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Impact Webs: A novel conceptual modelling approach for characterising and assessing complex risks

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Abstract

Identifying, characterising and assessing the complex nature of risks is vital to realise the expected outcome of the Sendai Framework for Disaster Risk Reduction. Over the past two decades, the conceptualization of risk has evolved from a hazard-centric perspective to one that integrates dynamic interactions between hazards, exposure, systems vulnerabilities and response risks. This calls for a need to develop tools and methodologies that can account for such complexity in risk assessments. However, existing risk assessment approaches are hitting limits to tackle such complexity. To this aim, we developed a novel complex risk assessment methodology named 'Impact Webs', inspired by a conceptual risk modelling approach named Climate Impact Chains that integrates aspects of various other conceptual models used in risk assessments such as Causal Loop Diagrams and Fuzzy Cognitive Mapping. Impact Webs are developed in a participatory manner with stakeholders and characterise and map interconnections between risks, their underlying hazards, risk drivers, root causes, responses to risks, as well as direct and cascading impacts across multiple systems and at various scales. In this methodological paper, we show how we developed the Impact Web methodology, including how we derived which elements to include in the model, demonstrating the logic and visual output and listing the steps we followed for construction. As proof of concept, we present the results of a complex risk assessments in Guayaquil, Ecuador, which investigated how COVID-19, concurrent hazards and responses propagate risks and impacts across sectors and systems during the pandemic. Reflecting on the utility of Impact Webs, application in case studies demonstrates the methodologies usefulness for understanding complex cause-effect relationships and informing decision-making across different scales. The participatory process of developing Impact Webs promotes stakeholder engagement, uncovers critical elements at risk and trade-offs in decision making, helping to evaluate both positive and negative outcomes of disaster risk management practices. Offering a system-wide perspective for modelling, Impact Webs stand as a valuable methodological contribution for complex risk assessment.

1. Introduction

Identifying, characterising and assessing the complexity of risks is vital to realise the expected outcome of the Sendai Framework for Disaster Risk Reduction (UNDRR, 2022). As sectors and systems become increasingly interconnected, the space in which risks can cascade is expanding (Helbing, 2013; UNDRR, 2022). This has been starkly evident throughout the COVID-19 pandemic, where impacts have not just arisen in the health system, generated by the hazard, but also from the cascading effects of impacts and from societal responses through global lockdowns, with different regions suffering from vastly different consequences depending on underlying societal vulnerabilities and the resilience of their systems (Hagenlocher et al., 2022). These characteristics are not limited to COVID-19, and have also been observed in other contexts, including from the compounding and cross-border effects of extreme climate events (Simpson et al., 2021; Zscheischler et al., 2018), or from the global ripple effects of armed conflicts (Cui et al., 2023).

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Over the past two decades, the conceptualization of risk has evolved from a hazard-centric perspective to a more encompassing notion that integrates the dynamic interactions between hazards, exposure, vulnerability (IPCC, 2014) and, more recently, response risks (Simpson et al., 2021; IPCC, 2023; Hagenlocher et al., 2023). Different terminologies have been used to conceptualise these dynamic interactions, including cascading, compound, and systemic risks. In this paper we use the term 'complex risks' to encapsulate these different risk framings. Given that complexity is now understood as a defining feature of risks, single-hazard and single-risk approaches, while useful in certain contexts, are becoming increasingly insufficient for comprehensive disaster risk management (Simpson et al., 2021; UNDRR, 2022; Schlumberger, et al., 2024; Sett et al., 2024; de Ruiter & van Loon, 2022). This has been recognised by the Intergovernmental Panel on Climate Change (IPCC) in the Sixth Assessment Report, which notes that risks and responses, including their determinants, can all interact dynamically in shaping the complexity of climate risk (Ara Begum et al., 2022). Additionally, the Global Assessment Report 2022 (GAR 2022) from UNDRR stresses the importance of understanding and assessing the complex nature of risks as a key foundation for risk informed decision making (UNDRR, 2022). However, existing data driven and quantitative modelling approaches are hitting limits to tackle such complexity. The combined effects of multiple hazards, threats or shocks should not be assessed just through the addition of each of their impacts independently, but instead require systems approaches to understand risk and impacts (de Ruiter et al., 2020; Ara Begum et al., 2022; Hagenlocher et al., 2023; de Brito et al., 2024). There is therefore a need to develop methodologies that take a system-wide lens for analysis, that can account for how multiple hazards and vulnerabilities of systems and sectors interact to better understand complex risks.

To this aim, we developed a novel complex risk assessment methodology named 'Impact Webs'. Impact Webs are inspired by a conceptual risk modelling approach named Climate Impact Chains (see Menk et al., 2022 for a review of applications), and draw inspiration from various other conceptual models used in risk assessments. Climate Impact Chains were originally developed for sectoral climate risk assessment (Schneiderbauer et al., 2013; Zebisch et al., 2023, 2021; Hagenlocher et al., 2018), in which elements of the model are assigned to the key risk components used in disaster and climate risk assessments of hazard, exposure and vulnerability, and cascading effects are assigned as intermediate impacts. One critique of Climate Impact Chains is that they often depict a linear cause-effect relationship for a single sector or hazard, and thus do not capture the complexity of systems interaction well (Harris et al., 2022). With Impact Webs, we built on Climate Impact Chains, integrating aspects of system mapping approaches such as Causal Loop Diagrams (Coletta et al., 2024), Fuzzy Cognitive Maps (Gómez Martín et al., 2020) and Bayesian Belief Networks (Scrieciu et al., 2021). With this, we aimed to integrate the key risk components in disaster and climate risk assessments with a systems perspective to identify, characterise and map interconnections between risks, their underlying hazards, risk drivers, root causes, responses to risks, as well as direct and cascading impacts across multiple systems and at various scales. Impact Webs aim to better account for the complexity of risk interaction compared with Climate Impact Chains, by developing flexible and less linear conceptual models that can help to understand complex risks.

In this methodological paper, we show how we developed the Impact Web methodology. To do this, we first conducted a non-systematic literature review of conceptual risk models that we drew inspiration from. We then undertook concept development within the research team, selecting constitutive elements and developing a graphical structure for the conceptual model. We also defined steps to follow in a complex risk assessment for constructing an Impact Web. To test our metholdogy, we then trailed Impact Webs in five cases, undertaking complex risk assessments to investigate how COVID-19, concurrent hazards (e.g. hydrological, geophysical, climatological) and responses too them (e.g. restriction measures) interacted with underlying societal vulnerabilities to propagate risks and impacts across sectors and systems during the pandemic (see section 2.3 for more on the five test cases) (Hagenlocher et al., 2022). COVID-19 was selected as the entry point for the risk assessments as the pandemic has been so diverse and cross-scale in its effects, therefore such an event was ideal to test a novel risk modelling approach for understanding complex risks. As proof of concept, we present the

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results and final output from one of the five test cases, showing an Impact Web and narrative storyline for the city of Guayaquil, Ecuador during the COVID-19 pandemic. Guayaquil was selected due to the city's high vulnerability and exposure to the compounding effects of multiple hazards and the presence of many drivers of risks creating numerous challenges for risk management.

The remainder of the paper is structured as follows: In section two we present the methodological development, which includes the literature review of conceptual risk models, concept development and introduces the five test cases. In section three, we present our results, listing the constitutive elements we selected to populate the model, discussing why they where selected and relevent for assessing complex risks. We then present the steps that were followed during the risk assessments to construct an Impact Web, and show the result from the Guayaquil test case. In the discussion in section 4, we reflect on the utility of Impact Webs, looking at strengths, limitations and potential future research directions. We conclude in section 5 with synthesis of the paper, highlighting Impact Webs as a conceptual model that moves beyond single-risk or single-hazard assessment, which can be used as an approach for system-wide complex risk assessment.

2. Methodological development

In section 2, we present our methodological development from Impact Webs. We show other conceptual risk modelling approaches we drew inspiration from, elaborate on our concept development and discuss how we trailed developing Impact Webs in five different test cases.

2.1. Review of conceptual risk models for inspiration

Given that we aimed to develop an approach that took a systems perspective for analysis to better understand complex risks, we reviewed the literature on conceptual risk models which do this. The review was non-systematic and not meant to be exhaustive. It was done to inspire concept development for our approach, looking at features of different methodologies that could be useful. Texts were selected and reviewed based on authors expert judgement after title and abstract screening using the Scopus search engine. We looked at features of different approaches and analysed strengths and weaknesses in a complex risk context, providing key references (see Table 1).

Table 1: Overview of conceptual models used in risk assessments

Approach	Features	Strengths in a complex risk context	Weaknesses in a complex risk context	Key references
Climate Impact Chains	*Model illustrates key risks and their drivers for a specific context, with elements assigned to hazard, exposure, vulnerability and intermediate impacts recognising that the system is affected by multiple risks that need to be prioritised*	*Opportunities pertain to the flexible and relatively simplistic form, making them more easy to develop through a participatory process, allowing for perspectives of vulnerable groups and impact dynamics for specific case studies.* *Innovative focus on intermediate impacts, making them conducive to analyse cascading impacts, as well as focus on risk drivers and the "cause–effect relationships" that define them* *Can identify entry points*	*Analytic emphasis on linear cause–effect relationships, neglecting and oversimplifying complex system interactions* *Narrow definitions of system boundaries* *Limited applicability to fragmented governance landscapes (in consideration of risk ownership), resulting in 'blind spots' for adaptation and response risks*	*Hagenlocher et al., (2018)* *Sett et al (2024)* *Zebisch et al (2023)* *Petutschnig et al (2023)* *Harris et al (2022)*

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		for adaptation across the model elements, including for risk drivers and root causes		
Fuzzy Cognitive Maps	*Semi-quantitative diagramming tool that maps the important elements of a system in nodes, providing the relationship between nodes in terms of direction and strength*	*Indicate the strength of the causal relationships (weak, medium, strong) and the ability to examine feedback effects in systems where exact relations are hard to quantify* *The vector-matrix structure facilitates the aggregation of different stakeholders' views, which is affective for participatory modelling exercises* *Can integrate temporal considerations by introducing delays in the model assuming that the weights can change over time, which is useful for assessment of the delayed cause-effect of relationships*	*Risks force-fitting archetype to the systems problems, rather than as a lens to look at the system from different perspectives* *Results can be difficult to communication to non-experts* *Often a lack of analysis on the difference in perspectives between stakeholders, leading to analysis that accounts for the trade-offs among co-benefits of interventions, and not for trade-offs between stakeholder's valuations*	*Gómez Martín et al (2020)* *Ahmeda et al (2018)* *Chandra & Gaganis (2016)* *Scrieciu et al (2021)*
Causal Loop Diagrams	*Tool for visualising the causal structure and delays between interacting system elements, demonstrating how change in one variable can influence others by reinforcing or balancing them, helping to describe how complex interconnections and feedback loops affect the systems dynamic evolution*	*Provide insights into behavioural trends and stakeholders interactions affected by risks as well as response measures, making them useful to support decision-making processes at a planning/ strategic level* *Allows for an examination of potential future trajectories of change based on whether feedback loops are reinforcing (indicating a dynamic situation) or balancing (indicating a more stable situation)* *Can be combined with quantitative indicators to create 'what if' scenarios that project how changes in one indicator (for example, by implementing a response measures) can make changes in other parts of the system*	*Inadequate representation of spatial dynamics* *The isolation and examination of specific dynamics may produce results which are misrepresentative of the system functioning as a complex whole* *Difficult to validate robustly, particularly affecting reliability when assessing social, economic and political sub-systems, which are more difficult to predict than physical based sub-systems* *Does not distinguish between physical and information links*	*Coletta et al (2024)* *Dianat et al (2020)* *Groundstroem & Juhola (2021)* *Rehman et al (2019)*

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Influence Diagrams	*System elements connected by arrows, indicating causal links through symbols that make distinctions between stocks & flows of information & physical assets, often to model a decision-making process*	*Making distinctions between stocks & flows of information & physical assets forces the modeller to think about operational factors of the model early in the modelling process* *Excel in identifying the effects of response measures across different social-ecological systems* *Through stakeholder input, they can represent the socially constructed nature of risks, and therefore can identify groups or individuals who perceive more system relationships and risks and thus have more insight into how to change the system*	*The greater level of detail requires many conventions and rules, which may not be easy to communicate to non-expert stakeholders* *Defining and assessing variables and strength of links can be seen as an exercise in power, in which dominant bodies can more strongly influence decision variables and 'push' the system into their preferred direction*	*Parviainen et al (2019)* Mühlhofer et al (2023) *Malekmohammadi et al (2023)* *ElSawah et al (2015)*
Bayesian Belief Networks	*Integrate qualitative data in the form of cause and effect diagrams and quantitative data in the form of assigning a value to the strength of the dependence between variables using conditional probability, offering a probabilistic representation of the relationships between system elements and how they influence one another*	*They can be used to perform sensitivity and scenario analysis, thereby allowing decision makers to predict the more probable outcomes of management actions and identify management actions that are most likely to lead to specific outcomes* *The conditional probability tables used with the cause and effect diagrams can be updated when new data generated or collected, for example from climate models, case studies or monitoring programs* *Link well with other conceptual modelling approaches to model quantitatively and assess uncertainty*	*Use directed acyclic graphs which cannot contain cycles or feedback loops* *A large amount of data is required for populating the conditional probability tables, which is a challenge in data scarce contexts* *A long cause-effect chain of nodes can show reduced sensitivity, which can propagate uncertainty from parent nodes to child nodes. This incentivises reducing the models complexity, which does not reflect risk in complex systems*	*Malekmohammadi et al (2023)* *Scrieciu et al (2021)* *Giordano et al (2013)* *Bashari et al (2016)*
Participatory Systems Mapping	*Facilitates the co-creation of conceptual models with groups of stakeholders, often to develop a shared vison of the systems structure with inputs from different expertise, perspectives and world views*	*The modelling is close to natural language, which captures the causal knowledge of stakeholders in a more comprehensive and less time-consuming manner than other methods and the results are easily comprehensible for*	*Often only permits qualitative assessment of the state of the system* *As with all participatory approaches, the facilitators must be mindful of power dynamics during the modelling exercise*	*Suriya & Mudgal (2012)* *Gómez Martín et al (2020)* *Giordano et al (2013)*

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		participants *Supports active collaboration and integration of different expertise and interdisciplinary skills, thus building greater trust in models* *Particularly well-suited for obtaining data coming from formal and non-formal sources*		

Lessons from the review

Many different conceptual modelling methodologies have been applied across disciplines for complex risk assessment. We observing three broad types of approaches, following Elsawah et al (2017). First are the use of conceptual models as predictive tools to simulate biophysical process interactions, often extreme events, with an additional dynamic input, often stakeholders' perceptions or risks or risk management decisions, to model system dynamics scenarios. For example, Scrieciu et al (2021) integrate hydraulic modelling and Bayesian Belief Networks to analyse stakeholders perceived effectiveness of Nature-based Solutions for reducing flood risk to support implementation. The second approach develops conceptual models as a framework to examine interconnections and feedback effects in one or multiple systems, usually to support integrated and cross sectoral decision making. For example, Dianat et al (2021) develop Causal Loop Diagrams to investigate the multi-dimensional implications and feedbacks of different risk management policies to multiple hazards, aiming to support decision-makers in improving city resilience. The third approach elicits stakeholder participation to develop shared system understanding and co-create outputs. For example, Sett et al (2024), engage a range of stakeholders, integrating scientific and non-scientific knowledge, to model key flood risks, their interconnections and underlying risk drivers in urban and peri-urban areas.

The three broad types of approaches are not mutually exclusive, and do cross over with one another. Methodological combinations of approaches are common and adjusted to suit the decision context or setting of the risk assessment. For example, there is often integration between Fuzzy Cognitive Maps, Influence Diagrams and Bayesian Belief Networks. The majority of studies also integrate some form of input from stakeholders through a participatory process, however, it is common for stakeholder participation to decrease with increasing complexity of the method used. This is due to difficulties in communicating and facilitating the approach. All three types of approaches use graphical methods to show cause-effect relationships, most commonly using arrows and symbols to signal a relationship and influence. A systems thinking perspective is commonly taken towards analysis across the papers, particularly with causal loop diagrams and participatory systems mapping. The aim of taking a systems perspective is to enhance system understanding and reduce uncertainty through modelling system element interactions and dynamics.

Observing different conceptual modelling methods, with Impact Webs we aimed to add novelty in areas that other approaches lacked as well as draw on their strengths. Novel additions we wanted to include were building on the hazard, exposure, vulnerability framing (i.e. from Impact Chains and the IPCC), expanding this to capture complex/ systemic interactions. We therefore included the dynamic interaction of multiple hazards, threats or shocks, multiple exposed elements and the drivers and root causes of vulnerabilities to exposed elements across different scales (i.e. from local to global). We expanded beyond a sectoral focus (e.g. drought risk for the agriculture sector), capturing cross-sectoral risks, impacts and vulnerabilities and their influences between one another. Drawing on Influence Diagrams and Bayesian Belief Networks, we included the addition of interventions and response risks arising from

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them. As done in all approaches, we also used graphical methods to model cause-effect relationships and feedbacks. We also took a strong participatory approach, aiming to reduce complexity in the development steps so the final output is a strong representation of what stakeholders value and want to protect.

2.2. Concept development

Building on lessons from the review, we undertook further theory and concept synthesis and adaption. Further content analysis of conceptual risk frameworks, academic papers and reports was undertaken in a non-systematic manner. Various different modelling approaches and graphical methods were trailed within the research team and put through rounds of feedback until we synthesised an agreed upon number of constitutive elements, steps for construction and output to trail (see section 3).

2.3. Trail in test cases

Moving from concept development into practice, five Impact Webs were made in test cases to assess complex risks (Hagenlocher et al., 2022). This was done to trail our methodology with groups of stakeholders across diverse case study contexts. Doing this had three purposes, First, it allowed for adjustment and improvement of the methodology through stakeholder feedback. Second, we could test Impact Webs across different locations each with their own with unique challenges, building from the same entry point to see if the approach was replicable and a useful risk assessment tool in different contexts. Third, we wanted to develop a methodology that was participatory, therefore we needed to trail it with stakeholders and get their input. Each case took COVID-19 as the entry 'seed' element, building from there to populate the model using desk study and stakeholder workshops. Two rounds of workshops were done with a range of different stakeholders (see section 3.2 for further details). The test cases include Coxes Bazar humanitarian camp (Bangladesh), Guayaquil (Ecuador), Sundarbans region (India), national scale (Indonesia), Maritime region (Togo). The cases were chosen to cover a wide thematic range. In this paper we only present the final Impact Web for one of the five cases (Guayaquil, Ecuador), to demonstrate our proof of concept.

3. Results

Here we present the results, showing how we developed our complex risk assessment methodology. This includes the final elements that were selected for an Impact Web and why, which steps were followed and refined in the test cases, and a proof of concept detailing the final output from the Guayaquil, Ecuador test case.

3.1. Selection of constitutive elements in an Impact Web

Here we present the elements that were selected for an Impact Web and include justifications for why they were selected.

Hazards, threats and shocks

Conceptual risk models are developed to better understand impacts arising from a hazard, threat or shock, such as hydrological extremes (e.g. flood and drought), biological hazards (i.e. COVID-19 or a cholera outbreak) or geopolitical aggression (e.g. a war or conflict). We wanted our model to improve understanding of compounding interaction, given the increasingly interconnected nature of multi-hazards impacts on systems (UNDRR, 2022). Therefore, we included multiple hazards, threats and shocks to the system in our model.

Direct and cascading impacts

Following the inclusion multiple hazards, threats and shocks, direct and cascading impacts were included in the element selection (Lawrence et al., 2020). This was done to identify impacts emerging from risks, and also model the system's interconnectedness through impact propagation (Mühlhofer et al., 2023; Carter et al., 2021), as linkages between sectors and sub-systems could emerge as

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connections were characterised. Both positive and negative impacts were included, as well compounding and cascading impacts from multiple hazards, threats or shocks (Simpson et al., 2023).

Interventions, response risks and risks that did not manifest

In response to or anticipation of risks and impacts, decisions are taken which also have effects in systems. Drawing on aspects of Fuzzy Cognitive Mapping, Influence Diagrams and Bayesian Belief Networks, which are useful for modelling the effects of decision-making processes (Scrieciu et al., 2021), as well as the more recent framing of "response risks" (Simpson et al., 2021; IPCC, 2023; Hagenlocher et al., 2023), both interventions and the effects of them were included in our conceptual model. Both positive and negative effects were included as positive and negative impacts, as well as risks that did not manifest as a result of interventions. The defined decision context and system boundaries denote the granularity of response risks and impacts included in the model, for example whether mapping the city level or intergovernmental level interventions.

Drivers of risk and root causes of risk and vulnerability

Understanding causality is a key rationale for disaster risk assessment (Oliver-Smith et al., 2017), and taking a systems approach facilitates looking into causal connections that can deepen the assessors understanding of how and why impacts can emerge (Gómez Martín et al., 2020; Coletta et al., 2024). Therefore, an important element for our model was to look at what was driving the risks and impacts in the system, as well as looking at the root causes behind them. Drivers of risk were included as an element, which asks the modeller to critically reflect on how and why societal functions, essential sectors, system elements or stakeholders were adversely affected, i.e. due to high susceptibility or low coping/ adaptive capacity. Moreover, exploring socio-economic and political structures and processes and choices that further explain the root causes (i.e. underlying reasons) for risk drivers was an important reflection and learning step for us to characterise and improve our own understanding of complex risks within the systems being modelled (Blaikie et al, 1994; Wisner et al., 2004; UNDRR, 2022; UNU-EHS, 2023). While drivers of risks and root causes are often distant in space and time (Wisner et al., 2004), they are relevant for multiple impacts in the model.

Connections between elements

Following the other conceptual modelling approaches we reviewed, we used graphical methods to show connection between our chosen elements and visualise risks. We selected arrows to indicate directional cause-effect relationships. Given the limitations of directed acyclic graphs used in many Bayesian Belief Networks and Influence Diagrams in showing feedback effects (Bashari et al., 2016), we took an approach more inspired by causal loop diagrams. This meant we could better demonstrate indirect effects and feedback loops (Groundstroem & Juhola., 2021), which is both more appropriate to a complex risks context and helped us understand interconnectivity between elements.

Multiple scales

From our review we did not find conceptual modelling approaches that were effective at demonstrating risk elements and their interactions across spatial scales. For example, a critique of Impact Chains and Fuzzy Cognitive mapping approaches is often that they have narrow definitions of system boundaries (Petutschnig et al., 2023; Ahmed et al., 2018). For Impact Webs, we included three spatial scales in our model (local, regional and global), which was intended to model globally networked risks, as well as demonstrate risk drivers, root causes and impacts that are often spatially distant but have effects in the local context (Helbing, 2013). As the test case study contexts were georaphically diverse, there was flexibilty in how the 'local' scale boundary was defined. For exmaple, for the Coxes Bazar case, the local scale was defined to inside the humanitarian camp. Compariatvely, Guayaquil focused on investigating the city municiality, whereas Indonesia was at the national scale.

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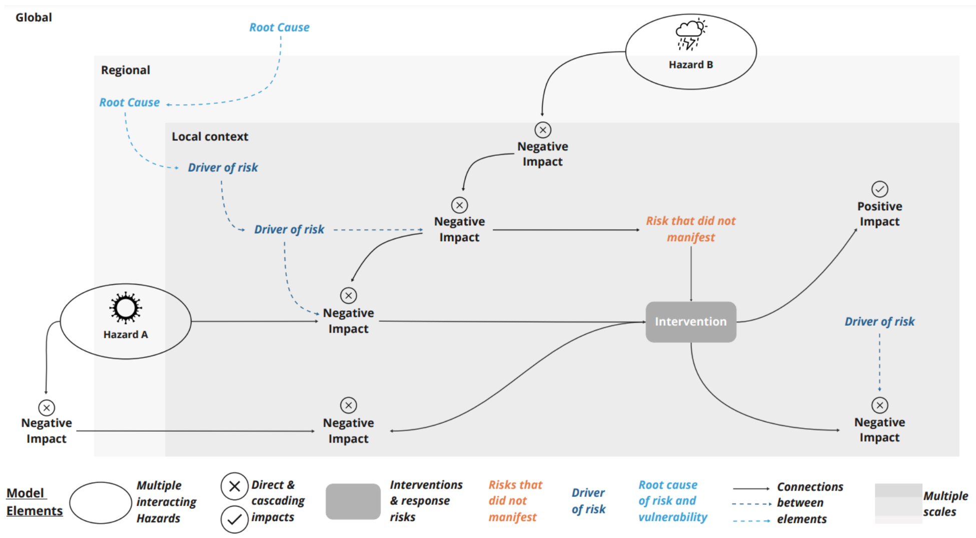

Figure 1: *Elements and possible graphical structure of an Impact Web. While here we present our chosen graphical output of the conceptual model with computerised tools, an Impact Web could equally be made with a pen and paper, for example if being developed in a community workshop. The model maps the direct and cascading impacts and their interactions resulting from a biological and climate-driven hazard. These impacts trigger an intervention, which results in further negative and positive impacts (i.e. response risks), as well as a risk that did not manifest. Drivers of risk and root causes linked to why impacts emerge are also included. The elements in the model are predominantly focused on the local context, however, important regional and global interactions are included.*

3.2. Steps for constructing an Impact Web

Here we present the steps that we followed to construct an Impact Web.

Step 1: Scoping

Risk assessments are done in a specific setting to support decision making processes. Following in the steps of risk assessments that have been successful in the past (e.g. Zebisch et al., 2023; Hagenlocher et al., 2018), the preliminary step for constructing an Impact Web was the scoping. Here, we defined objectives and the need for the multi-hazard risk assessments across each case, considering how the conceptual models could enhance understanding and inform decision making that reduced risks. While systems theory denotes that system boundaries change, for example due to shifting climatic conditions (Steffen et al., 2015), practically, selecting the scale to model across the test cases helped to refine decision context. This was done through looking at geographical or administrative boundaries to select the area of primary focus. We then identified critical societal functions, essential sectors and key elements at risk in each of the cases, as well as key stakeholders that were engaged later in the process. Once this was defined however, it was important that there was flexibility when populating the Impact Web with elements, given that we wanted to model cross scale dynamics including feedback effects, cascading effects and globally networked risks that were identified outside the geographic boundaries of the test cases ((Helbing, 2013; Sparkes & Werners., 2023).

Step 2: Identifying and mapping a preliminary number of elements

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While there are not restrictions in terms of the order for selecting the elements in an Impact Web, we found it was preferable to start from a limited number of key elements that you want to better understand and then progressively build up the causal connections. In our test cases, we wanted to understand multi-hazard interaction of COVID-19 and concurrent hazards, threats and shocks, therefore COVID-19 was the logical entry point. This perspective acknowledged that the systems relationships emerge more clearly when under stress, i.e. become more visible and therefore easier to observe. In this sense, the first number of elements functioned as "seeds" for the identification of the systems interdependencies. We found building from key hazards, threats and shocks as the 'seed' elements facilitated following a more simplistic cause-effect chain at the start of construction, i.e., direct impacts arising from each of the hazards, threats or shocks. From direct impacts, cascading impacts then interventions and response risks, and finally drivers of risks and root causes followed. While Impact Webs eventually aim to map risk complexity, we found it difficult to start from the more complex interactions (i.e. feedback effects). Rather, starting with more simple connections is easier for the modeller and stakeholders to begin with, and the more complex interactions will emerge later as system understanding improves with desk study and futher stakeholder interactions.

Step 3: Workshops and stakeholder participation

Nearly all conceptual models that we reviewed integrated some form of stakeholder input, which was variable depending on the decision context and method chosen. Participatory Systems Mapping and Impact Chains for example, generally elicit the integration of more stakeholder input than Influence Diagrams, which have a strong quantitative component. A key step in our approach was to draw on diverse knowledge from a range of expertise across the test case. This way, the Impact Web would be co-created to develop a mutually agreed upon visual output of complex risks, as well as heuristic of the system. Building on the preliminary number of mapped elements, we held two workshops in each test case with a range of different stakeholders from communities, policy, practice, civil society, academia and governments that were identified in the scoping in Step 1. The first workshop focused on identifying new elements for the Impact Web, as well as reviewing the ones that had already been identified and mapped in Step 2. We then included these inputs into the model, and held a second workshop to re-validate the logic and elements, as well as look at entry points for risk management. This stakeholder backstopping provided better understanding of otherwise unknown or missed model elements and their connections, and helped to characterised the complex risk characteristics that could not be captured through desk study alone.

Step 4: Review of model and visualisation

After collecting stakeholder inputs across the five test cases, an important step was to review the model within the research team. This included in-depth structuring of the information gathered in the workshops and cross referencing it from available literature sources gathered in the desk study. Where possible, we also refined the number of elements, for example by clustering two elements that represented the same issues. This was done to reduce the model's complexity and ensure the final visual could be an effective communication tool. We also reviewed causal connections and logic behind them, reflecting to understand what this meant in a systems context, thus enhancing our own understanding of complex risks. We then reworked the graphical design to create a visual and causal connections which could be simpler to follow.

Step 5: Drafting narrative storyline

As a final step to accompany the Impact Web model, a narrative risk storyline was drafted for each test case that described the model and its connections in a narrative format. This helped to communicate in a descriptive and engaging manner the complex model output that results from following the previous steps, making it more engaging for both experts and non-experts (van den Hurk et al., 2023).

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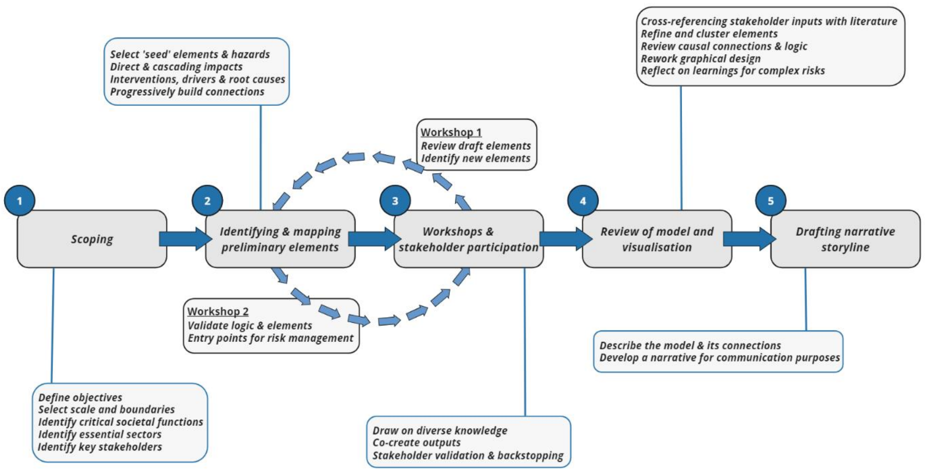

Figure 2: *Workflow of the steps that were followed for constructing an Impact Web. We trailed the approach in 5 test cases, which allowed for adjustment and improvement of the methodology as well as stakeholder feedback. The workflow followed a flexible stepwise methodology in five steps (scoping, identifying & mapping a preliminary number of elements, workshops and stakeholder participation, reviewing the models logic and visualisation and drafting an accompanying narrative storyline). Workshop 1 allowed for new inclusions and adjustment of already identified elements in the draft model. Once included, workshop 2 allowed for validating the logic and looking at entry points for risk management. This is shown in the figure through the circular blue arrows, which indicates iteration in the models development.*

3.3. Proof of concept: Complex risks linked to COVID-19, concurring hazards and responses in Guayaquil, Ecuador

Here we show our proof of concept, presenting the results and final outcome of one of the test cases, from Guayaquil, Ecuador. We only show the results of one case in this paper as our aim has been to demonstrate how we developed the methodology. Selecting Guayaquil to showcase Impact Webs highlights the outcomes of steps 4 and 5 in Figure 2.

Step 1: Scoping

We developed an Impact Web to study risks and impacts emerging from the COVID-19 pandemic and concurrent hazards, threats and shocks in the city of Guayaquil, Ecuador. Guayaquil was selected due to its high population density, high levels of poverty and inequality, its large informal work sector, overcrowded housing (Delgado et al., 2018) and high exposure to climate related and geophysical hazards (Hallegatte et al., 2013). These factors make the city's inhabitants vulnerable to the compounding effects of multiple hazards, and presents challenges for risk management that are exacerbated by limited financial resources at both the municipal and national level. These factors additionally have numerous and compounding drivers of risks and root causes making it an important case in which to undertake a complex risk assessment. We used COVID-19 as the 'seed' element for developing the Impact Web as the hazard has been so diverse in its effects across communities, sectors and economies, which additionally provided important lessons for the application of a novel conceptual risk modelling approach using a systems lens. It was decided that taking a case study at the city scale supported in defining system boundaries and decision context, for which COVID-19 has been cross-scale and highly dynamic (Hagenlocher et al., 2022).

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Steps 2, 3 & 4: Impact Web of Guayaquil, Ecuador

Figure 3 presents the final conceptual model of the complex risk assessment in Guayaquil. The Impact Web visualises (i) multiple interacting hazards, threats and shocks across various scales, (ii) the identification of different risks/impacts for communities, sectors and societal functions as well as their interconnections and cascading effects (iii) their underlying risk drivers as well as (iv) the root causes behind underlying risk drivers, some of which can be spatial and temporally distant from newly emerging risks/impacts. Further, the Impact Web model also maps (v) risks and impacts linked to responses (e.g. policy interventions aimed to reduce risks) as well as (vi) risks that did not manifest due to the interventions.

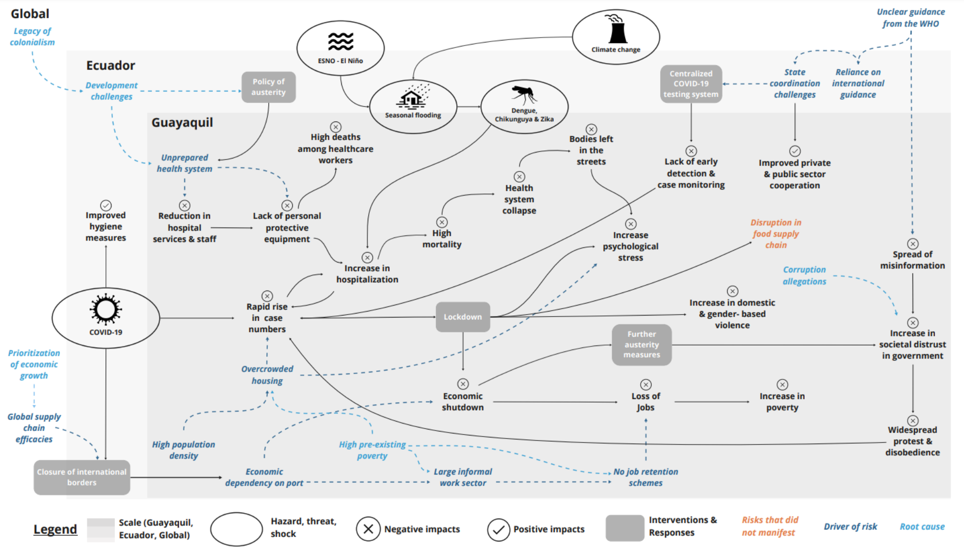

Figure 3: *Impact Web for the test case of Guayaquil, Ecuador. The conceptual model visualises complex risks and impacts linked to the COVID-19 pandemic, concurring hazards and the responses to it, as well as interconnections between system elements and drivers and root causes of risks.*

Step 5: Narrative storyline for Guayaquil, Ecuador

The first confirmed case of COVID-19 in Guayaquil was 29 February, 2020. Driven by the city's high population density, challenges with overcrowded housing and unpreparedness in the health system, there was a rapid rise in cases and hospitalizations. Governmental policies of austerity in the five years prior to the pandemic meant that hospitals and healthcare facilities were understaffed and under equipped. The lack of personal protective equipment resulted in a high number of cases and deaths among healthcare workers, which put further pressure on a health system that was already burdened by increases in vector borne diseases due to seasonal flooding exacerbated by climate change. From the compounding effects of multiple hazards and cascading impacts that emerged, the health system reached a tipping point and collapsed, tragically resulting in a large number of bodies being left in the streets, hospitals and care homes. This significantly increased psychological stress for the city's residents. In March of 2020, Guayaquil had an excess mortality rate five times that of the same month in the previous year and the highest COVID-19 mortality rate of any Latin-American city.

Economic disruptions from the intervention to close international borders were particularly severe in Guayaquil due to the city's high dependency on the port. The closing of borders triggered economic shutdown, with widespread adverse effects on employment and livelihoods. Due to the lack of job retention schemes, many citizens, a lot of whom were already living in poverty before the pandemic, were left without income generating opportunities. These impacts were exacerbated for the large informal employment sector in Guayaquil. Due to the limited availability of space per person driven by

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the high population density and overcrowded housing, lockdown interventions and social distancing were difficult to follow for a large segment of the population. As seen in many places, there were also sharp increases in domestic and gender-based violence during lockdown. As Guayaquil is a food-producing country, one risk that did not manifest as a result of lockdowns was disruption in the food supply chain and food shortages that were prevalent in some other countries in the region.

State coordination challenges and reliance on international guidance, which was unclear and contradictory in the early stages of the pandemic, meant there was a lack of an integrated, cross-sectoral and multi-scale response between Guayaquil's and Ecuador's public institutions. The national government maintained a centralised COVID-19 testing system, which hindered the effectiveness of city institutions to set up early-detection and monitoring systems such as contact-tracing and testing facilities. The unclear guidance from the World Health Organisation resulted in the output of unclear information and the national level, which was one of the factors that contributed to the spreading of misinformation throughout digital networks. One positive impact that arose from state coordination challenges was the strengthening of public and private sector cooperation.

In response to the economic disruptions, the government of Ecuador brought in more austerity measures. Furthermore, corruption allegations were brought against some city and state-level actors for capitalising on the emergency healthcare situation. These factors saw increasing societal distrust in the government, which was already underlying. This came to fruition in Guayaquil when a societal tipping point was reached in May of 2020, resulting in widespread protest and civil disobedience.

The application of the Impact Web approach in Guayaquil highlights how COVID-19 and concurrent hazards have compounded to create cascading impacts across sectors. Key risk drivers identified included initial unpreparedness in the health system, high population density and overcrowded housing, economic dependency on the port and state coordination challenges linked to reliance on international guidance among others. The cascading nature of response risks are also characterised through the Impact Web, such as the widespread economic effects of lockdown and closure of international borders, or the increase in societal distrust and subsequent protest and civil disobedience in part due to further austerity interventions in response. A number of considerations for risk management emerge from developing the Impact Web for Guayaquil. These include focusing attention, resources and efforts towards multi-sectoral and multi-scale coordination across public and private institutions, as well as ensuring strong reach and availability of social protection mechanisms and investment in risk monitoring and data systems. The case also highlights that clear guidance and risk communication are key to building societal trust during times of crisis.

4. Discussion

With Impact Webs, we integrated Climate Impact Chains with aspects of system mapping approaches. Doing this aimed to close gaps in current conceptual models of risks, through characterising dynamic interactions between hazards, exposure, vulnerability, response risks drivers and root causes (IPCC, 2023), improving our understanding of complex risks through following a flexible stepwise methodology. In the discussion we reflect on strengths and limitations of Impact Webs, and provide future research directions.

4.1. Strengths

The application of the Impact Web methodology in case studies showed that the approach is useful to conceptualise, identify and visualise networks of interconnected elements across different systems and sectors. The conceptual model's suitability to map the interactions of multiple, concurrent hazards with multiple pre-existing drivers of risk and root cases helps to uncover underlying societal vulnerabilities, and is useful to derive storylines of how interconnected risks and impacts emerge from a hazard or shock events. In the context of Guayaquil, the Impact Web and narrative storyline characterises how COVID-19 revealed vulnerability in the health system, resulting in lockdowns that subsequently affected

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many other systems and exacerbated already existing economic, domestic, governance challenges in the city and country. Taking COVID-19 as the 'seed' element for our Impact Web resulted in constructing a more simplistic cause-effect chain at the beginning of the modelling exercise, which can be useful for replicability. Given the models effectiveness for mapping the complexity of an event such as COVID-19 suggests that you could equally develop an Impact Web to understand the complexity of climate change risks. Moreover, modelling five test cases with a flexible approach towards the 'local scale' (e.g. a humanitarian camp in Coxes Bazar, a city scale in Gauaquil, a regional focus in Togo and the Indian Sundarbans and a national scale in Indonesa) suggests that you could create an Impact Web to meet needs for a variety of decision contexts. For example, one could create the model to assess complex risks for a river basin, town, or even a specific community.

Applying a systems lens towards analysis and mapping elements in the conceptual model, the developer of an Impact Web as well as the stakeholders engaged gain a more comprehensive overview of complex risks in the system they are mapping. While the final visual and the narrative storyline is the output, it is the process of developing an Impact Web that stimulates critical reflection in the modeller and involved stakeholders, thus enhancing understanding of complex risks, which is the key outcome. Involving stakeholders throughout the modelling process can help identify key agents who can act as a catalyst for change (Renn et al., 2022; Özesmi and Özesmi., 2004). These can be, for example, stakeholders who perceive more causal relationships or options to change the system. Working with stakeholders to co-create the model can widen the lens for identifying critical elements, such as feedback effects and trade-offs, which can then be further analysed. Additionally, taking a participatory or bottom up approach for the risk assessment brings in perspectives that can influence top-down decision making.

As the conceptual model not only accounts for negative impacts, but also how policy responses and societal reactions to policies can lead to additional positive outcomes, as well as unintended consequences, i.e. risks arising from responses (Simpson et al., 2021), Impact Webs are useful to reflect on positive and negative outcomes of previous disaster risk management practices. The inclusion of interventions and response risks and impacts additionally allows for the identification and management of trade-offs or maladaptation that can occur through decision making processes. While the outputs of an Impact Web do not quantify the severity or probability of such trade-offs, the approach is informative by revealing sometimes unclear or more nuanced relationships between decisions and negative outcomes in the system you are analysing. The visual and accompanying narrative storyline can thus inform policy and risk management by learning from past impacts, and how these have or have not disrupted critical societal functions, and are effective for pre-intervention evaluation and for communication purposes (Termeer et al., 2017; Wiebe et al., 2018).

Limitations

Given the complexity of interconnected systems and the ambiguity of system boundaries (Sparkes & Werners, 2023), it is not possible to characterise all interconnections using Impact Webs. These models are a simplification of reality and only the most prominent outcomes are derivable. These prominent outcomes are shaped by the developers own inherent biases, although the participatory approach aims to reduce this by providing a mutually agreed upon heuristic of complex risks in a system. In consideration of this, it is important to acknowledge that participatory modelling is an exercise in which power dynamics come into play. Therefore, this should be considered when identifying key agents as catalyst of change. Communicating that the model is a simplification of real-world interactions, as well who it was developed and with to decision makers is important, to ensure these factors are considered for in policy making.

Even though we recommend standardized constitutive elements and steps for construction, given the sheer variety of effects originating from one or multiple hazard events, no one Impact Web would be

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replicable even if it was developed for the same hazards at the same scale and focus if done by different stakeholders. Where to define the boundaries of the systems being mapped is vauge, and which elements are selected for the model dependings on stakeholders views on key protection targets and societal functions. A system is usually defined according to its elements within defined system boundaries (i.e. endogenous system elements) and outside of its boundaries (i.e. exogenous system elements) (Sillmann et al., 2022) which are selected based on the scale and objectives of analysis. However, given that we developed a model with COVID-19 as the seed element, which affected all corners of society and did not occur within defined boundaries, it was difficult to know where to stop. This challenge could equally arise for developing Impact Web in a multi-hazard multi-risk climate change context, where the cascading impacts of events are also felt across sectors and scales (van den Hurk et al., 2023). This 'messiness' of complex and ongoing cascading effects that the Impact Web sheds light on is a challenge for policy, which often requires sectorally and spatially defined targets, and equally can render the direct visual output of an Impact Web difficult to engage with.

An additional challenge regards how the outputs of the conceptual model can be integrated with quantitative data for further analysis. While the logic for our model drew inspiration from reviewing data driven models including Fuzzy Cognitive Maps, Influence Diagrams and Bayesian Belief Networks, our approach instead combines stakeholder inputs, desk review and the outcomes of historic events to arrive at characterisation of how the system of investigation has been affected. As data limitations are often a challenge when modelling socio-ecological systems, analytics on interactions in a multi-hazard context would be difficult.

4.2. Future research directions

A number of questions emerge from the application of our methodology that would benefit from further research. Following the steps for construction enhanced our own understanding of complex risks in the systems under investigation, and the outputs are useful to communicate complexity. However, a number of modelling considerations remain to be explored that are important for disaster risk management, such as temporal dimensions, critical vulnerability moments and system tipping points (Lenton et al., 2023). Bridging conceptual models of complex risks with data-driven modelling approaches would be useful in this regard. Additionally, while the model is affective for assessing risks and trade-offs of interventions, a more structured, decision focused approach and methodology to see how Impact Webs can provide comprehensive entry points for disaster risk management and climate change adaptation would be useful. For example, pathways methodologies have been applied to evaluate risk management decisions in complex systems (Schlumberger, et al., 2024; Haasnoot et al., 2013, Werners et al., 2021). Thus, integrating conceptual risk modelling with a pathways approach is one avenue that warrants further exploration. Understanding and mapping risk complexity is only useful if cascading effects and systemic risks can be minimised, for example through decoupling unnecessary connections across sectors. Moving from complex risk assessment to complex risk management needs further attention in order strengthen the resilience of systems.

5. Conclusions

This paper has presented a novel conceptual modelling approach called Impact Webs which identifies, characterises, and maps complex risks. The inadequacy of single-hazard and single-risk approaches in the face of global challenges like COVID-19 and climate change emphasizes the need for comprehensive risk assessment that account for interconnectivity. Impact Webs are one such methodology that do this. Their application in test cases identified critical links between multiple hazards, responses to them, drivers of risk, root causes as well as pre-existing societal vulnerabilities. The conceptual model provides a more nuanced understanding of how risks propagate through systems, offering valuable insights into potential feedback effects, trade-offs, and key agents that can act as catalysis of change and influence risks in a system. While the approach contributes to improving complex risk assessment, a number of future research directions presented in this article would further advance the methodology. These include bridging the conceptual model with data-driven approaches

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and transitioning from complex risk assessment to complex risk management that strengthens systemic resilience. In the evolving and interconnected landscape of communities and societies, disaster risk reduction and climate change adaptation must account for complexity. The Impact Webs approach stands as one valuable contribution to realise this, offering a system-wide perspective for complex risk assessment.

Data availability. The data can be provided by the authors upon reasonable request.

Author contribution. ES: conceptualization, methodology, formal analysis, writing – original draft and visualization. DC: conceptualization, methodology, formal analysis, writing – original draft and visualization. AV: investigation, formal analysis and visualization. SW: conceptualization, methodology, writing – review & editing, visualization. MH: conceptualization, methodology, formal analysis, writing – review & editing, visualization.

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Disclaimer.

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Review statement.

References

Ahmed, A., Woulds, C., Drake, F., & Nawaz, R. (2018). Beyond the tradition: Using Fuzzy Cognitive Maps to elicit expert views on coastal susceptibility to erosion in Bangladesh. *CATENA*, *170*, 36–50. https://doi.org/10.1016/j.catena.2018.06.003

Ara Begum, R., R. Lempert, E., Ali, T., Benjaminsen, T., Bernauer, W., Cramer, X., Cui, K., Mach, G., Nagy, N. C., Stenseth, R., & Sukumar, P. (2022). *2022: Point of Departure and Key Concepts. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter01.pdf

Bashari, H., Naghipour, A. A., Khajeddin, S. J., Sangoony, H., & Tahmasebi, P. (2016). Risk of fire occurrence in arid and semi-arid ecosystems of Iran: An investigation using Bayesian belief networks. *Environmental Monitoring and Assessment*, *188*(9), 531. https://doi.org/10.1007/s10661-016-5532-8

Blaikie, P., Cannon, T., Davis, I., & Wisner, B. (1994). *At Risk: Natural Hazards, People's Vulnerability, and Disasters* (1st ed.). Routledge.

de Brito, M., Sodoge, J., Fekete, A., Hagenlocher, M., Koks, E., Kuhlicke, C., Messori, G., Ruiter, M. de, Schweizer, P.-J., & Ward, P. J. (2024). Uncovering the Dynamics of Multi-

https://doi.org/10.5194/egusphere-2024-2844
Preprint. Discussion started: 19 September 2024

Sector Impacts of Hydrological Extremes: A Methods Overview. *Earth's Future*, *12*(1), Article e2023EF003906. https://doi.org/10.1029/2023EF003906

Carter, T. R., Benzie, M., Campiglio, E., Carlsen, H., Fronzek, S., Hildén, M., Reyer, C. P., & West, C. (2021). A conceptual framework for cross-border impacts of climate change. *Global Environmental Change*, *69*, 102307. https://doi.org/10.1016/j.gloenvcha.2021.102307

Chandra, A., & Gaganis, P. (2016). Deconstructing vulnerability and adaptation in a coastal river basin ecosystem: a participatory analysis of flood risk in Nadi, Fiji Islands. *Climate and Development*, *8*(3), 256–269. https://doi.org/10.1080/17565529.2015.1016884

Coletta, V. R., Pagano, A., Pluchinotta, I., Zimmermann, N., Davies, M., Butler, A., Fratino, U., & Giordano, R. (2024). Participatory Causal Loop Diagrams Building for Supporting Decision-Makers Integrating Flood Risk Management in an Urban Regeneration Process. *Earth's Future*, *12*(1), e2023EF003659. https://doi.org/10.1029/2023EF003659

Cui, L., Yue, S., Nghiem, X.-H., & Duan, M. (2023). Exploring the risk and economic vulnerability of global energy supply chain interruption in the context of Russo-Ukrainian war. *Resources Policy*, *81*, 103373. https://doi.org/10.1016/j.resourpol.2023.103373

Delgado, A., Peek, O., & d'Auria, V. (2020). *The Routledge Handbook on Informal Urbanization*. Routledge.

Dianat, H., Wilkinson, S., Williams, P., & Khatibi, H. (2021). Planning the resilient city: Investigations into using "causal loop diagram" in combination with "UNISDR scorecard" for making cities more resilient. *International Journal of Disaster Risk Reduction*, *65*, 102561. https://doi.org/10.1016/j.ijdrr.2021.102561

Eberle, C., O'Connor, J., Narvaez, L., Mena Benavides, M., & Sebesvari, Z. (2023). *Interconnected Disaster Risks 2023: Risk Tipping Points*. United Nations University - Institute for Environment and Human Security (UNU-EHS). https://doi.org/10.53324/WTWN2495

ElSawah, S., McLucas, A., & Mazanov, J. (2015). Communicating About Water Issues in Australia. *Simulation & Gaming*, *46*(6), 713–741. https://doi.org/10.1177/1046878115580410

ElSawah, S., Pierce, S. A., Hamilton, S. H., van Delden, H., Haase, D., Elmahdi, A., & Jakeman, A. J. (2017). An overview of the system dynamics process for integrated modelling of socio-ecological systems: Lessons on good modelling practice from five case studies. *Environmental Modelling & Software*, *93*, 127–145. https://doi.org/10.1016/j.envsoft.2017.03.001

Giordano, R., Preziosi, E., & Romano, E. (2013). Integration of local and scientific knowledge to support drought impact monitoring: some hints from an Italian case study. *Natural Hazards*, *69*(1), 523–544. https://doi.org/10.1007/s11069-013-0724-9

Gómez Martín, E., Giordano, R., Pagano, A., van der Keur, P., & Máñez Costa, M. (2020). Using a system thinking approach to assess the contribution of nature based solutions to sustainable development goals. *The Science of the Total Environment*, *738*, 139693. https://doi.org/10.1016/j.scitotenv.2020.139693

Groundstroem, F., & Juhola, S. (2021). Using systems thinking and causal loop diagrams to identify cascading climate change impacts on bioenergy supply systems. *Mitigation and Adaptation Strategies for Global Change*, *26*(7), 29. https://doi.org/10.1007/s11027-021-09967-0

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & Maat, J. ter (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, *23*(2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Hagenlocher, M., Naumann, G., Meza, I., Blauhut, V., Cotti, D., Döll, P., Ehlert, K., Gaupp, F., van Loon, A. F., Marengo, J. A., Rossi, L., Sabino Siemons, A. S., Siebert, S., Tsehayu, A. T., Toreti, A., Tsegai, D., Vera, C., Vogt, J., & Wens, M. (2023). Tackling Growing Drought Risks—The Need for a Systemic Perspective. *Earth's Future*, *11*(9), Article e2023EF003857. https://doi.org/10.1029/2023EF003857

Hagenlocher, M., Banerjee, S., Bermudez-Zambrano, D. A., Cotti, D., Hassel, J., Masys, A. J., Nawawi, Y. E. P., Rana, S., Rimmert, M., Roy, P., Schütze, S., Shekhar, H., Sodogas, V., Sparkes, E., Ketut Surtiari, A., Valdiviezo-Ajila, A., & Werners, S. E. (2022). *Understanding and managing cascading and systemic risks: lessons from COVID-19*. UNDRR & UNU-EHS.

Hagenlocher, M., Schneiderbauer, S., Sebesvari, Z., Bertram, M., Renner, K., Renaud, F., Wiley, H., & Zebisch, M. (2018). *Climate Risk Assessment for Ecosystem-based Adaptation – A* *guidebook for planners and practitioners*. https://www.adaptationcommunity.net/wp-content/uploads/2018/06/giz-eurac-unu-2018-en-guidebook-climate-risk-asessment-eba.pdf

Hallegatte, S., Green, C., Nicholls, R. J., & Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. *Nature Climate Change*, *3*(9), 802–806. https://doi.org/10.1038/nclimate1979

Harris, K., Lager, F., Jansen, M. K., & Benzie, M. (2022). Rising to a New Challenge: A Protocol for Case-Study Research on Transboundary Climate Risk. *Weather, Climate, and Society*, *14*(3), 755–768. https://doi.org/10.1175/WCAS-D-21-0022.1

Helbing, D. (2013). Globally networked risks and how to respond. *Nature*, *497*(7447), 51–59. https://doi.org/10.1038/nature12047

IPCC. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ ar5/wg2/

IPCC. (2023). *Synthesis report of the IPCC Sixth Assessment Report (AR6).* Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/sixth-assessment-report-cycle/

Lawrence, J., Blackett, P., & Cradock-Henry, N. A. (2020). Cascading climate change impacts and implications. *Climate Risk Management*, *29*, 100234. https://doi.org/10.1016/j.crm.2020.100234

Lenton, T. M., Armstrong McKay, D. I., Loriani, S., Abrams, J. F., Lade, S. J., Donges, J. F., Milkoreit, M., Powell, T., Smith, S. R., Zimm, C., Buxton, J. E., Bailey, E., Laybourn, L., Ghadiali, A., & Dyke J.G. (2023). *The Global Tipping Points Report 2023*. https://global-tipping-points.org/

Malekmohammadi, B., Uvo, C. B., Moghadam, N. T., Noori, R., & Abolfathi, S. (2023). Environmental Risk Assessment of Wetland Ecosystems Using Bayesian Belief Networks. *Hydrology*, *10*(1), 16. https://doi.org/10.3390/hydrology10010016

Menk, L., Terzi, S., Zebisch, M., Rome, E., Lückerath, D., Milde, K., & Kienberger, S. (2022). Climate Change Impact Chains: A Review of Applications, Challenges, and Opportunities for Climate Risk and Vulnerability Assessments. *Weather, Climate, and Society*, *14*(2), 619–636. https://doi.org/10.1175/WCAS-D-21-0014.1

Mühlhofer, E., Koks, E. E., Kropf, C. M., Sansavini, G., & Bresch, D. N. (2023). A generalized natural hazard risk modelling framework for infrastructure failure cascades. *Reliability Engineering & System Safety*, *234*, 109194. https://doi.org/10.1016/j.ress.2023.109194

Oliver-Smith, A., Alcántara-Ayala, I., Burton, I., & Lavell, A. (2017). The social construction of disaster risk: Seeking root causes. *International Journal of Disaster Risk Reduction*, *22*, 469–474. https://doi.org/10.1016/j.ijdrr.2016.10.006

Özesmi, U., & Özesmi, S. L. (2004). Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. *Ecological Modelling*, *176*(1-2), 43–64. https://doi.org/10.1016/j.ecolmodel.2003.10.027

Parviainen, T., Lehikoinen, A., Kuikka, S., & Haapasaari, P. (2019). Risk frames and multiple ways of knowing: Coping with ambiguity in oil spill risk governance in the Norwegian Barents Sea. *Environmental Science & Policy*, *98*, 95–111. https://doi.org/10.1016/j.envsci.2019.04.009

Petutschnig, L., Rome, E., Lückerath, D., Milde, K., Gerger Swartling, Å., Aall, C., Meyer, M., Jordá, G., Gobert, J., Englund, M., André, K., Bour, M., Attoh, E. M. N. A. N., Dale, B., Renner, K [Kathrin], Cauchy, A., Reuschel, S., Rudolf, F., Agulles, M., . . . Kienberger, S [Stefan] (2023). Research advancements for impact chain based climate risk and vulnerability assessments. *Frontiers in Climate*, *5*, Article 1095631. https://doi.org/10.3389/fclim.2023.1095631

Rehman, J., Sohaib, O., Asif, M., & Pradhan, B. (2019). Applying systems thinking to flood disaster management for a sustainable development. *International Journal of Disaster Risk Reduction*, *36*, 101101. https://doi.org/10.1016/j.ijdrr.2019.101101

Renn, O., Laubichler, M., Lucas, K., Kröger, W., Schanze, J., Scholz, R. W., & Schweizer, P.-J. (2022). Systemic Risks from Different Perspectives. *Risk Analysis : An Official Publication of the Society for Risk Analysis*, *42*(9), 1902–1920. https://doi.org/10.1111/risa.13657

Ruiter, M. C. de, Couasnon, A., van den Homberg, M. J. C., Daniell, J. E., Gill, J. C., & Ward, P. J. (2020). Why We Can No Longer Ignore Consecutive Disasters. *Earth's Future*, *8*(3), Article e2019EF001425. https://doi.org/10.1029/2019EF001425

https://doi.org/10.5194/egusphere-2024-2844
Preprint. Discussion started: 19 September 2024

Ruiter, M. C. de, & van Loon, A. F. (2022). The challenges of dynamic vulnerability and how to assess it. *IScience*, *25*(8), 104720. https://doi.org/10.1016/j.isci.2022.104720

Schlumberger, J., Haasnoot, M., Aerts, J. C. J. H., Bril, V., van der Weide, L., & Ruiter, M. de (2024). Evaluating Adaptation Pathways in a Complex Multi-Risk System. *Earth's Future*, *12*(5), Article e2023EF004288. https://doi.org/10.1029/2023EF004288

Schneiderbauer, S., Zebisch, M., Kass, S., & Pedoth, L. (2013). *Assessment of vulnerability to natural hazards and climate change in mountain environments – examples from the Alps: Measuring Vulnerability Chapter: Assessment of vulnerability to natural hazards and climate change in mountain environments – examples from the Alps*. United Nations University Press. https://collections.unu.edu/eserv/UNU:2880/n9789280812022_text.pdf

Scrieciu, A., Pagano, A., Coletta, V. R., Fratino, U., & Giordano, R. (2021). Bayesian Belief Networks for Integrating Scientific and Stakeholders' Knowledge to Support Nature-Based Solution Implementation. *Frontiers in Earth Science*, *9*, Article 674618. https://doi.org/10.3389/feart.2021.674618

Sett, D., Trinh, T. P., Wasim, T., Ortiz-Vargas, A., Nguyen, D. G. C., Büche, K., Assmann, A., Nguyen, H. K. L., Walz, Y., Souvignet, M., Bachofer, F., Vu, T. B., Garschagen, M., & Hagenlocher, M. (2024). Advancing understanding of the complex nature of flood risks to inform comprehensive risk management: Findings from an urban region in Central Vietnam. *International Journal of Disaster Risk Reduction*, *110*, 104652. https://doi.org/10.1016/j.ijdrr.2024.104652

Sillmann J, Christensen I, Hochrainer-Stigler S, Huang-Lachmann J-T, Juhola S, Kornhuber K, Mahecha MD, Mechler R, Reichstein M, Ruane AC, Schweizer P-J, Williams S. (2022). *ISC-UNDRR-RISK KAN Briefing Note on Systemic Risk.* UNDRR.

Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J., Lempert, R. J., Muccione, V., Mackey, B., New, M. G., O'Neill, B., Otto, F., Pörtner, H.-O., Reisinger, A., Roberts, D., Schmidt, D. N., Seneviratne, S., Strongin, S., . . . Trisos, C. H. (2021). A framework for complex climate change risk assessment. *One Earth*, *4*(4), 489–501. https://doi.org/10.1016/j.oneear.2021.03.005

Simpson, N. P., Williams, P. A., Mach, K. J., Berrang-Ford, L., Biesbroek, R., Haasnoot, M., Segnon, A. C., Campbell, D., Musah-Surugu, J. I., Joe, E. T., Nunbogu, A. M., Sabour, S., Meyer, A. L. S., Andrews, T. M., Singh, C., Siders, A. R., Lawrence, J., van Aalst, M., & Trisos, C. H. (2023). Adaptation to compound climate risks: A systematic global stocktake. *IScience*, *26*(2), 105926. https://doi.org/10.1016/j.isci.2023.105926

Sparkes, E., & Werners, S. E. (2023). Monitoring, evaluation and learning requirements for climate-resilient development pathways. *Current Opinion in Environmental Sustainability*, *64*, 101329. https://doi.org/10.1016/j.cosust.2023.101329

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., Vries, W. de, Wit, C. A. de, Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Sustainability. Planetary boundaries: Guiding human development on a changing planet. *Science (New York, N.Y.)*, *347*(6223), 1259855. https://doi.org/10.1126/science.1259855

Suriya, S., & Mudgal, B. V. (2013). Soft systems methodology and integrated flood management: a study of the A dayar watershed, C hennai, I ndia. *Water and Environment Journal*, *27*(4), 462–473. https://doi.org/10.1111/j.1747-6593.2012.00365.x

Termeer, C. J., Dewulf, A., & Biesbroek, G. R. (2017). Transformational change: governance interventions for climate change adaptation from a continuous change perspective. *Journal of Environmental Planning and Management*, *60*(4), 558–576. https://doi.org/10.1080/09640568.2016.1168288

UNDRR. (2022). *Global Assessment Report on Disaster Risk Reduction 2022: Our World at Risk: Transforming Governance for a Resilient Future.* United Nations Office for Disaster Risk Reduction.

van den Hurk, B. J., Baldissera Pacchetti, M., Boere, E., Ciullo, A., Coulter, L., Dessai, S., Ercin, E., Goulart, H. M., Hamed, R., Hochrainer-Stigler, S., Koks, E., Kubiczek, P., Levermann, A., Mechler, R., van Meersbergen, M., Mester, B., Middelanis, R., Minderhoud, K., Mysiak, J., Witpas, K. (2023). Climate impact storylines for assessing socio-economic responses to

https://doi.org/10.5194/egusphere-2024-2844
Preprint. Discussion started: 19 September 2024

remote events. *Climate Risk Management*, *40*, 100500. https://doi.org/10.1016/j.crm.2023.100500

Werners, S. E., Wise, R. M., Butler, J. R., Totin, E., & Vincent, K. (2021). Adaptation pathways: A review of approaches and a learning framework. *Environmental Science & Policy*, *116*, 266–275. https://doi.org/10.1016/j.envsci.2020.11.003

Wiebe, K. S., Bjelle, E. L., Többen, J., & Wood, R. (2018). Implementing exogenous scenarios in a global MRIO model for the estimation of future environmental footprints. *Journal of Economic Structures*, *7*(1). https://doi.org/10.1186/s40008-018-0118-y

Wisner, B., Blaikie, P., Cannon, T., & Davis, I. (2004). *At Risk: Natural Hazards* (2nd ed.). Routledge.

Zebisch, M., Renner, K., Pittore, M., Fritsch, U., Fruchter, S., Kienberger, S., Schinko, T., Sparkes, E., Hagenlocher, M., Schneiderbauer, S., Delves, J. L. (2023). *Climate Risk Sourcebook.* Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). https://www.adaptationcommunity.net/climate-risk-assessment-management/climate-risk-sourcebook/

Zebisch, M., Schneiderbauer, S., Fritzsche, K., Bubeck, P., Kienberger, S., Kahlenborn, W., Schwan, S., & Below, T. (2021). The vulnerability sourcebook and climate impact chains – a standardised framework for a climate vulnerability and risk assessment. *International Journal of Climate Change Strategies and Management*, *13*(1), 35–59. https://doi.org/10.1108/IJCCSM-07-2019-0042

Zscheischler, J., Westra, S., van den Hurk, B. J. J. M., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M., Wahl, T., & Zhang, X. (2018). Future climate risk from compound events. *Nature Climate Change*, *8*(6), 469–477. https://doi.org/10.1038/s41558-018-0156-3