International Journal of Disaster Risk Reduction 106 (2024) 104425

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Risk management against indirect risks from disasters: A multi-model and participatory governance framework applied to flood risk in Austria

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ARTICLE INFO

Keywords:
Indirect risk
Risk management
Multi-model approach
Risk governance
Natural disasters
Austria

ABSTRACT

Indirect effects resulting from natural disasters, such as the follow-on consequences of initial destruction, are attracting growing attention. This is because economic losses in the aftermath of disaster events have escalated in recent years and are expected to continue to rise in the future. Despite this, the primary focus of most countries' disaster risk management approaches remains centered on mitigating the direct effects of such events, with little attention being paid to strategies aimed explicitly at reducing indirect effects. As a result, there are limited practical solutions available for reducing these indirect damages. Most efforts remain theoretical, lacking real-world testing of frameworks specifically designed to reduce indirect risks. To address this gap, this paper aims to illuminate the issue by proposing and empirically testing how existing risk management frameworks designed for direct risks could be expanded to encompass indirect effects as well. In doing so, we create and use a framework to manage indirect risks in a collaborative process for dealing with major flood risk in Austria. We test specific challenges and explore ways to integrate the management of these indirect risks in a complex real-world scenario. Our findings suggest that linking indirect and direct risk management can be achieved with relatively modest effort. A precise systems definition proves particularly beneficial in this regard, as it can link disaster risk related dimensions with non-disaster related targets. This approach thereby opens up the possibility to explicitly include multiple dividends in the decision-making process about indirect risk management strategies.

1. Introduction

Indirect effects due to natural disaster events, i.e. follow-on effects due to the initial destruction [1], are garnering more focus due to the mounting economic losses and repercussions observed in the past [2,3] with expectations of further increases in the future [4]. It is widely recognized that natural disasters can place significant strain on social, economic and political systems [5–7]. However, be-

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https://doi.org/10.1016/j.ijdrr.2024.104425
Received 18 September 2023; Received in revised form 15 March 2024; Accepted 18 March 2024
Available online 22 March 2024
2212-4209/

cause our socio-economic system as well as production chains have become increasingly interwoven and intricate, indirect effects caused by a disaster [8,9] can lead to large losses that even can surpass the hazard's direct damages. Consequently, concerns of these indirect impacts are on the rise, especially in regard to compound events (i.e. when multiple hazards and/or climate drivers co-occur [10]) and multi-risks (e.g. the increase in fiscal debt due to COVID-19 or recent regional crisis and the ability to respond to disaster events [11]). Therefore, highly detailed modelling approaches which are better suited to determine such indirect risks are urgently needed, as are prevention and management strategies [4].

Most of today's disaster risk management approaches primarily aim to reduce the direct consequences of natural disasters. In the majority of countries' risk management strategies, the mitigation of indirect effects is not explicitly addressed [12]. There are numerous challenges hindering their active integration, with one of the most prominent being the inherent difficulty in assessing and modelling indirect effects [12,13]. Consequently, risk management options to decrease such indirect effects are mostly limited to a conceptual (e.g. using feedback loop diagrams) and generic level (e.g. providing broad-based indicators such as GDP per capita, see for example [14]), with a near complete lack of empirical applications of possible frameworks that explicitly target indirect risks [15]. In light of these limitations, our study endeavours to provide possible ways forward by expanding existing risk management frameworks, originally designed for direct risks, to explicitly encompass indirect effects. To achieve this, we develop and apply a framework that focuses on indirect risk management within a participatory process for the case of Austria. To the authors' best knowledge, it is one of the first studies that empirically tests challenges and ways forward to explicitly integrate the management of indirect risks within a complex real-world case study.

Based on our analysis, we conclude that both, indirect and direct risk management can be achieved with relatively modest effort, in the sense that existing methods can capture indirect risks, but modelling capacities must be in place. A specific systems definition may be especially helpful in that regard as it can link disaster risk related dimensions (e.g. destruction of public and private assets) with non-disaster related targets (e.g. in regards to development or sustainability issues) and therefore opens up the possibility to explicitly include multiple dividends (or benefits) in the decision making process about indirect risk management strategies. To address indirect risk, we suggest to clearly delineate the affected system and its components and interactions that enable spreading throughout the system due to direct risk realizations. In practical terms, our system under study is the country Austria and the parts of the system we are identifying for indirect risk management are the sectors of the Austrian economy and Austrian households. We thus take a socio-economic perspective on indirect risk. We address the interactions through multiple models that provide quantitative information about the dependencies and dynamics during and after a disaster event. In addition, we engaged key stakeholders during this process to also provide a qualitative description of how direct risk can trigger indirect risks and possible ways forward to manage them.

Importantly, the analysis enables a clear identification of winners and losers across sectors and households and therefore provides a more nuanced identification of appropriate indirect risk management that can target specific groups, sectors or inequalities (see also for a review [16]). We contend that this approach should help to pave the way for a more comprehensive risk management that is better equipped to confront the multifaceted challenges of the 21st century. Furthermore, we show that the output from complex quantitative models can usefully complement (or support) stakeholder-oriented objectives, including the social and qualitative ones, which will be one of the focal points of our framework and empirical analysis (as suggested for example by [4]).

The structure of our paper is as follows: Section 2 describes the framework and corresponding methodology in detail and applies it to the case study of Austria for extreme flood risk in section 3. Afterwards, section 4 puts the ideas in a broader context before we arrive at a conclusion and provide an outlook to the future in section 5.

2. Methodology and framework

We integrate our framework within the context of risk governance, a concept that encompasses a wide array of processes, actions, traditions, and both formal and informal institutions, all of which collectively influence the decision-making and implementation processes [17]. *Risk* in this context pertains to outcomes that are uncertain, including both positive and negative possibilities. “Risk governance”, then, can be understood as “the totality of actors, rules, conventions, processes and mechanisms concerned with how relevant risk information is collected, analyzed and communicated and management decisions are taken” [18]. Therefore, risk governance is concerned with managing changes and seizing opportunities within societies while concurrently minimizing potential negative repercussions, often categorized as downside risk, such as losses. It is essential to note that disaster risk typically falls under the category of pure downside risk, as the occurrence of a disaster, by its very definition, results in unplanned losses [19]. We shall call those risks and corresponding losses which are caused directly by the hazard *direct risks*, while *indirect risks* refers to those risks that are subsequently caused by the realization of direct risk. Furthermore, direct losses as well as indirect effects (including also possible positive outcomes within part of the system) can be tangible as well as intangible, some of them can be assessed in monetary terms by using market-based methods or economic models (e.g. changes in turnover or profits), whereas some of them are very hard or not possible to monetarize (e.g. loss of life, psychological trauma) (we refer to a detailed literature review of these terms to [20]).

2.1. Framework

There is a fundamental change in perspective when shifting one's view from direct to indirect risks. This can be understood via the notion of dependency and made operational using a specific definition of a “system”. We define a “system” in broad terms as a collection of (individual) elements that are, to some extent, interconnected within clear boundaries. A system thus clearly delineates which elements lie within its boundaries and which do not [21]. A simple example of such a system is a geographic region or political unit that have boundaries with certain households and firms as individual elements within these boundaries. Some elements in this system may be at risk, e.g. due to hazards, and could experience losses in case a hazardous event occurs. Without any dependencies between the system's elements, the losses that affect a certain part of the system's elements cannot spread to other elements which are not directly affected by the disaster. Therefore, no indirect effects can be caused in this case. If the individual elements are, however, to some extent dependent on one another (Fig. 2), indirect effects may spread which can cause cascading and systemic risks to realize [22]. Hence, we argue that indirect risks, which are a result of individual risks interacting, cannot be quantified by the simple summation of the isolated impacts on individual system components. One rather needs to explicitly consider the dependencies between the elements (see the suggestions by Holling [23] in the context of ecological risks or Haldane and May [24] in regard to banking risk). Consequently, the governance of indirect risk must scrutinize the interconnections among the system's elements [25], with a specific focus on the dependencies among individual risks (e.g. as done within systemic risk research).

There are many established approaches for multi-hazard as well as multi-risk analysis (see e.g. Schlumberger et al. [26] for a detailed review). For our specific purposes, particularly to align our research with Austria's intricate disaster policy landscape, we adopted a pragmatic approach and utilized the framework initially proposed by Schinko et al. [27] , and notably Leitner et al. [28], given their emphasis on multi-risks, including drought and flooding, and successful application in directing risk management within the Austrian context. This decision was based on the importance, practicality, and conceptual wise of integrating potential direct and indirect risk management strategies within already established policy processes, approaches, and instruments (as also suggested by [29]). The methodology applied in the aforementioned frameworks was developed through extensive participation of key Austrian stakeholders and was based on IPCC related ideas (especially from Field et al. [30], see also [31]). We expanded upon their methodology, which outlines different phases for the potential implementation of strategies against natural hazards, by incorporating an indirect risk management dimension into each phase.

In essence, our integrated direct and indirect risk governance framework revolves around four fundamental steps. Ideally, these steps are to be ingrained within a comprehensive participatory process (Fig. 1). As will be discussed, especially the integrated appraisal step 3 opens up the possibility for a multiple dividends approach for indirect risk management strategies by taking on a systems perspective. As shown in the middle part of Fig. 1, disaster risk management is, here, considered as the combination of direct, indirect risk management as well as climate change adaptation. Climate Change Adaptation (CCA) is commonly characterized as the proactive response to expected climate variations, intending to mitigate resultant harm while capitalizing on potential advantages [32]. Due to space constraints, we will, however, focus only on current risk but indicate ways forward how to embed it within CCA (see in this context also the discussion in [33]).

Essentially, the framework we propose should be flexible enough to accommodate new approaches, extra components, or systems in the risk management process. This flexibility could lead to a significant change in the network structure and the initial systemic risk challenges that are identified. This broader transformation should be seen as a cultural shift that naturally involves changes in institutions. While not employed here, Dynamic Adaptive Policy Pathway (DAPP) approaches [35] and Climate Storylines [36] seem to be

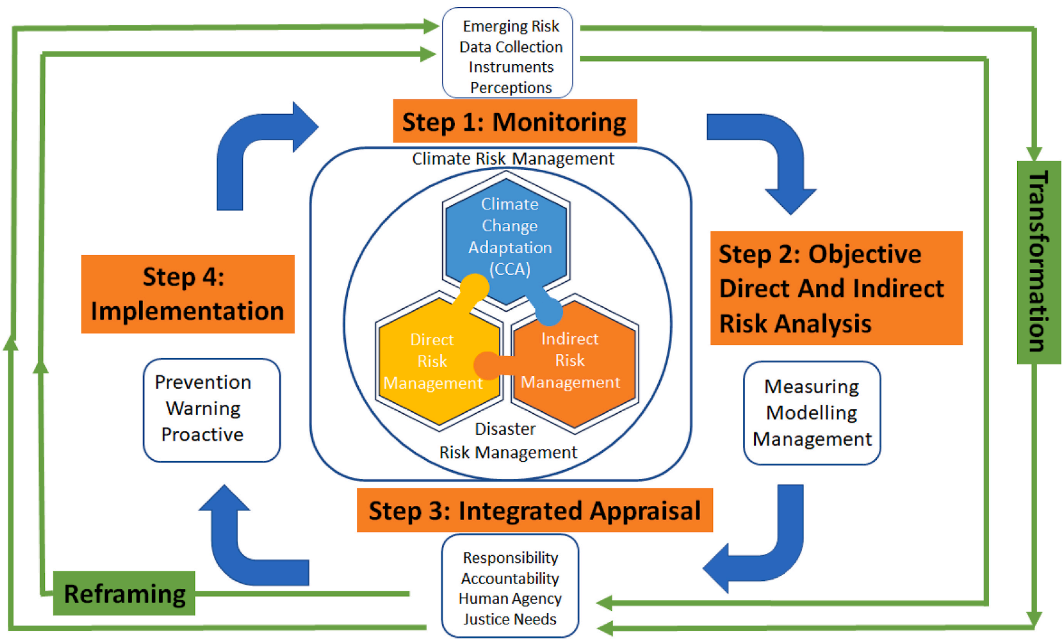

Fig. 1. Visual representation of an iterative framework, serving as a dynamic model for the seamless integration of direct and indirect risk assessment and management, operating within a continuous triple-loop learning process. The illustration at the centre shows indirect risk management as its own pillar within disaster risk management (in addition to direct risk management). The interplay of these components, complemented by the incorporation of climate change adaptation measures, embodies a comprehensive approach to tackling climate-related risks. This approach adeptly addresses both the immediate and future challenges posed by direct and indirect risks. Source: Adapted from Schinko et al. [34] and Leitner et al. [28].

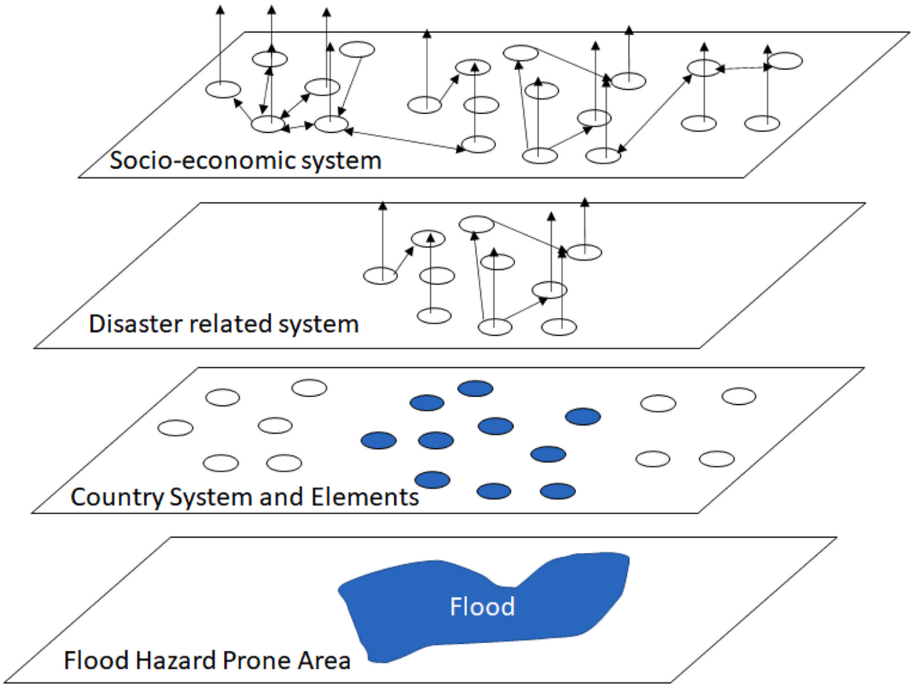

Fig. 2. Two overlapping systems with different focal areas, i.e. socio-economic development and disaster related. Due to interactions between systems a multi-dividend approach can be applied and integrated within both perspectives. Source: Own Authors.

especially useful for these two loops as they can be used to manoeuvre through deep uncertainties as well as explicitly incorporating tipping points. As we are focusing on application aspects, we will discuss the four steps in some detail next within our case study.

2.2. Methodology applied

In the initial phase of the framework, referred to as the monitoring stage, several key activities take place. This includes the identification of emerging risks, the continuous oversight of existing tools and strategies aimed at mitigating both direct and indirect risks, monitoring shifts in the perception of these risks, and the accumulation of data necessary for the calibration and simulation of relevant systems and associated risks. Additionally, this stage encompasses a comprehensive review to assess the need for any new data or instruments. The complexity of this task becomes apparent due to the dynamic nature of dependencies and their ever-evolving dynamics, particularly in contexts like trade networks, where rapid increases in indirect risks can manifest over a short time span.

In our case study, the monitoring phase comprised a literature review and an extensive stakeholder engagement process to identify current challenges and gaps in the identification and management of both direct and indirect risks at various scales. At the national level, we consulted various ministries, including the finance ministry and the ministry of the interior. We also engaged with representatives of specific sectors, especially the production, finance, and infrastructure sector, as well as the insurance industry (such as the Hagelversicherung) and stakeholders from particularly vulnerable municipalities and regions. This phase revealed that different sectors and stakeholders focus on separate and sometimes conflicting objectives (see Reiter et al. [37] for a detailed discussion).

The data collected during this monitoring phase, along with the tools under surveillance and the identification of emerging risks, serve as the foundation for the subsequent model-based quantitative analysis of both direct and indirect risks. Therefore, methodologies for assessing, predicting, rectifying, and managing indirect risks need to be compiled. As mentioned earlier, modeling indirect risks is challenging, but various techniques are now available, including statistical/econometric approaches, Input-Output analysis, General Equilibrium Models, Agent-Based Modeling approaches (for a review see Botzen et al. [12]) as well as System Dynamics modelling (see Mishra et al. [38]). Each of these approaches has its advantages as well as limitations in regard to representing specific dynamics during disaster events (e.g. linear vs. non-linear), time scales (e.g. from months to decades) as well as risk measures (e.g. averages vs. quantiles). We argue that a multi-model or even multi-approach perspective is essential for indirect risks. Due to the complexity of the issue, different models are necessary to shed light on the different and specific aspects. On the contrary, the application of a single model may provide an incomplete or biased view of the system [39]. The notion of a multi-model assessment, often referred to as a “toolbox approach” is intimately associated with the idea that complex systems typically yield a spectrum of outcomes, spanning equilibria, complexity, patterns, and randomness. These diverse outcomes need to be handled by different modelling approaches to effectively navigate the intricate dynamics at play.

Within the case study, we therefore used three high-resolution economic modelling approaches to assess indirect risks, including a General Equilibrium Model, an Agent-based model and an Input-Output model (due to space constraints the main focus will be on results of the first two). These models have been chosen as particularly appropriate to capture sectoral and behavioral transmission mechanisms connecting direct and indirect disaster risks. The detailed description of the joint application of these models is reported in Bachner et al. [40] and discussed within Supplementary B and C. Its results were used in step 2.

Quantitative assessments, and consequently, modelling approaches, play a crucial role in supporting decision-making processes [41]. However, they can only capture a portion of the possible trade-offs that real-world decision-makers must confront. The more complex dimensions of responsibilities, accountabilities, justice, and solidarity have been addressed in a subsequent step of the process through an inclusive evaluation involving participation. This brings us to a crucial observation: we have defined a system as comprising interconnected elements with well-defined boundaries. Let's consider a country as such a system (with clear political boundaries), with households and firms as the elements of the system. By focusing on only those elements exposed to hazards (with clear boundaries determinable), we can define a subset of the elements of the system, calling it the disaster-related system and the socio-economic system (Fig. 2). Due to interdependencies among the system elements, both should not be examined separately, as they mutually influence each other.

The integrated appraisal step is particularly crucial as it provides an opportunity to think beyond the disaster risk domain and identify trade-offs or complementarities with broader economic or social development considerations. In this context, indirect risk management can be linked to ongoing discussions on triple or multi-dividend approaches. The triple dividend approach [42], for instance, advocates for a comprehensive case of disaster risk reduction and investments that yield benefits even in the absence of disasters. The first dividend focuses on averting or mitigating both direct and indirect disaster risks; the second dividend involves diminishing background risks to facilitate development initiatives; the third dividend entails fostering the development of co-benefits that unfold irrespective of whether or not a disaster event occurs. It is important to note that all three dividends can be discussed in the integrated appraisal within step 3 from different system perspectives. For example, the first dividend remains disaster-related, the second dividend is approached through development dimensions (e.g., stimulating innovation and sustaining economic growth), and the third is considered in relation to general challenges that support the same solution. The multiple dividend proposition is similar to the triple dividend and essentially spans the two extreme ends of a continuum. On one end, risk management in the disaster domain is approached in a way that creates co-benefits in other policy domains. On the other end, it starts from a sectoral perspective, implying that disaster risk management options are integrated into development investments for current and future challenges. In our case study, it was particularly interesting to observe how indirect risk management strategies, originally tailored for disaster events, could be extended to other fields of economic development, thus providing multiple dividends from different system perspectives.

Crucially, a second phase may become necessary if efforts to bring down both direct and indirect risks to acceptable levels fall short, intensify during monitoring, or if new risks arise. This phase involves considering a potential reframing of the issue itself, the tools and methods in use, and, ultimately, the overall governance objectives. For instance, imposing taxes within financial markets (see as one example [43]), could be a practical approach for dealing with systemic risk within the banking system by making direct changes to the level of interconnectedness. As will be discussed, similar ideas could also be incorporated for the case of indirect risk management against disasters (in the case of transformation we refer to [44]).

3. Application

The framework and methodology for indirect risk management suggested in Fig. 1 were applied and tested in the case of Austria over a three-year period (2019–2022). To provide an overview, we present only the most significant outcomes generated by the process, which yielded a substantial amount of output. The selection of Austria as a case study to apply the suggested framework is not only due to its heavy exposure to flood risk but also because large indirect effects can be expected, particularly for industrialized countries. This is attributed to their strong internal connectivity (e.g. across sectors) with highly specialized businesses. For instance, the flood events in 2002 led to EUR 200 million in production losses, with estimated overall costs of EUR 3.1 billion [45]. This example highlights not only the vulnerability of Austria to flood risk but also the potential for substantial indirect economic consequences, making it a suitable case study for applying and testing the proposed framework.

3.1. Current situation about direct risk assessment and management

Often governments are seen responsible for managing indirect risks or losses, including the distribution of a potential economic burden (e.g., to the taxpayer) [46]. Recognizing this, we proactively engaged government entities and corresponding ministries as key stakeholders in our framework. These entities are pivotal decision-makers and indirect risk "bearers" in both the public and private sectors. Additionally, we approached representatives from regional and municipal governments, the insurance sector, risk managers, spatial planners, and water engineers. The **first step of our framework** aimed to assess the current situation regarding indirect risks, including stakeholders' risk perception, the instruments deployed against indirect risks, and the data required to calibrate and simulate indirect risks post a hazard event. This involved conducting a total of 26 stakeholder interviews and three workshops held from 2019 to 2022. During these interactions, stakeholders were questioned (i) to which extent they might be affected by indirect risks and if they think that indirect risks are/will be of importance within their field of activity (ii) which instruments (if any) are being/are planned to be used to manage, define and/or quantify indirect risk and (iii) which data they use in order to quantify indirect risks and/or determine the effectiveness of management instruments of indirect flood risks (a detailed description of questions asked as well as stakeholder selection process and related workshops can be found in Supplementary A).

The stakeholder interviews included a mapping process that identified relationships among stakeholders and the sectors they oversee, revealing possible interlinkages during disaster events. While stakeholders demonstrated a high awareness of indirect damages caused by floods and the importance of managing them, the management of indirect damages received higher priority from those involved in the prevention and/or recovery phases of flood risk management than those responding to crises. Despite wide-spread awareness and concern about indirect risks, few stakeholders considered their management as their primary responsibility. This is attributed mainly to existing institutional structures that compartmentalize tasks and responsibilities. Although indirect risk management strategies are acknowledged as important, they have been implemented only rudimentarily. While flood risk management in Austria is well-organized, with a complex network of institutions contributing to it, significant challenges remain. One key challenge is the quantification of indirect risks, which has not been undertaken for past events, hindering the development of strategies to reduce such risks. Existing management instruments include insurance products like business interruption insurance (though not widely accessible or affordable), cost-benefit analyses reporting indirect damages qualitatively, legislature mandating critical infrastructure protection, and (inter)national financial aid programs such as the Natural Disaster Fund and the European Solidarity Fund.

In summary, the monitoring of indirect risk in Austria is still in its early stages but is recognized as crucial by decision-makers across sectors, both presently and in the future. For specific challenges, detailed results from stakeholder interactions, and proposed ways forward, we refer to Reiter et al. [37]. It should be noted that stakeholders were additionally questioned about the information and risk measures from modeling approaches, as well as the time horizon, that would be most useful for them, leading us to step 2 of the framework.

3.2. Quantitative modelling of indirect effects due to flooding

In the **second step of the iterative risk management framework,** we employed three sectoral-disaggregated economic models to compute economic losses resulting from large-scale flood events and to identify appropriate management strategies for indirect flood risks. The chosen approaches comprised an Input-Output (IO) model, a Computable General Equilibrium (CGE) model, and an Agent-Based Model (ABM). The selection of these models was based on their complementarity, their ability to address diverse questions, and their capacity to illuminate different facets of indirect risks, socio-economic repercussions, and management options, while also revealing potential uncertainties. This decision aligns with the recommendation in section 2 to use an ensemble of modeling approaches for a more comprehensive and robust set of insights.

The Austrian flood management strategy adheres to a risk-based approach, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030 and the EU risk reduction strategy. Consequently, we followed this approach in our analysis, requiring the estimation of risk-based flood events to apply the chosen models. This estimation was accomplished using a copula approach, allowing for the analysis of large-scale hazard events on a countrywide scale (for further details we refer to [34]). Assets exposed to flood events were linked to high granularity exposure and hazard mapping, enabling the allocation of inundation damages at the firm level, offering a unique level of detail within Austria. Eventually, damages were determined for each economic sector according to the spatial distribution of capital owned by non-financial, financial, and government entities. Different flood scenarios were considered accounting for events with different return periods as well as multiple consecutive events (see [40]). The selection of scenarios included 20-, 100- and 1000-year loss events, two consecutive events of varying intensity hitting at different points in time as well as four so-called "Armageddon Scenarios", in which a fictional 3, 5, 17, or 34% of capital stock losses were assumed. They were selected based on previous research [47] as well as due to stakeholder interest. These were used as input to the three modelling approaches with some of the most important results discussed next (for a discussion of the CGE and ABM model we refer to Supplementary B and C, respectively).

The **Input-Output Model** revealed that each sector is affected in its own way by different hazard intensity levels. Also the demand for each sector can be expected to be quite different depending on the hazard event. Threshold levels may be reached in the sense that demand exceeds supply for some sectors. Importantly, the input-output model revealed potential bottlenecks in the aftermath of an event; i.e. showing which goods are particularly needed for reconstruction. Therefore, input-output models can emphasize which sector is affected which way, when, and for which hazard scenario from a demand perspective. These results can thus serve as a guide for identifying key sectors in the reconstruction phase for different magnitudes of flood risk. Sectoral losses need to be combined with a spatially explicit analysis to make the best use of this kind of approach. However, some sectors are key for almost all scenarios, particularly the transportation sector (for more information we refer to Bachner et al. [48]). It should be noted that due to the assumed very rigid structure of the economy (e.g. prices do not change) this type of analysis is only suited for short-term analysis, typically periods of up to one year.

An alternative approach is **CGE** modeling, which captures intersectoral relationships similar to IO models but offers greater flexibility in the behavior of economic agents and markets (see Supplementary B). For instance, prices change according to shifts in supply and demand, allowing CGE to account for indirect and potential non-linear long-term effects. The CGE analysis revealed that flood damages trigger distributional effects at both the sectoral and household levels. There are distinct sectoral winners and losers, with some being primarily affected through economy-wide interlinkages, while direct impacts (such as direct capital losses) may not be as severe, indicating a high level of indirect risk. Furthermore, the CGE analysis identified significant distributional implications at the household level, with variations in the short- and long-term. In the short term, capital owners and higher-income households are most strongly affected by a flood event. However, in the longer term, lower-income households tend to suffer relatively more. This is due to changes in price levels and factor remuneration working to their disadvantage, with lower wages and higher prices for goods in high demand for lower-income households. The findings underscore the importance of distributional effects as a crucial indirect risk. Another noteworthy result is that, for most households, the decline in public service provision (resulting from lower tax income) has a more significant impact on their welfare than the reduction in private consumption possibilities. Lower public service provision also implies high indirect risks for economic sectors in the public domain, such as health or education. Fig. 3 illustrates additional macroeconomic results from the CGE model, highlighting distributional effects through opposing changes in factor remuneration (labor and capital).

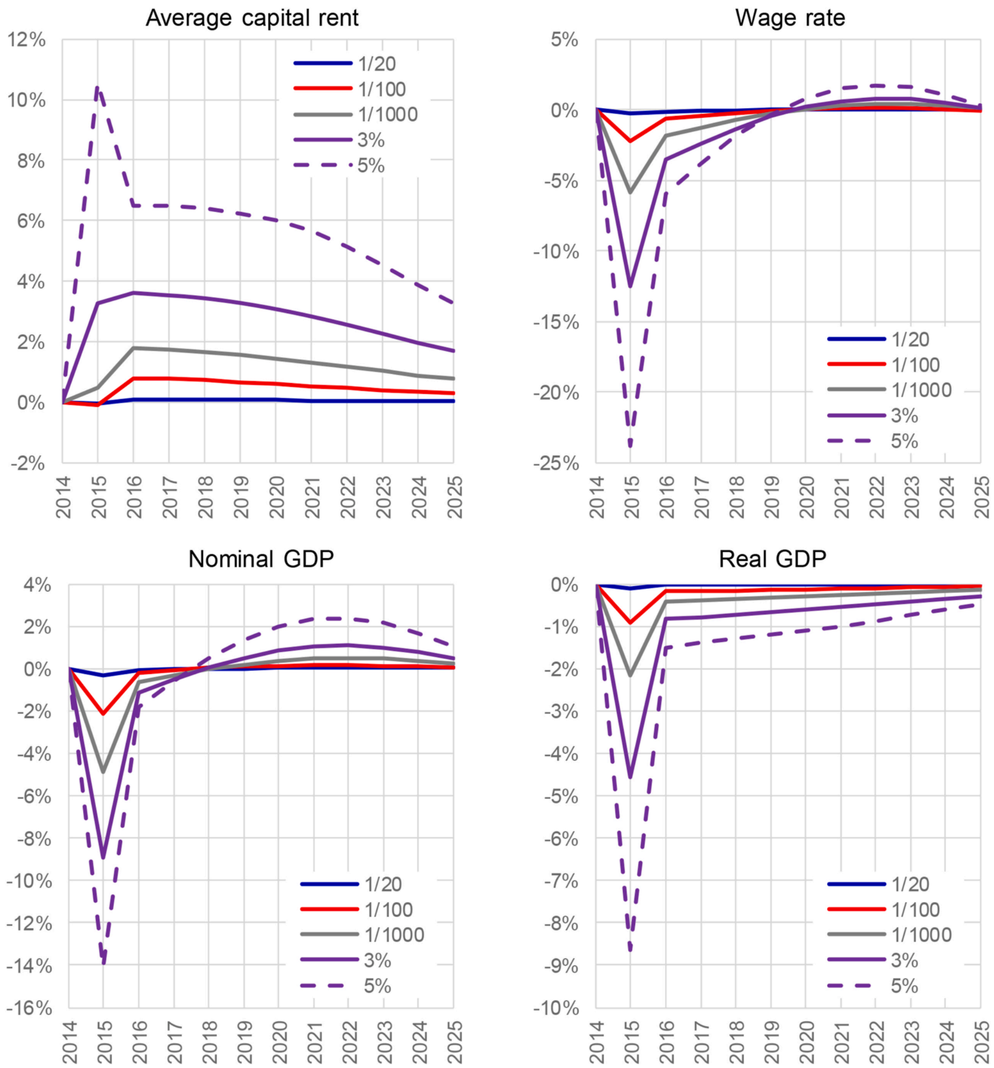

Fig. 3. Effects on average capital rents (weighted average over all sector specific capital rents), wage rates, nominal GDP (including relative price effects) and real GDP (at constant prices). Source [40]

Compared to the very short-term perspective of the IO model the CGE brought in the long-term perspective of up to 10 years into the future. In comparison, the **ABM** model can be used for a time-horizon of up to 3 years into the future. In our case, it provided quarterly estimates up to three years after the disaster event (see Supplementary C). The ABM model showed that firms could have problems borrowing money due to capital shortages and therefore cannot recover quickly enough leading to a decrease in growth and some medium-term negative consequences. Interestingly, for very large events (e.g. 1000 year event, Armageddon scenarios), our results showed that some possible sector bubbles were created due to high demand in some sectors (e.g. the reconstruction sector), which could cause serious negative effects once the high demand passes (as everything is finished rebuilding, see also [49]). As indicated,we could only include some selected outcomes from the models and refer to Bachner et al. [48] for a comprehensive discussion. It should be noted that an active stakeholder participation was ensured by various meetings with key stakeholders (especially from the ministry of finance) to get feedback and include suggestions as well as questions in regard to the assumptions needed to be made for the various modelling approaches.

3.3. Integrated appraisal through a participatory process

The **third step** of the framework consisted of an integrated appraisal developed within a **participatory process**. This refers to a process in which the economic, social and environmental repercussions of a proposed management strategy and the dimension of responsibility, accountability, justice, and solidarity are addressed. The results from the indirect risk modelling step indicated a variety of directions in which policy action can be focused in order to deal with indirect flood risks. For example, the topics of multiple benefits were discussed in quite some detail in a stakeholder workshop held towards the end of the project. During this workshop, stakeholders were presented with the modelled effects of flood events. Subsequently, the validity and feasibility of different management options were analyzed and overlaps identified. A key point emerged during the discussion was related to the expected increase of flood losses over time related to climate change, demographic changes and accumulation of assets. Stakeholders recognized the need to adapt current mechanism in place in financial assistance and risk reduction: Processes need to be made more socially just as our research shows that the long-term, negative effects are strongest for households with low-income after, for instance, a flood event while high-income households recover more quickly from these shocks.

Using the quantitative models more information on these issues could be provided. One possibility to counteract this trend is to develop a compensation scheme that takes income levels into account. Another consists of decreasing the shortage of skilled workers especially in those sectors which are relevant in post-disaster times as, for instance, construction and the production of machinery. Fig. 4 illustrates how, for a 1000-year event, negative short-term effects from labor scarcity can be mitigated by spontaneously increasing labor supply (e.g., by hiring workers from foreign countries). Both measures would address indirect risks, leading to reductions in GDP losses and adverse distributional consequences. Additionally, the ABM model demonstrated that enhancing accessibility to debt financing and government funding for reconstruction results in a notable improvement in the debt-to-GDP ratio and unemployment rate (see for a full discussion [40]).

Summarizing, the modelling results showed that management strategies have to account for the fact that there are, in an economic sense, "winners" and "losers" when a flood event hits. In other words, there are economic sectors which benefit from the reconstruction works (e.g., construction, machinery, motor vehicles) while other sectors suffer greatly from such an event (e.g., public administration, arts, education). Furthermore, the issue of responsibility revealed itself to be especially hard to tackle as there seems to be challenges to address the issue of accountability for indirect flood risk management in the current flood risk management apparatus in Austria. Given that hydro-geological risks are predicted to rise in the future, it is all the more important that anticipatory measures are implemented that increase resilience to flood risks. Based on our analysis for example to do so, more skilled labor force is needed. From a multiple dividends perspective, the benefits of availability of labor for the reconstruction process overlaps within the general economic development of Austria in the future. In other words, from a disaster system-centric point of view, the need to have enough labor available to provide rapid reconstruction and, in doing so, minimize indirect risks, can be seen as one indirect risk management strategy. But also from an economic development system perspective, the availability of labor is needed. Hence, for both objectives, the same strategy seems to be beneficial and, therefore, provides multiple synergies and benefits.

3.4. Implementation aspects

The **last and fourth step** would consist in the implementation of indirect risk management. At this point little can be said since indirect flood risk management is barely established in Austria. However, the project's insights should form a starting point for the establishment of indirect risk management in the future. A development in that regard is that indirect economic effects of floods are to play a more crucial role in cost-benefit-analyses in the future. Currently, they are merely qualitatively described, which is a laborious and slow process [50]. According to officials from the Federal Ministry of Agriculture, Regions and Tourism, this process may need to be automatized so that the indirect economic effects are recorded as a mark-up factor, for example via a fixed factor for each lost production day, in the cost-benefit-analysis. Furthermore, a recent project tackles the issue of the lack of a recorded data on flood effects by building a nationwide database of disaster losses in Austria (CESARE). Several scientific institutions and ministries joined in this effort and although the project focused on collecting data on direct losses, also indirect damages of natural disasters are being accounted for. Both of these developments are evidence of the growing awareness of the significance of indirect flood risks within the

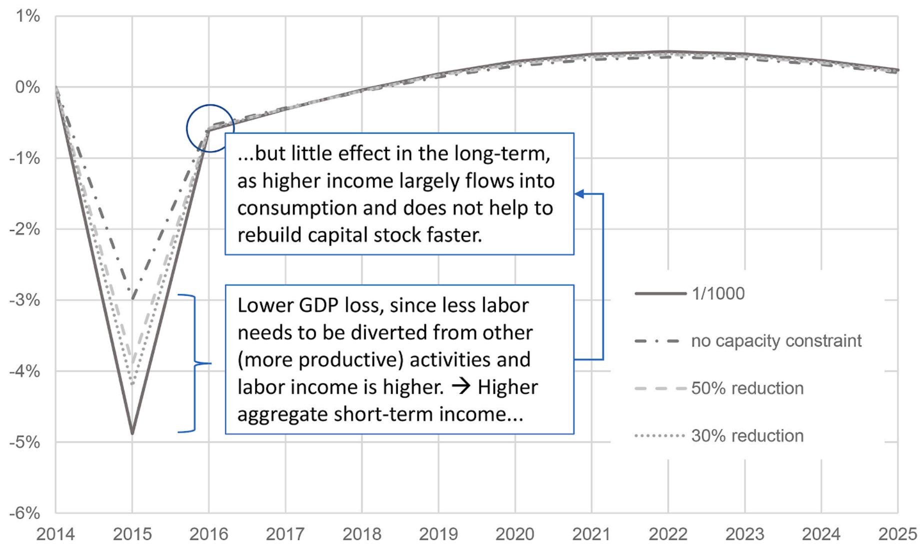

Fig. 4. GDP losses with a 1/1000-year flood event (solid line) and under different management strategies addressing skill shortage with a 30% (dotted line), 50% (dashed line) and complete ("no capacity constraint", dashed-dotted line) reduction of skill shortage. Source: Own Authors.

flood risk management cycle. Nevertheless, more fundamental or even transformational changes in current approaches are required in the future, especially when accounting for further changes in the climate and demographics.

3.5. Reframing and transformation

Two other loops of the framework, the **reframing** as well as **transformation** loop, were difficult to be explicitly incorporated in our case study due to the shear complexity already involved within the assessment cycle. Nevertheless, from a multiple dividends perspective a reframing of the problems encountered within flood risk into a general system approach is currently underway in Austria and our analysis can give useful insights on which sectors as well as interdependencies are at play. Given climate change impacts and increases in variability, however, a transformational approach may be necessary to be thought of as well. Be as it may, iterative and adaptable risk management strategies will very likely serve best to respond to upcoming challenges due to the large uncertainties involved, both in the short-as well as long-term perspective [51,52].

4. Discussion

The 6th IPCC assesment report [53] highlighted interactions and coupled systems, particularly those involving different actors, the climate, and human society. While the report frequently referenced systems, a precise definition of the term and a concrete actionable approach to address emerging challenges were lacking. The report underscored the need to address cascading risks and tipping points as a major challenge [4,54]. In response, there is a call for conceptual approaches and advanced models capable of incorporating complex interactions and non-linearities. In our study, we demonstrated the development and application of such methodologies within an adaptive 4-step framework, extending established risk assessment and management cycles from climate and disaster research. We tested the framework reporting outcomes and challenges encountered during a 3-year study for major flood risk in Austria. Our results contribute to illustrating how dynamic impacts, cascading and indirect risks can be integrated into current direct risk assessment and management.

The conceptual starting point of our framework involves defining the system, establishing clear boundaries, and identifying differences in the dynamics of system elements. A system definition aids in identifying options to address multiple risks beyond hazards, employing a procedure known as the multiple dividend approach. This approach involves making disaster risk management investments that enhance resilience, yielding co-benefits irrespective of disasters. The integrated appraisal phase provides an outsider's perspective, offering evidence and pathways for management strategies to simultaneously address multiple threats and provide additional benefits for the system.

Given the large uncertainties, an iterative approach is essential, allowing each step to be updated based on the trajectories of underlying risks in the short and long run ([30]). Conflicting interests among various systems and risk bearers necessitate overlapping strategies to overcome implementation barriers. A toolbox approach is particularly useful for dealing with indirect risk estimates, given their uncertainties and diverse risk measures, guiding decision-makers toward options and strategies with multiple benefits and fostering a continuous and iterative process of adaptation [55]. In regard to possible future changes, approaches such as Dynamic Adaptive Policy Pathways (DAPP) [35] as well as Climate Storylines [36,56] can help to design (long-term) strategies that can be separated into manageable steps which need to be implemented and adapted over time.

We emphasized the intrinsic relationship between direct and indirect risks, noting that even small direct losses may cause significant indirect losses depending on the interconnectedness of agents in the system. This is an important point to consider in our increasingly interconnected world that relies, for example, on global supply chains prone to multiple hazards or other events, such as pandemics [9]. Therefore, the management of both direct and indirect risks is intrinsically related. Regarding direct risk, there is a growing consensus that effective management should explicitly encompass human interactions, incorporating adaptive behaviours and even seemingly irrational ones, such as the natural disaster syndrome [57]. Consequently, it is imperative to adopt not only natural but also social science-based approaches for comprehensive risk management, extending to indirect risk as discussed here.

A final, noteworthy consideration pertains to the normative connotation associated with the term “risk.” As demonstrated, the realization of risk may prove advantageous for some while detrimental for others, contingent upon numerous factors and often elusive dependencies. Justice considerations become particularly significant, prompting ongoing discussions on potential frameworks [58]. Various dimensions of human agency, such as culpability or the role of free will, may be deemed less significant in certain risk contexts, like supply chains, compared to others, such as migration or political turmoil. This underscores the complexity that should be incorporated into risk analysis to govern current and emerging threats. The determination of the “optimal” level of complexity, influenced by factors like limited resources and data constraints, has not been addressed here and may only be resolved on a case-by-case basis. Substantial future research is necessary to confront this significant yet challenging problem.

5. Conclusion

We presented a possible extension of a risk governance framework for disaster risk to indirect risk and indicated overlaps with other system objectives that can enable multiple benefits on many scales. We especially emphasized a system definition that focuses on boundaries and dependencies which is particular useful for the management of indirect risks and the integration with already established direct risk related approaches. Our application indicated that various different dynamics have to be assumed after direct risk realizes. Therefore, multiple modelling approaches to manage possible indirect risks are needed. We introduced three highly detailed macro-economic approaches and results to lay out which options as well as multiple-benefits could be assumed for different decision makers as well as how to govern such risks within a broader setting. Our results call for a toolbox-based approach to appreciate the complex nature of indirect risks and to provide multiple entry points for its analysis, including choices of methods, models and approaches. This should also be beneficial to better relate the various tools that currently exist as well as their limitations and possible ways forward to provide further insights under a variety of circumstances considered important within risk governance processes.

We applied our suggested framework for the case of Austria focusing on large scale flood risk and identified ways forward on how to implement the framework in practice using a multi-model approach embedded within a participatory process. Our study should give some indications as to how the management of indirect and cascading risks could be embedded within ongoing policy processes, especially focusing on integration of both types of risks as they are intrinsically related. Given the intricate nature of assessing and quantifying indirect risks, mainstreaming them into policy might prove challenging, especially in the short term. To facilitate their better integration into ongoing policy-making processes or existing risk management frameworks, we propose the following practical measures: Firstly, institutions could initiate by employing relatively straightforward models, such as Input-Output modelling. Secondly, institutions could enhance their modelling capabilities internally (e.g., by recruiting experts from academia), enabling them to conduct analyses tailored to their specific needs. Thirdly, efforts to strengthen the science-policy interface should be intensified, moving beyond project-based research towards establishing long-term cooperation. This would ensure continuous and comprehensive guidance from science, bolstering science-informed policy and decision-making processes over the long haul.

We did not discuss climate change aspects and due to the large uncertainties in that regard, a risk-based approach as suggested here may be difficult to be implemented. Rather new approaches such as Climate Storylines [56] as well as Dynamic Adaptation Policy Pathway approaches [35] should be looked up for these reasons. This is in the spirit of a toolbox approach that can take such considerations explicitly into account and provide various entry points for the analysis of indirect risks due to hazard events on various scales. As indicated, the optimal level of complexity to achieve this task is an important question and needs further research.

CRediT authorship contribution statement

Stefan Hochrainer-Stigler: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Gabriel Bachner:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Software, Writing – original draft, Writing – review & editing. **Nina Knittel:** Formal analysis, Software, Writing – original draft, Writing – review & editing. **Sebastian Poledna:** Formal analysis, Funding acquisition, Software. **Karina Reiter:** Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Francesco Bosello:** Investigation, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

Funding for this research was granted by the Austrian Climate and Energy Fund under its 11th Call of the Austrian Climate Research Program (grant number B960222; project “MacroMode— Macroeconomic Modeling of Indirect Risks for Climate Risk Management”). The authors acknowledge the financial support by IIASA for publishing open access.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2024.104425.

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