume that individuals and governments find it too costly to use risk-financing instruments, as these very extreme risks occur with very low frequency, and we treat them as residual risk. By using the fiscal resource gap return period estimated earlier, it is now possible to determine the risk-layer that a country belongs to, as well as what risk management options need to be used to decrease such risks for today and in the future (Fig. 1, right-hand side). In other words, the fiscal gap return period enables to answer two questions, (i) which risk instrument has to be used first and (ii) how much it would cost to cover the losses in the given risk-layers (Hochrainer-Stigler and Pflug, 2012). For clarity, we provide a concrete example of the approach at the very beginning of the results section.

For each of the risk layers described above, we use the corresponding ES (step 5 in Fig. 1) to calculate costs of adaptation and risk management portfolios beyond currently implemented measures (i.e., current physical flood risk protection as provided by Scussolini et al. (2016) and

estimated fiscal resilience levels). For risk reduction costs and benefits, we use overall estimates of cost–benefit ratios based on a review by Mechler (2016). In the review the average cost–benefit ratio of risk reduction projects was estimated to be 4 (i.e., 1 dollar invested will reduce losses by 4 dollars). To determine the additional risk management costs for the *middle-risk layer*, we assume an insurance mechanism based on the actuarial fair premium multiplied by 20 plus a variance measure (in common with the insurance industry, we use a 250-year loss event). Finally, the *high-risk layer*, where physical protection measures or conventional market-based insurance schemes become infeasible, is considered as residual risk. In the future, risk will change due to global and climate changes (as depicted in Fig. 1, step 2); this raises the question as to whether the risk management strategies currently applied will eventually need to be adapted due to such changes. Using our approach, it can be determined for each individual country whether further adaptation is needed due to changes in risk and, if so, when and how much. The future fiscal resources available for each country (step 1) are kept constant as this the most transparent method (and is also suggested in similar approaches such as the one by Hochrainer-Stigler and Pflug, 2012 and Abadie et al., 2017). For example, it enables an iterative assessment of future risk over time as discussed in more detail in Section 5. It should also be noted that future projections do not provide yet the necessary details for applying the CatSim methodology.

The final question, how to fund these risk management strategies in the future, will be addressed by a relatively simple economic growth model, specifically through the analysis of a possible global fund that would assist countries with respect to risks not covered by their fiscal resilience (i.e., all risk beyond the resource gap). In doing so, we follow the approach suggested in Hochrainer-Stigler et al. (2014) and determine the capitalization needs based on the ES of each individual country (i.e., by summing all the individual ES). We extend this approach by including future funding requirements due to climate and global change and by assessing the macroeconomic effects of different solidarity principles as a basis for sharing the funding requirements of such a flood risk pool among individual countries. We use the FAIR model (Hof et al., 2009; Schinko et al., 2020), a climate policy model linked to the well-established integrated assessment model IMAGE (Stehfest et al., 2014) to analyze how a risk-based funding method would differ compared with solidarity schemes based on the polluter-pays and ability-to-pay principles. For the polluter-pays principle, we determined a country's contribution to the fund based on (i) the share of its total greenhouse gas (GHG) emissions in global emissions in the year 2015, and (ii) the share of its total cumulative GHG emissions in total global cumulative GHG emissions in the period 1850–2015. The first scheme is directed more toward current contributions to climate change and the second to past contributions to current climate change. For the ability-to-pay principle, we determined a country's contribution to the fund based on its share of global GDP—using either 2015 GDP levels or projected GDP levels for future years in which the fund is to be capitalized. For both methods, we used GDP measured in PPP. For the above solidarity schemes, we calculated the contribution to the fund for 26 world regions and how GDP would be affected.

3. Data, scenarios, and modeling assumptions

Flood damage calculations are based on the GLOFRIS modeling framework, which is described in detail in Winsemius et al. (2013) and Ward et al. (2013). Flood losses for different return periods at the country level are taken from simulations using GLOFRIS from Winsemius et al. (2016) and Ward et al. (2017). In more detail, GLOFRIS estimates global large-scale river flood risk, excluding pluvial or flash floods. The GLOFRIS framework is comprised of a hydrological model, an inundation model, and an impact model. The hydrological model and inundation model are used to produce flood hazard maps, showing flood depths for different return periods, at a resolution of 30" x 30". In the impact module, these hazard maps are combined with information on

Table 1

Losses in million constant 2010 USD and corresponding return periods for two countries for the baseline and the future (2080).

Country/ Return Period		5	10	25	50	100	250	500	1000
Afghanistan	Current	65	118	162	197	229	270	301	337
	Future	5506	9101	13,242	16,182	19,212	23,117	25,758	29,128
	Increase	5441	8,983	13,080	15,985	18,983	22,847	25,457	28,791
Albania	Current	60	124	216	275	332	398	455	508
	Future	331	718	1251	1616	1962	2372	2680	3019
	Increase	271	594	1035	1341	1630	1974	2225	2511

Source: Based on data from Winsemius et al. (2016) and Ward et al. (2017). Scenario: RCP4.5 & SSP2, IPSL GCM.

exposure (using urban density data and assigning an economic value to each grid cell depending on the national GDP per capita) and vulnerability (using a stage-damage function that indicates the percentage of exposed assets that would be damaged for different flood depths) to calculate flood losses for each return period. The gridded flood impacts can then be aggregated to any user-defined geographical unit (e.g. countries and basins) (Ward et al., 2013) by assuming full dependence (e.g. a 100 year loss event in one grid is summed up with other 100 year loss events in other grid cells during the aggregation process). Hence, the flood risk estimates represent an upper bound on possible losses on the aggregate scale. The framework essentially follows the logic of so-called catastrophe modeling approaches which evaluate risk as a function of the hazard, exposure and vulnerability (see for an introduction Grossi and Kunreuther, 2005).

Regarding future climate scenarios, riverine flood risk estimates are based on two different global climate models (GCMs), namely, IPSL-CM5A-LR and MIROC-ESM-CHEM, to account for model ambiguity (for a detailed explanation see Ward et al., 2017) and two Regional Concentration Pathways (RCPs), RCP2.6 and RCP4.5 to account for different future emission scenarios. The historical GHG emissions are taken from the PRIMAP database (Gütschow et al., 2019), using AR4 100-year Global Warming Potentials. Regarding the socioeconomic dimension, we applied a middle-of-the-road scenario, namely, the Shared Socioeconomic Pathway (SSP) 2 projections, i.e. with medium challenges to mitigation and adaptation in the future (Riahi et al., 2017). We did not account for other pathways because our focus in this paper is on the climate change impact part and to keep the model outputs tractable. In the text, the baseline period represents the time slice 1960–1999, the 2030 period the time slice 2010–2049 and the 2080 period the time slice from 2060 to 2099.

As indicated, country-specific flood protection levels are based on the FLOPROS database (Scussolini et al., 2016) and are kept at the same level for the future scenarios. In other words, we assume that current flood protection levels (which are defined in terms of no damages below a given loss return period), will be adapted to more extreme risks in the future (as the same loss return period in the future would cause larger losses) by autonomous adaptation which is not explicitly accounted for in the analysis. Furthermore, we assumed that the government would finance 50% of total direct losses. This number is based on the fact that it is usually the case that, on average, around 20–30% of direct losses are related to public sector damages (e.g. infrastructure, roads, schools) and that due to moral implicit obligations (e.g. helping the poor and those who cannot help themselves) another 20–30% of the direct losses from the private sector are financed by government resources (Hochrainer, 2006). We also tested a series of other assumptions to review the sensitivity of our results, especially with regard to the global fund analysis. In the following section, we present country-specific adaptation portfolio results for 2030 and 2080 for the IPSL GCM and RCP4.5 scenario combination only. The results of further scenarios, based on different assumptions, can be found in the various corresponding supplementary sections.

4. Results

We separate the presentation and discussion of the results into two parts: the individual country-specific riverine flood risk management strategies analysis and, based on these results, the funding requirements and capitalization possibilities for a global fund to assist countries experiencing a fiscal gap. For the former, we introduce two specific examples to better clarify the approach and its advantages.

4.1. Country-specific adaptive riverine flood risk management strategies

To explain our national-level results, we take a closer look at two specific countries, Afghanistan and Albania, selected for their very different risk profiles (Table 1). For the more frequent events, today's risk in terms of riverine flood losses looks very similar for both countries. However, they differ quite considerably for more extreme events. For example, a 500-year event loss would correspond to around USD 301 million for Afghanistan, while it would amount to USD 455 million for Albania. While losses may be lower for Afghanistan, the country's fiscal resilience is also low, with about USD 80 million available for financing losses by taking loans. For Albania, budgetary diversions and domestic credits are an additional source, resulting in USD 358 million being available for financing losses. Contrasting direct risk with fiscal resilience and assuming that the government will be responsible for 50% of the losses, we found that for Afghanistan a fiscal gap would be caused for the first time by a 54-year return period loss event (as we also assumed that 10.4% of total losses will be covered by outside assistance, see Hochrainer-Stigler et al., 2014). In contrast, Albania would not experience a resource gap, given current socioeconomic and climatic conditions.

Taking future climate change and socioeconomic development into consideration, we used the direct flood loss estimates for 2080 according to the RCP4.5 and SSP2 scenario assumptions, and for the IPSL GCM model. Losses in 2080 are magnitudes higher compared to the current situation. Assuming no change in fiscal sources, a resource gap would occur at a 2-year loss return period for Afghanistan and at a 13-year return period for Albania (the results for all countries in the world and scenarios can be found in Supplementary II).

In the next step, we calculated the ES (i.e., the expected losses that a specific country would not be able to finance given that the resource gap year event is exceeded). For current climatic and socioeconomic conditions, the ES is USD 0.33 million for Afghanistan; for Albania, there is no ES simply because the country is not currently experiencing any resource gap. However, taking the results for the future scenario as presented in Table 1, the ES increases quite substantially by 2080. For Afghanistan, it increases drastically to about USD 1.13 billion. For Albania, which will also face a resource gap according to our model results, it increases from 0 to about USD 17.73 million (results for all countries and all scenarios can be found in Supplementary III). These country-specific ES estimates can be used to determine capitalization needs for today and the future for international assistance in cases where events exceed the available resources of a given country (see the global

Table 2
Additional adaptation and risk management needs.

		Low-Risk Layer	Middle-Risk Layer	High-Risk Layer
Afghanistan	Current	0.04	30	53
	2030	2	265	346
	2080	279	9,354	11,441
Albania	Current	0	0	0
	2030	0	0	17
	2080	4	612	836

Red = needed, green = not needed; and costs (million USD) beyond currently implemented measures, for three risk layers (low, middle, and high), and for the current and future (2030, 2080) scenarios: RCP4.5 and SSP2, IPSL GCM.

Source: Coloring coding based on scorecard approach discussed in Markanday et al. (2020).

flood risk pool funding section below).

With the risk-layer approach presented above, further analysis related to specific adaptation options can be made. For the three risk layers (i.e. low, medium and high), Afghanistan currently has the following ES: USD 0.16, USD 0.15, and USD 0.02 million USD (i.e., an overall ES total of USD 0.33 million), which would increase according to our scenario assumptions to USD 1116, USD 13, and USD 2 million by 2080 (i.e., an overall ES total of USD 1.13 billion). For Albania, there is no ES for today's situation, but ES would increase in the future, namely, to USD 16, USD 1.5, and USD 0.2 million, respectively, for the low-, middle- and high-risk layers (results for all countries and scenarios can be found in the [Supplementary III](#)).

The increase in ES is particularly pronounced for the low-risk layer. This is because the probability of events in the high-risk layer is very low, leading to small expected annual losses even if the losses involved in the events themselves are large. To better account for extreme events, tail measures are more appropriate for indicating the magnitude of a possible event. We thus used the 250-year return period fiscal gap event as an additional risk indicator. This is current practice in the insurance industry for dealing with such large-scale events. In addition, we used the 1,000-year event to indicate the largest losses possible in our approach. For Afghanistan, the 250-year event fiscal gap is about USD 27 million, and the 1,000-year fiscal gap event is USD 53 million. By 2080 these tail measures will increase for the 250-year event to USD 9.1 billion and USD 11.4 billion, respectively. The tail measures for Albania show gaps of USD 279 million (50-year event), USD 3.9 billion (250-year event), and USD 7.5 billion (1,000-year event), respectively.

For each of the risk layers described above, we have calculated the costs of risk management portfolios beyond currently implemented measures (based on current physical flood risk protection, as provided by Scussolini et al. (2016) and estimated fiscal resilience levels). Again, we use Afghanistan and Albania as illustrative examples for countries with very different risk profiles (Table 2). In Afghanistan, additional measures beyond those currently implemented are needed for all three risk layers, and this will not change in the future under the given assumptions. However, while Albania is currently fiscally resilient to flood hazards, this will change in the long run and additional adaptation and risk management measures will be needed. Using the assumptions for calculating adaptation risk management costs as described above, for Afghanistan, the additional costs would be about USD 0.04 (= 0.16/4), USD 30 (0.15 * 20 + 27), and USD 53 million (i.e., the 1,000-year event losses) USD for the low-, middle-, and high-risk layers, respectively. No additional adaptation costs appear for Albania today, as the country is not experiencing a fiscal gap under current climatic and socioeconomic conditions. In the near future (2030), adaptation and risk management

Table 3

Global annual capitalization requirements (billion USD) for different time periods and models.

Scenario	Year	RCP2.6		RCP4.5	
		Baseline	2030	2080	2030
IPSL, no restrictions	64	359	1690	318	1805
MIROC, no restrictions	64	244	1102	229	1227
IPSL, 10% resilience	319	719	2128	686	2241
MIROC, 10% resilience	319	613	1546	598	1647
IPSL, 50 bn cap	24	135	418	153	394
MIROC, 50 bn cap	24	95	408	94	417
IPSL, 50 bn cap, 10% resilience	127	258	537	266	499
MIROC, 50 bn cap, 10% resilience	127	232	526	224	540
IPSL, 8 bn cap; 10% resilience	11	48	147	52	136
MIROC, 8 bn cap	11	43	150	41	151
IPSL, 8 bn cap, 10% resilience	61	97	190	93	182
MIROC, 8 bn cap, 10% resilience	61	99	188	94	187
AVERAGE	101	245	752	237	785
MIN	11	43	147	41	136
MAX	319	719	2128	686	2241

needs in Afghanistan increase to USD 2.3, USD 265, and USD 346 million for the three layers, respectively, and Albania would experience a fiscal gap in the high-risk layer with related costs at USD 17 million. In the distant future, additional adaptation and risk management costs for Afghanistan are USD 279, USD 9353, and USD 11,441 million, and for Albania, USD 4, USD 612, and USD 836 million for the three layers, respectively (results for all countries and scenarios can be found in [Supplementary IV](#)).

The approach, as exemplified by Afghanistan and Albania, was applied to over 200 countries across the world where data was available. Of these 200 countries, 52 experienced a fiscal gap in the low-risk layer, and can therefore be considered as very vulnerable with respect to fiscal risk. About 20 countries experienced a fiscal gap in the middle-risk layer, and the remaining 128 countries experienced a fiscal gap above the 500-year event (high-risk layer). Things quickly change when looking at 2030. The number of countries experiencing a gap below the 100-year event increases to 86, the countries in the middle-risk layer will stay nearly the same (21 countries), and the rest (93 countries) are above the 500-year event. In 2080, 122 countries will experience a fiscal gap in the low-risk layer, with about 18 countries in the middle-risk layer, and only 60 countries above the 500-year risk layer. Again, the tables in the Supplementary show the corresponding results for all countries and for different RCP and GCM scenario combinations. In the next section, we discuss the idea of a global fund for dealing with losses that a government is no longer able to finance, namely, in cases where fiscal resilience

Table 4
Contribution to the pool in 2030, according to different allocation approaches.

Country	GHG emissions 2015	GHG emissions 1850–2015	GDP 2030	GDP 2015	Risk-based IPSL26 (50 bn cap)	Risk-based MIROC26 (50 bn cap)
India	6%	4%	9%	0%	9%	9%
Western Europe	8%	17%	12%	18%	14%	21%
USA	14%	24%	15%	20%	14%	16%
China region	28%	12%	29%	23%	2%	3%

sources are exceeded.

4.2. Capitalization requirements and macroeconomic effects of a global riverine flood risk financing pool

The above country-specific analysis can be extended to the global level by estimating capitalization requirements for a global disaster fund that could assist countries in cases where their own fiscal resources are exceeded. We estimated capitalization needs at the global level by summing up the individual ES of each country. This can lead to an underestimation of risk a country is exposed to as multiple events are not considered in our analysis and would seriously affect the available resources, as calculated in the previous section, e.g. while resources may be sufficient for the first flood event, they would be depleted in a second flood event (Hochrainer, 2006). Hence, we also considered scenarios where only 10% of the maximum amount of fiscal resources available can actually be used. Furthermore, due to large absolute losses in some countries (e.g., United States, Germany), the funding requirements would be biased toward richer countries. Hence, we follow current practices in the insurance industry, where insurance schemes' claim payments are usually capped. On the one hand, we use the median of global insured losses over the period of 2000–2017 (i.e., USD 8 billion according to (Aon, 2019) as the reference point for capping [similar to (Hochrainer-Stigler et al., 2014)]). On the other hand, we set the cap at USD 50 billion to include a buffer above the average USD 8 billion claim payments to include larger-scale losses. Table 3 summarizes the various

scenarios we assessed in our model to generate estimates of funding requirements for a global flood risk financing pool.

According to our estimates based on the RCP2.6 scenario in combination with SSP2, the mean average funding needs at the global level would be 101 billion euros in 2010, increasing to 245 billion in the near future (2030) and to 752 billion in the distant future (2080). If RCP4.5 is used instead, the estimated funding needs amount to 237 and 785 billion euros for 2030 and 2080, respectively. The sensitivity of the results is quite large, and funding needs could be well above USD 2 trillion. However, this is mainly due to the cap assumptions for payments claims and resilience sources that could be used and less to model ambiguity (e.g., IPSL or MIROC) or the RCP scenario used (see Supplementary V for a sensitivity analysis).

Table 4 provides the contributions to the pool by 2030 according to different burden-sharing approaches for four countries (country specific contributions for different burden sharing mechanisms can be found in Supplementary VI). This table shows that it matters how contributions to the pool are allocated—and that the way in which an equity-based approach is implemented is just as important as the equity-based approach itself. For instance, employing a “polluter pays” justice principle, China would contribute 28% to the pool according to its GHG emissions share in 2015, but only 12% according to cumulative historical emissions. For Western Europe and the USA, basing the allocation on historical emissions would lead to much higher contributions. Using GDP rather than GHG emissions, and hence an “ability to pay” justice principle, as the basis for allocation would in general lead to lower

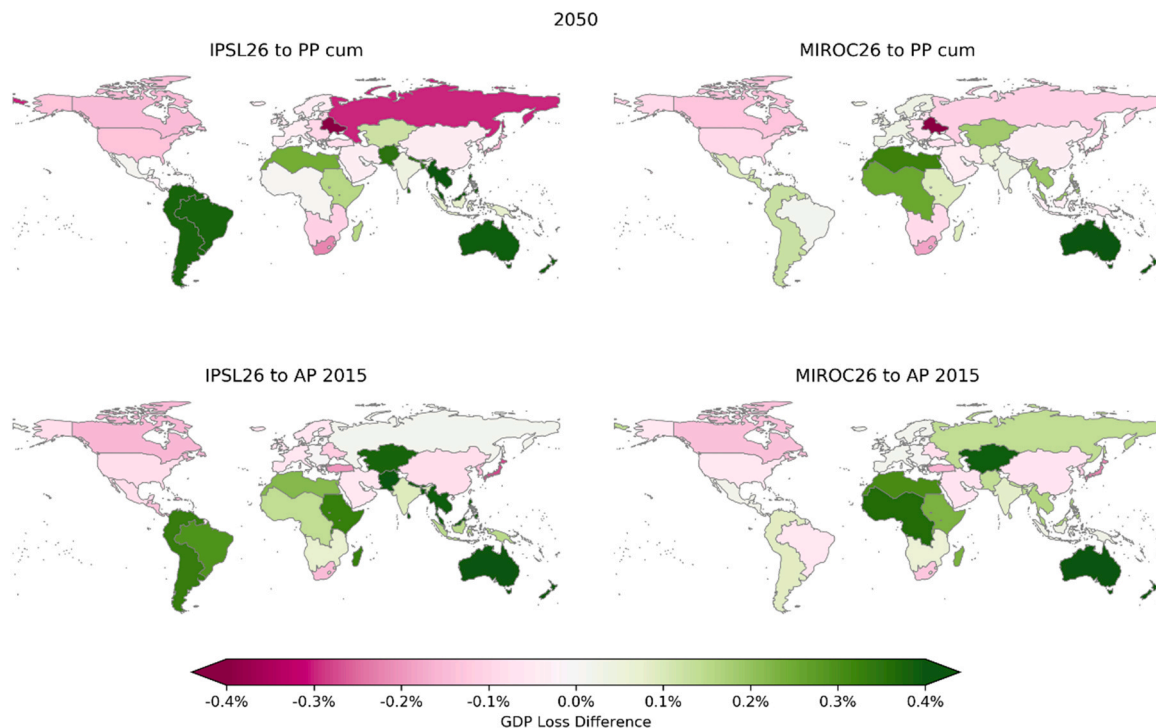


Fig. 3. Regional GDP effects of adopting equity-based capitalization approaches instead of risk-based approaches, 2050. PP cum = Polluter pays based on cumulative GHG emissions 1850–2015; AP 2015 = Ability to pay based on 2015 GDP levels measured in PPP.

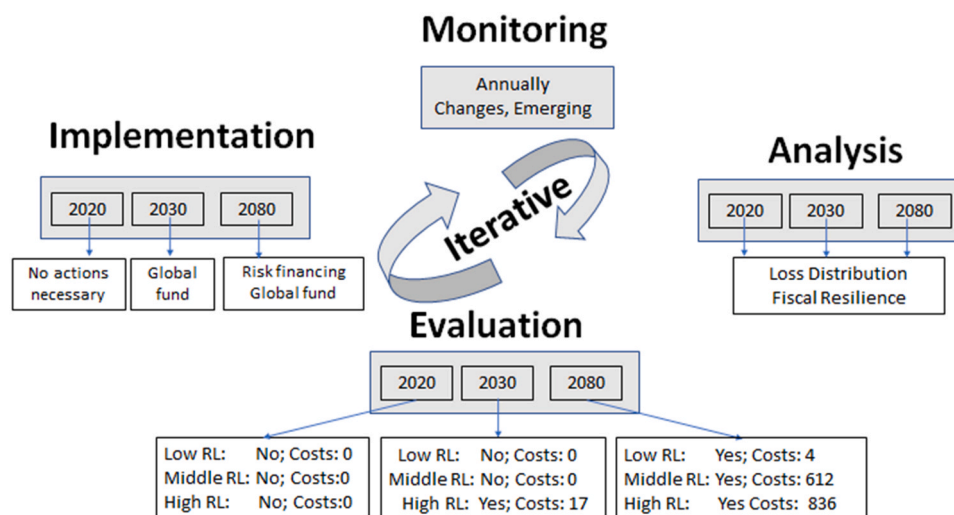


Fig. 4. Risk-layering methodology depicted in an iterative risk management framework. Source: Adapted from IPCC (2012), Abadie et al. (2017), and Schinko and Mechler (2017).

contributions from lower-income countries, as lower-income countries generally have higher carbon intensities of their economy. However, we have assumed that the poorest countries in terms of GDP per capita do not have to contribute to the pool, with the limit set at USD 5500 per capita. This income threshold leads to no contributions from the lowest-income countries, such as India, if GDP were based on 2015 levels. Regarding risk-based approaches, the differences between the RCP2.6 and 4.5 climate pathways are much smaller than the differences between the climate models. We therefore focus on the differences, in terms of macroeconomic implications, between the equity-based approaches and the risk-based RCP2.6 pathways only—assuming the 50 billion cap cases.

Different capitalization approaches lead to different global GDP losses (Table 1 in the Appendix). Interestingly, all equity-based capitalization methods lead to lower global GDP losses than a risk-based capitalization method would. This is because a risk-based method leads to more heterogeneous funding across regions, and economies can adjust better where expenses are smaller. Therefore, a more equal capitalization as is the case for the two equity-based approaches we present in this paper, leads to lower global GDP loss. The difference in global GDP loss across the equity-based approaches is relatively small, with the highest decrease being according to the polluter-pays principle, which is based on historic cumulative emissions and the lowest decrease for ability-to-pay approaches.

Fig. 3 shows the regional GDP effects in 2050 of adopting equity-based approaches instead of the risk-based approach. Results for the polluter-pays principle, based on cumulative historic greenhouse gas emissions, and for ability to pay, based on 2015 GDP levels measured in PPP, are provided (Fig. 1 in Supplementary VII provides the maps for all four equity approaches). The figure shows that by switching from a risk-based to an equity-based capitalization approach, some regions always gain, while other regions always lose. This depends on the relative risk level of world regions. Regions with a relatively high risk include South America (especially according to the IPSL climate model), Northern Africa, Australia, India, Southeast Asia, and Western Europe. These regions show positive GDP effects if capitalization is based on equity principles instead of risk. Regions with very low risk levels include the rest of southern Africa and South Asia, Canada, Japan, Turkey, and China. These regions would therefore contribute more to a global pool

under an equity-based capitalization approach. Russia and Ukraine have significant risks, but their 2015 and historical GHG emissions are both relatively high, resulting in higher contributions according to equity-based approaches.

5. Discussion

The suggested risk-threshold approach can and should be embedded within an iterative risk management approach. The benefits of iterative approaches are now well documented in the literature, most importantly they enable a more dynamic proactive and risk-based assessment and management of future challenges ahead (IPCC, 2012). In particular, they can enable learning and eventually a reframing of the problem; the latter may be needed due to the uncertainties associated with the complex dynamics of socio-ecological systems and their interactions (Schinko and Mechler, 2017). We therefore suggest embedding the generic risk-threshold assessment methodology, as discussed in Abadie et al. (2017) and as substantiated in the present paper, in an iterative risk management framework depicted in Fig. 4. We again use the Albania country example for illustration purposes.

First, monitored and expected future changes have to be analyzed at the country level for both the loss distribution and fiscal resilience. Second, these changes will be evaluated according to the risk-layer approach. For example, for Albania in 2030 the high-risk layer will be affected by a resource gap and corresponding adaptation costs of USD 17 million. In the distant future, however, all risk layers will be affected, with corresponding adaptation costs of USD 4 (low risk layer) 612 (medium risk layer) and 836 million for the high risk layer, respectively. Third, these gaps can be avoided by implementing country-specific portfolios of risk management measures. The implemented risk management strategies, the economic situation related to fiscal resilience, as well as the climate-related risks that have materialized should be monitored and updated according to the risk layers on a continuous basis (e.g., annually). In due course, learning and possible re-framing will take place, which again can be included in the overall process.

It should be noted that we only included direct risk in our analysis and there is increasing concern about indirect effects as well and how to cope with them (Reichstein et al., 2021). However, such indirect effects require different modeling approaches as suggested here (for a literature

review see for example Meyer et al., 2013), including Agent-Based Models or CGE models with a detailed representation of economic sectors and their interlinkages, that can thus take cascading effects explicitly into account (Poledna, 2018). Hence, our risk related results should be rather treated as a lower bound as not all damages are incorporated in our analysis. Furthermore, our risk-layer approach essentially focusses on risk-reduction and financing instruments and neglect important “root causes” (Blaikie et al., 1994; Lamoree et al., 2005; Wisner, 2016) that need to be incorporated within iterative approaches as suggested above. Especially vulnerability creation through the interconnectedness of distant spatial (e.g. investment decision) and temporal systemic conditions has given rise to various models for “root cause analysis” which could be easily embedded within an iterative framework as described above (for a review see Fraser et al., 2016 and in a local context Fraser et al., 2020).

The analysis of the global fund capitalization requirements and funding schemes provides the basis for linking country risk management efforts to global efforts in managing risks. Capitalization of this fund can be done by various means. Here, we looked at different approaches, based on equity principles, to determine how much a country is responsible to contribute to the pool. We considered two approaches based on ability to pay (capitalization in proportion to a country’s share of global GDP, using either 2015 GDP levels or projected future levels) and two approaches based on the polluter-pays principle (capitalization in proportion to a country’s share of global GHG emissions, using either 2015 or cumulative 1850–2015 emissions). We contrasted these capitalization methods based on equity principles according to the risk each country is exposed to and found that all equity-based capitalization methods lead to lower global GDP losses than a risk-based capitalization method. However, our results also indicate that this global improvement is not distributed evenly across the globe. Certain regions (those with a relatively high exposure to riverine flood risk) always gain when moving from a risk-based allocation scheme to an equity-based scheme, while those with a relatively low exposure to riverine flood risk always experience GDP losses. Our analysis thus provides insights into the effect of capitalization based on equity or solidarity principles as opposed to capitalization according to the risk countries are exposed to. Our results provide an argument for an equity-based capitalization principle, as this makes local damages a global responsibility. Such information is highly relevant in light of the important UNFCCC principle, Common but Differentiated Responsibilities and the ongoing negotiations under the 3rd pillar of international climate policy, Loss and Damage from Climate Change, which eventually aims at integrating climate risk management and normative discourses, in order to support the global South to tackle climate change impacts (Schinko et al., 2019). Moreover, given the large uncertainties with respect to the different dimensions needed to assess risk (e.g., different climate models lead to quite different regional risk patterns), it seems beneficial to capitalize a global risk fund based on equity principles.

6. Conclusion

The work presented here is an integration of two currently separated research strands that focus either on expected losses from climate-related impacts or on probabilistic assessments of extreme event risk. We have suggested a comprehensive dynamic risk-based modeling approach based on loss distributions to be used for the evaluation and implementation of an adaptive risk management strategy in the context of riverine flood risk. The benefit of including frequent as well as infrequent events through a risk-layer approach is that it provides a simultaneous assessment of the needs for risk reduction and risk financing. Furthermore, identifying context-specific risk thresholds, defined according to the potential fiscal coping capacity of a given country, allows for the estimation of residual risks that could be dealt with by establishing a global flood risk pool. The sum of the resulting expected fiscal shortfalls provides an estimate for the funding requirements of such a global risk pool. By using an economic growth model we were able to test the macroeconomic implications of different capitalization burden-sharing schemes, either risk-based or based on justice principles, and thereby provide policy-relevant insights for the deliberations under the UNFCCC, particularly in regard to dealing with losses and damages from climate change that lie beyond limits to adaptation.

CRedit authorship contribution statement

All authors conceived and designed the research question and contributed material. S.H-S and A.H designed and performed the modeling and statistical analysis. All authors contributed writing the paper.

Declaration of Competing Interest

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

Acknowledgments

We acknowledge funding for this research by the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 642147 (‘CD-LINKS’ project) and grant agreement no. 776479 (‘COACCH’ project). Additionally, P.J.W was supported by the Dutch Research Council (NWO) in the form of a VIDI grant (grant no. 016.161.324).

Appendix

See Table A1.

Table A1
Global GDP effects of different capitalization approaches.

Billion 2005 USD Climate scenario	IPSL						MIROC					
	2.6			4.5			2.6			4.5		
	None	10%	50bn	None	10%	50bn	None	10%	50bn	None	10%	50bn
Restrictions												
Ability to pay (projected GDP levels)	1020	1707	319	994	1692	337	681	1379	259	695	1387	259
Ability to pay (2015 GDP levels)	986	1654	308	960	1639	326	657	1336	250	671	1344	250
Polluter pays (cumulative emissions)	1081	1820	337	1052	1803	357	720	1469	273	735	1477	274
Polluter pays (emissions 2015)	1038	1746	325	1010	1729	344	693	1412	263	707	1419	264
Risk-Based			357			370			293			289

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.envsci.2021.08.010](https://doi.org/10.1016/j.envsci.2021.08.010).

References

- Abadie, Luis, Maria, Ibon, Galarraga, de Murieta, Elisa Sainz, 2017. Understanding risks in the light of uncertainty: low-probability, high-impact coastal events in cities. *Environ. Res. Lett.* 12 (1), 014017. <https://iopscience.iop.org/article/10.1088/1748-9326/aa5254/meta>.
- Alfieri, Lorenzo, Bisselink, Berny, Dottori, Francesco, Naumann, Gustavo, Roo, Ad. de, Salamon, Peter, Wyser, Klaus, Feyen, Luc, 2017. Global projections of river flood risk in a warmer world. *Earth's Future* 5 (2), 171–182. <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016EF000485>.
- Aon, 2019. Weather, climate and catastrophe insight: 2018 annual report. Aon Rep., p. 86 pp. <http://thoughtleadership.aonbenfield.com/Documents/20190122-ab-if-annual-weather-climate-report-2018.pdf>
- Blaikie, Piers, Cannon, Terry, Davis, Ian, Wisner, Ben, 1994. At risk. *Nat. Hazards, People's Vulnerability Disasters*. <https://www.routledge.com/At-Risk-Natural-Hazards-Peoples-Vulnerability-and-Disasters/Blaikie-Cannon-Davis-Wisner/p/book/9780415252164>.
- Dottori, Francesco, Wojciech, Szweczyk, Juan-Carlos, Ciscar, Fang, Zhao, Lorenzo, Alfieri, Yukiko, Hirabayashi, Alessandra, Bianchi, Ignazio, Mongelli, Katja, Frieler, Richard A, Betts, 2018. Increased human and economic losses from river flooding with anthropogenic warming. *Nat. Clim. Change* 8 (9), 781–786. <https://www.nature.com/articles/s41558-018-0257-z>.
- Fraser, Arabella, Shona, Paterson, Mark, Pelling, 2016. Developing frameworks to understand disaster causation: from forensic disaster investigation to risk root cause analysis. *J. Extrem. Events* 03 (02), 1650008. <https://www.worldscientific.com/doi/abs/10.1142/S2345737616500081>.
- Fraser, Arabella, Mark, Pelling, Anna, Scolobig, Stavros, Mavrogenis, 2020. Relating root causes to local risk conditions: a comparative study of the institutional pathways to small-scale disasters in three urban flood contexts. *Glob. Environ. Change* 63, 102102. <https://www.sciencedirect.com/science/article/pii/S0959378020300212>.
- Galarraga, Ibon, Murieta, Elisa Sainz de, Markandya, Anil, Abadie, Luis María, 2018. Addendum to 'understanding risks in the light of uncertainty: low-probability, high-impact coastal events in cities'. *Environ. Res. Lett.* 13 (2), 029401. <https://iopscience.iop.org/article/10.1088/1748-9326/aaa513/meta>.
- Gaup, Franziska, Hall, Jim, Hochrainer-Stigler, Stefan, Dadson, Simon, 2020. Changing risks of simultaneous global breadbasket failure. *Nat. Clim. Change* 10 (1), 54–57. <https://www.nature.com/articles/s41558-019-0600-z>.
- Grossi, Patrici, Kunreuther, Howard, 2005. *Catastrophe Modeling: A New Approach to Managing Risk*. Huebner International Series on Risk, Insurance and Economic Security. Springer. <https://www.springer.com/gp/book/9780387230825>.
- Gütschow, J., Jeffery, L., Gieseke, R., Günther, A., Gebel, R., StevensD., KrappM., and RochaM. (2019) *The PRIMAP-Hist National Historical Emissions Time Series (1850–2017)* (v2. 1, Updated November 2019).
- Hinkel, Jochen, Jaeger, Carlo, Nicholls, Robert J., Lowe, Jason, Renn, Ortwin, Peijun, Shi, 2015. Sea-level rise scenarios and coastal risk management. *Nat. Clim. Change* 5 (3), 188–190. <https://www.nature.com/articles/nclimate2505>.
- Hochrainer-Stigler, Stefan, Mechler, Reinhard, Mochizuki, Junko, 2015. A risk management tool for tackling country-wide contingent disasters: a case study on Madagascar. *Environ. Model. Softw.* 72, 44–55. <https://www.sciencedirect.com/science/article/pii/S1364815215001693>.
- Hochrainer-Stigler, Stefan, Mechler, Reinhard, Pflug, Georg, Williges, Keith, 2014. Funding public adaptation to climate-related disasters. Estimates for a Global Fund. *Glob. Environ. Change* 25, 87–96. <https://www.sciencedirect.com/science/article/pii/S0959378014000259>.
- Hochrainer-Stigler, Stefan, Pflug, Georg, 2012. Risk management against extremes in a changing environment: a risk-layer approach using copulas. *Environmetrics* 23 (8), 663–672. <https://onlinelibrary.wiley.com/doi/full/10.1002/env.2182>.
- Hochrainer, Stefan, 2006. *Macroeconomic Risk Management Against Natural Disasters*. Springer. <https://link.springer.com/book/10.1007%2F978-3-8350-9441-3>.
- Hof, Andries F., de Bruin, Kelly C., Dellink, Rob B., den Elzen, Michel G.J., van Vuuren, Detlef P., 2009. The Effect of different mitigation strategies on international financing of adaptation. *Environ. Sci. Policy* 12 (7), 832–843. <https://www.sciencedirect.com/science/article/pii/S1462901109001154>.
- IPCC, 2012. In: Field, P.M.M., Barros V., C.B., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K. L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M. (Eds.), *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Cambridge University Press, Cambridge. <https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/>.
- Jongman, Brenden, Stefan, Hochrainer-Stigler, Luc, Feyen, Aerts, Jeroen C.J.H., Reinhard, Mechler, Wouter Botzen, W.J., Bouwer, Laurens M., Pflug, Georg, Rojas, Rodrigo, Ward, Philip J., 2014. Increasing stress on disaster-risk finance due to large floods. *Nat. Clim. Change* 4, 264–268. <https://www.nature.com/articles/nclimate2124>.
- Lamoree, G.B., Garcia, L.E., Perez, R., Castro, E., 2005. Methodology for the Assessment of Institutional Frameworks for Water Resources Management. *Water Int.* 30 (3), 283–293. <https://www.tandfonline.com/doi/abs/10.1080/02508060508691869>.
- Linnerooth-Bayer, Joanne, Hochrainer-Stigler, Stefan, 2015. Financial instruments for disaster risk management and climate change adaptation. *Clim. Change* 133 (1), 85–100. <https://link.springer.com/article/10.1007/s10584-013-1035-6>.
- Markanday, A., de Murieta, E.S., Hochrainer-Stigler, S., Mechler, R., Zverinova, I., Ščasný, M., Jech, M., 2020. D4. 1 Elicitation Results and Conceptual Framework on Risk Attitudes, Brussels.
- Mechler, Reinhard, 2016. Reviewing estimates of the economic efficiency of disaster risk management: opportunities and limitations of using risk-based cost–benefit analysis. *Nat. Hazards* 81 (3), 2121–2147. <https://link.springer.com/article/10.1007/s11069-016-2170-y>.
- Mechler, Reinhard, Bouwer, Laurens M., Linnerooth-Bayer, Joanne, Hochrainer-Stigler, Stefan, Aerts, Jeroen C.J.H., Surminski, Swenja, Williges, Keith, 2014. Managing unnatural disaster risk from climate extremes. *Nat. Clim. Change* 4 (4), 235–237. <https://www.nature.com/articles/nclimate2137>.
- Mechler, Reinhard, Hochrainer-Stigler, Stefan, 2014. Revisiting arrow-lind: managing Sovereign disaster risk. *J. Nat. Resour. Policy Res.* 6 (1), 93–100. <https://www.tandfonline.com/doi/abs/10.1080/19390459.2013.873186>.
- Meyer, Volker, Becker, Nina, Markantonis, Vasileios, Schwarze, Reimund, van den Bergh, Jeroen C.J.M., Bouwer, Laurens M., Bubeck, Phillip, Ciavola, Paolo, Genovese, Elisabetta, Green, C., 2013. Assessing the costs of natural hazards—state of the art and knowledge gaps. *Nat. Hazards Earth Syst. Sci.* 13 (5), 1351–1373. <https://nhes.copernicus.org/articles/13/1351/2013/>.
- NCC Editorial, 2016. The devil is in the deep tail. *Nat. Clim. Change* 6 (5), 431. <https://doi.org/10.1038/nclimate3021>.
- Nordhaus, William D., 2011. The economics of tail events with an application to climate change. *Rev. Environ. Econ. Policy* 5 (2), 240–257. <https://www.journals.uchicago.edu/doi/10.1093/reep/rr004>.
- Reichstein, M., Riede, F., Frank, D., 2021. More floods, fires and cyclones—plan for domino effects on sustainability goals. *Nature*. <https://www.nature.com/articles/d41586-021-00927-x>.
- Poledna, S., Hochrainer-Stigler, S., Miess, M.G., Klimek, P., Schmelzer, S., Sorger, J., Thurner, S., 2018. When does a disaster become a systemic event? Estimating indirect economic losses from natural disasters. arXiv:1801.09740. <https://arxiv.org/abs/1801.09740>.
- Riahi, Keywan, Van Vuuren, Detlef P., Kriegler, Elmar, Edmonds, Jae, O'Neill, Brian C., Fujimori, Shinichiro, Bauer, Nico, Calvin, Katherine, Dellink, Rob, Fricko, Oliver, 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Glob. Environ. Change* 42, 153–168. <https://www.sciencedirect.com/science/article/pii/S0959378016300681>.
- Schinko, Thomas, Drouet, Laurent, Vrontisi, Zoi, Hof, Andries, Hinkel, Jochen, Mochizuki, Junko, Bosetti, Valentina, Fragkiadakis, Kostas, Vuuren, Detlef Van, Lincke, Daniel, 2020. Economy-wide effects of coastal flooding due to sea level rise: a multi-model simultaneous treatment of mitigation, adaptation, and residual impacts. *Environ. Res. Commun.* 2 (1), 015002. <https://iopscience.iop.org/article/10.1088/2515-7620/ab6368/meta>.
- Schinko, T., Mechler, R., 2017. Applying recent insights from climate risk management to operationalize the loss and damage mechanism. *Ecological Economics* 136. <https://www.sciencedirect.com/science/article/pii/S0921800916307455>.
- Schinko, Thomas, Mechler, Reinhard, Hochrainer-Stigler, Stefan, 2019. The risk and policy space for loss and damage: integrating notions of distributive and compensatory justice with comprehensive climate risk management. In: *Loss and Damage from Climate Change*. Springer, pp. 83–110. https://link.springer.com/chapter/10.1007/978-3-319-72026-5_4.
- Scussolini, Paolo, Aerts, Jeroen C.J.H., Jongman, Brenden, Bouwer, Laurens M., Winsemius, Hessel C., Moel, Hans de, Ward, Philip J., 2016. FLOPROS: an evolving global database of flood protection standards. *Nat. Hazards Earth Syst. Sci.* 16, 5. <https://nhes.copernicus.org/articles/16/1049/2016/>.
- Stehfest, Elke, Vuuren, Detlef van, Bouwman, Lex, Kram, Tom, 2014. *Integrated Assessment of Global Environmental Change with IMAGE 3.0: Model Description and Policy Applications*. Netherlands Environmental Assessment Agency (PBL). https://dspace.library.uu.nl/bitstream/handle/1874/308545/PBL_2014_Integrated_Assessment_of_Global_Environmental_Change_with_IMAGE_3.0_735.pdf.
- UNDP, 2015. *Sustainable Development Goals*, Geneva, Switzerland.
- UNDRR, 2015. *Sendai Framework for Disaster Risk Reduction 2015–2030*, Geneva, Switzerland.
- Ward, Philip J., Jongman, Brenden, Aerts, Jeroen C.J.H., Bates, Paul D., Botzen, Wouter J.W., Diaz Loaiza, Andres, Hallegatte, Stephane, Kind, Jarl M., Kwadijk, Jaap, Scussolini, Paolo, 2017. A global framework for future costs and benefits of river-flood protection in urban areas. *Nat. Clim. Change* 7 (9), 642–646. <https://www.nature.com/articles/nclimate3350>.
- Ward, Philip J., Jongman, Brenden, Weiland, Frederiek Sperna, Bouwman, Arno, van Beek, Rens, Bierkens, Marc F.P., Ligtoet, Willem, Winsemius, Hessel C., 2013. Assessing flood risk at the global scale: model setup, results, and sensitivity. *Environ. Res. Lett.* 8 (4), 044019. <https://iopscience.iop.org/article/10.1088/1748-9326/8/4/044019/meta>.
- Weitzman, Martin L., 2013. A precautionary tale of uncertain tail fattening. *Environ. Resour. Econ.* 55 (2), 159–173. <https://link.springer.com/article/10.1007/s10640-013-9646-y>.
- Willner, Sven N., Levermann, Anders, Zhao, Fang, Frieler, Katja, 2018. Adaptation required to preserve future high-end river flood risk at present levels. *Sci. Adv.* 4 (1), 1914. <https://doi.org/10.1126/sciadv.aao1914>.

- Winsemius, H.C., Van Beek, L.P.H., Jongman, B., Ward, P.J., Bouwman, A., 2013. A framework for global river flood risk assessments. *Hydrol. Earth Syst. Sci.* 17 (5), 1871–1892. <https://hess.copernicus.org/articles/17/1871/2013/>.
- Winsemius, Hessel C., Aerts, Jeroen C.J.H., Van Beek, Ludovicus P.H., Bierkens, Marc F. P., Bouwman, Arno, Jongman, Brenden, Kwadijk, Jaap C.J., Ligtoet, Willem, Lucas, Paul L., Van Vuuren, Detlef P., 2016. Global drivers of future river flood risk. *Nat. Clim. Change* 6 (4), 381–385. <https://www.nature.com/articles/nclimate2893>.
- Wisner, B., 2016. Vulnerability as concept, model, metric, and tool. In: *Oxford Research Encyclopedia of Natural Hazard Science*. Oxford University Press. <https://doi.org/10.1093/acrefore/9780199389407.013.25>.