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

3 **Authors:** Edward Sparkes[1], Davide Cotti[1], Angel Valdiviezo Ajila [2], Saskia E. Werners[1, 3], Michael
4 Hagenlocher[1]

5 1) United Nations University - Institute for Environment and Human Security, Germany
6 2) Escuela Superior Politécnica del Litoral, Ecuador
7 3) Wageningen University & Research, the Netherlands
8
9 Correspondence to: Edward Sparkes (esparkes1@gmail.com)
10

11 **Abstract**
12 Identifying, characterising and assessing the complex nature of risks is vital to realise the expected
13 outcome of the Sendai Framework for Disaster Risk Reduction. Over the past two decades, the
14 conceptualization of risk has evolved from a hazard-centric perspective to one that integrates dynamic
15 interactions between hazards, exposure, systems vulnerabilities and responses risks. This calls for a
16 need to develop tools and methodologies that can account for such complexity in risk assessments.
17 However, existing risk assessment approaches are hitting limits to tackle such complexity. To this aim,
18 we developed a novel complex risk assessment methodology named 'Impact Webs', inspired by a
19 conceptual risk modelling approach named Climate Impact Chains that integrates aspects of various
20 other conceptual models used in risk assessments such as Causal Loop Diagrams and Fuzzy Cognitive
21 Mapping. Impact Webs are developed in a participatory manner with stakeholders and characterise and
22 map interconnections between risks, their underlying hazards, risk drivers, root causes, responses to
23 risks, as well as direct and cascading impacts across multiple systems and at various scales. In this
24 methodological paper, we show how we developed the Impact Web methodology, including how we
25 derived which elements to include in the model, demonstrating the logic and visual output and listing
26 the steps we followed for construction. As proof of concept, we present the results of a complex risk
27 assessments in Guayaquil, Ecuador, which investigated how COVID-19, concurrent hazards and
28 responses propagate risks and impacts across sectors and systems during the pandemic. Reflecting
29 on the utility of Impact Webs, application in case studies demonstrates the methodologies' usefulness
30 for understanding complex cause-effect relationships and informing decision-making across different
31 scales. The participatory process of developing Impact Webs promotes stakeholder engagement,
32 uncovers critical elements at risk and trade-offs in decision making, helping helps to evaluate trade-offs
33 in decision making by both improving understanding of both positive and negative outcomes of disaster
34 risk management practices. Offering a system-wide perspective for modelling, Impact Webs stand as a
35 valuable methodological contribution for complex risk assessment.
36

37 **Copyright statement:**
38

39 **1. Introduction**

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

49 climate events (Simpson et al., 2021; Zscheischler et al., 2018), or from the global ripple effects of
50 armed conflicts (Cui et al., 2023).

51 Over the past two decades, the conceptualization of risk has evolved from a hazard-centric perspective
52 to a more encompassing notion that integrates the dynamic interactions between hazards, exposure,
53 vulnerability (IPCC, 2014) and, more recently, response risks (i.e. risks that can arise from responses
54 to risks and impacts) (Simpson et al., 2021; Ara Begum et al., 2022; IPCC, 2023; Hagenlocher et al.,
55 2023). Different terminologies have been used to conceptualise these dynamic interactions, including
56 cascading, compound, and systemic risks. In this paper we use the term 'complex risks' to encapsulate
57 these different risk framings. Given that complexity is now understood as a defining feature of risks,
58 single-hazard and single-risk approaches, while useful in certain contexts, are becoming increasingly
59 insufficient for comprehensive disaster risk management (Simpson et al., 2021; UNDRR, 2022;
60 Schlumberger, et al., 2024; Sett et al., 2024; de Ruiter & van Loon, 2022). This has been recognised
61 by the Intergovernmental Panel on Climate Change (IPCC) in the Sixth Assessment Report, which
62 notes that risks and responses, including their determinants, can all interact dynamically in shaping the
63 complexity of climate risk (Ara Begum et al., 2022). Additionally, the Global Assessment Report 2022
64 (GAR 2022) from UNDRR stresses the importance of understanding and assessing the complex nature
65 of risks as a key foundation for risk informed decision making (UNDRR, 2022). However, existing data
66 driven and quantitative modelling approaches are hitting limits to tackle such complexity. The combined
67 effects of multiple hazards, threats or shocks should not be assessed just through the addition of each
68 of their impacts independently, but instead require systems approaches to understand risk and impacts
69 (de Ruiter et al., 2020; Ara Begum et al., 2022; Hagenlocher et al., 2023; de Brito et al., 2024). There
70 is therefore a need to develop methodologies that take a system-wide lens for analysis, that can account
71 for how multiple hazards and vulnerabilities of systems and sectors interact to better understand
72 complex risks.

73 To this aim, we developed a novel complex risk assessment methodology named 'Impact Webs'. Impact
74 Webs are inspired by a conceptual risk modelling approach named Climate Impact Chains (see Menk
75 et al., 2022 for a review of applications), and draw inspiration from various other conceptual models
76 used in risk assessments. Climate Impact Chains were originally developed for sectoral climate risk
77 assessment (Schneiderbauer et al., 2013; Zebisch et al., 2023, 2021; Hagenlocher et al., 2018), in
78 which elements of the model are assigned to the key risk components used in disaster and climate risk
79 assessments of hazard, exposure and vulnerability, and cascading effects are assigned as intermediate
80 impacts. One critique of Climate Impact Chains is that they often depict a linear cause-effect relationship
81 for a single sector or hazard, and thus do not capture the complexity of systems interaction well (Harris
82 et al., 2022). With Impact Webs, we built on Climate Impact Chains, integrating aspects of system
83 mapping approaches such as Causal Loop Diagrams (e.g Coletta et al., 2024; Groundstroem & Juhola,
84 2021; Dianat et al., 2020; Rehman et al., 2019), Fuzzy Cognitive Maps (e.g. Gómez Martín et al., 2020;
85 Ahmeda et al., 2018; Chandra & Gaganis, 2016) and Bayesian Belief Networks (e.g. Malekmohammadi
86 et al., 2023; Scrieciu et al., 2021; Bashari et al., 2016; Giordano et al., 2013). With this, we aimed to
87 integrate the key risk components in disaster and climate risk assessments with a systems perspective
88 to identify, characterise and map interconnections between risks, their underlying hazards, risk drivers,
89 root causes, responses to risks, as well as direct and cascading impacts across multiple systems and
90 at various scales. Impact Webs aim to better account for the complexity of risk interaction compared
91 with to Climate Impact Chains, by developing flexible and less linear conceptual models that can help
92 to understand complex risks.

93 In this paper, we offer a new complex risk assessment methodology in Impact Webs, detailing how we
94 developed it. To do this, we first conducted a scoping review of literature on conceptual risk models that
95 we drew inspiration from. Informed by the review, we identified constitutive elements for the model and
96 developed a graphical structure within the research team. We then developed key steps for doing a
97 complex risk assessment with Impact Webs. To test our methodology, we followed these steps and
98 made Impact Webs in five cases. These cases were Coxes Bazar humanitarian camp (Bangladesh),

99 the Sundarbans region (India), a national scale assessment (Indonesia), the Maritime region (Togo)
100 and the city of Guayaquil (Ecuador). ~~undertaking complex~~ The complex risk assessments ~~to~~
101 investigate~~d~~ how COVID-19, concurrent hazards (e.g. hydrological, geophysical, climatological) and
102 responses too them (e.g. restriction measures) interacted with underlying societal vulnerabilities to
103 propagate risks and impacts across sectors and systems during the pandemic (Hagenlocher et al.,
104 2022). COVID-19 was selected as the entry point for the risk assessments as the pandemic has been
105 so diverse and cross-scale in its effects, therefore such an event was ideal to test a novel risk modelling
106 approach for understanding complex risks. As proof of concept, we present the results and final output
107 from one of the five test cases, showing an Impact Web and narrative storyline for the city of Guayaquil,
108 Ecuador during the COVID-19 pandemic. Guayaquil was selected to demonstrate our proof of concept
109 due to the city's high vulnerability and exposure to the compounding effects of multiple hazards and the
110 presence of many drivers of risks creating numerous challenges for risk management, therefore making
111 it a fitting case to showcase a new risk assessment methodology.

112 ~~In this methodological paper, we show how we developed the Impact Web methodology. To do this, we~~
113 ~~first conducted a non-systematic literature review of conceptual risk models that we drew inspiration~~
114 ~~from. We then undertook concept development within the research team, selecting constitutive~~
115 ~~elements and developing a graphical structure for the conceptual model. We also defined steps to follow~~
116 ~~in a complex risk assessment for constructing an Impact Web.~~

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

128 2. Methodolog**y** ~~ical development~~

129 In section 2, we present our ~~methodological development from~~methodology to develop Impact Webs.
130 We show our methodological pre-development, with a scoping review of other conceptual risk modelling
131 approaches we drew inspiration from. ~~, ~~We then elaborate on the elements that were selected in the
132 model, and present the steps we followed to construct it, ~~our concept development and~~ discuss~~ing~~ how
133 we ~~trailed~~ tested ~~developing~~ Impact Webs in five different test cases to achieve our result.~~.~~

134

135 2.1. Methodological pre-development: Scoping review of conceptual risk models
136 for inspiration

137 Given that we aimed to develop an approach that took a systems perspective for analysis to better
138 understand complex risks, we conducted a scoping review~~ed the~~ of literature on conceptual risk models
139 which do this. The scoping review was non-systematic and not meant to be exhaustive. It was done to
140 support methodological synthesis and inspire the concept development for our approach by~~,~~ looking at
141 features of different methodologies that could be useful. A non-systematic scoping review was chosen
142 it has advantages for developing new methodologies. It allowed for exploratory flexibility, drawing on
143 grey literature, emerging studies and integration of methodological aspects that authors had used in
144 past research. This supported creative synthesis by combining ideas from various disciplines (Munn et
145 al., 2022). Texts were selected and reviewed based on authors own experience, expert judgement, and
146 searching using the Scopus search engine. ~~after title and abstract screening using the Scopus search~~
147 ~~engine. We looked at~~ A general description of the approach's features ~~of different approaches~~ is given,

148 ~~and analysed~~ as well as the strengths and weaknesses in a complex risk context~~.~~, We provide select
149 ~~providing~~ key references -(see Table 1).
150
151 **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 for adaptation across the model elements, including for risk drivers and root causes*	*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* *Given the often strong participatory focus, expert facilitation is needed. This can be useful for managing power dynamics during the modelling exercise and for explaining conceptualisations of risk to non-experts*	*Hagenlocher et al., (2018)* *Sett et al (2024)* *Zebisch et al (2023)* *Petutschnig et al (2023)* *Harris et al (2022)*
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*	*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)*

		relationships		
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)* *Often conducted in a participatory manner, obtaining data coming from formal and non-formal sources* *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)*
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 interventions in response to risks 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*	*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)*

		system relationships and risks and thus have more insight into how to change the system		
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~~interventions in response to risks 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*	*Malekmoha mmadi 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 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~~*	*~~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)~~*

152

153 **Lessons from the review**

154 ~~Many different conceptual modelling methodologies have been applied across disciplines for complex~~
155 ~~risk assessment. We observing three broad types of approaches, following Elsawah et al (2017). First~~
156 ~~are the use of conceptual models as predictive tools to simulate biophysical process interactions, often~~

extise 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 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.

Different conceptual modelling methodologies have been applied across disciplines for assessing complex risks which have provided useful lessons for our approach. From the papers we reviewed, Influence Diagrams and Bayesian Belief Networks show usefulness to understand interactions of biophysical processes such as extreme events, with additional dynamic inputs, such as interventions in response to risks or stakeholders' perceptions of risks and risk management decisions (e.g. Scrieciu et al., 2021). Causal Loop Diagrams and Fuzzy Cognitive Maps provide a useful framework to examine interconnections and feedback effects between elements in one or multiple systems to support integrated and cross sectoral decision making (e.g. Dianat et al., 2021), and Climate Impact Chains are effective for eliciting stakeholder knowledge due to their flexible and relatively simplistic form, which is useful to develop shared system understanding and co-create policy recommendations, and their innovative focus on intermediate impacts makes them conducive to analyse cascading impacts (e.g. Sett et al., 2024). It is important acknowledge that the approaches in Table 1 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. With Impact Webs we drew on observed strengths in the literature we reviewed, aiming to create a model that was useful for; 1) understanding interactions of impacts from extreme events, stakeholders' responses to them, as well as stakeholders perceptions of risks and risk management, 2) examining interconnections and feedback effects in one or multiple systems to support integrated and cross sectoral decision making, and 3) eliciting stakeholder knowledge to develop shared system understanding and co-create policy recommendations.

In order to achieve these aims, with Impact Webs we built on the hazard, exposure, vulnerability framing from Climate Impact Chains, which is useful to understand how risks emerge from extreme events (e.g. Hagenlocher at al., 2018; Sett et al., 2024), expanding this to include aspects such as feedbacks and non-linear interconnections which are well suited to Fuzzy Cognitive Maps and Causal Loop Diagrams (e.g. Coletta et al., 2024; Ahmed et al., 2018). To do this we included the dynamic interaction of multiple hazards, threats and shocks, multiple exposed elements and the impacts to exposed elements. We additionally included the drivers and root causes of vulnerabilities to exposed elements in Impact Webs. Including drivers and root causes in the model helped us to understand not just what impacts occurred, but also why they occurred (Blaikie et al., 1994; Wisner et al., 2004). Drawing on strengths of Influence Diagrams and Bayesian Belief Networks (e.g. Mühlhofer., 2024; Scrieciu et al., 2021), we included interventions in response to risks and impacts, as well as response risks arising from them. We did this as it was important for us to align with the most recent IPCC risk framing (Simpson et al., 2021; Ara Begum et al., 2022). All types of approaches we reviewed use graphical methods to show cause-effect relationships, most commonly using arrows and symbols to signal a relationship and influence. We also adopted this, using graphical methods to show cause-effect relationships and feedbacks. The majority of studies we reviewed integrate some form of input from stakeholders. However, it was common for stakeholder participation to decrease with increasing complexity of the method used, due to difficulties in communicating and facilitating the approach (Parviainen et al., 2019). This was an important lesson for us from the review. We aimed for a strong participatory approach that involved collaboration and integration of different expertise and knowledge. Given this, drawing on the strengths of Climate Impact Chains (Harris et al., 2022) we aimed to make the steps for developing the model simplistic so that stakeholders were not overwhelmed and could be highly engaged during the modelling process. This helped to identify key system elements that stakeholders felt were important, valued highly and wanted to protect from risks and impacts, for example key economic sectors. A systems thinking perspective was commonly taken towards analysis in all approaches. We did the same for Impact Webs. The aim of taking a systems perspective was to enhance systems' understanding and reduce uncertainty through modelling non-linear interactions and dynamics. Lastly, we wanted to model interactions across different scales (i.e. from global to local). Therefore, we expanded beyond a sectoral focus (e.g. drought risk for the agriculture sector) often used with Climate Impact Chains, aiming to capture cross-sectoral risks, impacts and vulnerabilities and their influences between one another. Lastly, we observed in the majority of papers that the visual output of the model was also accompanied by narrative-based methods used to explore and communicate findings. We followed this by including a narrative storyline which described the findings of the assessment and described the Impact Web in a structured and relatable way.

2.2. Selection of constitutive elements in an Impact Web

Building on the lessons from the scoping review, Hhere we present the elements that were selected for visualisation in for an Impact Web. We elaborate on and include justifications for why they these elements were selected, including the conceptual backing for choosing them and system interactions we wanted to assess.

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 sectors and systems (UNDRR, 2022). Therefore, we included multiple hazards, threats and shocks to the system being modelled in ~~our model~~Impact Webs.

Impacts ~~Direct and cascading impacts~~

~~Following the inclusion multiple hazards, threats and shocks, direct and cascading i~~

Impacts were the second element we included after our scoping review ~~included in the element selection~~ (Sett et al., 2024; Zebisch et al., 2023; Lawrence et al., 2020). This was done to identify direct negative impacts ~~emerging~~ from hazards, threats and shocks~~risks~~, as well as cascading impacts and any potential positive impacts that may have arisen (often as a result of interventions) in the system being modelled. Modelling cascading impacts, which arise through impact propagation (Mühlhofer et al., 2023; Carter et al., 2021), ~~also model the system's interconnectedness through~~ helped to understand the systems interconnectedness ~~impact propagation~~ as linkages between sectors and sub-systems could emerge as connections were characterised. In the visualisation of the model (See Figure 1) we do not make a visual distinction between direct and cascading impacts. There is however, a conceptual distinction as every impact that is not directly connected to a hazard threat or shock can be understood as cascading. Additionally, through modelling impacts, the compounding effects of multiple hazards, threats or shocks occurring simultaneously could be analysed (Simpson et al., 2023). We did make a visual distinction between negative and positive impacts, using a cross and a tick (see Table 2). ~~Both positive and negative impacts were included, as well compounding and cascading impacts from multiple hazards, threats or shocks~~

Interventions~~, response risks and risks that did not manifest~~

With Impact Webs, we wanted to characterise and assess how decisions ~~I~~in response to or anticipation of risks and impacts~~, decisions are taken which also~~ have ~~effects~~ impacts 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. When developing the model, ~~Bb~~oth positive and negative impacts from interventions were included (e.g. the negative impacts that occurred because of COVID-19 lockdowns). ~~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.

Risks that did not manifest

When modelling a system that has been affected by hazards, threats or shocks, there can be potential adverse consequences that are avoided, often as a result of interventions (e.g. the risk of a healthcare system collapsing, or a bread basket failure). We included these in Impact Webs and named the element risks that did not manifest. These are conceptually different from positive impacts, as they are potential negative consequences that did not happen.

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~~drivers of risks and impacts in the system. ~~, as well as looking at the root causes behind them. Drivers of risk were~~

312 ~~included as an element,~~ Drivers of risks are processes or conditions that influence the level of risks and
313 impacts by increasing levels of exposure and vulnerability, or reducing the capacity of people to manage
314 or adapt to risks. We were motivated to include drivers ~~which~~ as it asks the modeller to critically reflect
315 on how and why societal functions, essential sectors, system elements or stakeholders were adversely
316 affected~~, i.e.~~ due to high susceptibility or low coping/ adaptive capacity.
317 ~~Moreover, exploring socio-economic and political structures and processes and choices that further~~
318 ~~explain the root causes (i.e. underlying reasons) for risk drivers was an important reflection and learning~~
319 ~~step for us to characterise and improve our own understanding of complex risks within the systems~~
320 ~~being modelled (Blaikie et al, 1994; Wisner et al., 2004; UNDRR, 2022; UNU-EHS, 2023). While drivers~~
321 ~~of risks and root causes are often distant in space and time (Wisner et al., 2004), they are relevant for~~
322 ~~multiple impacts in the model.~~
323
324 ### Root causes of risk and vulnerability
325 An additional step to further understand causality was to model root causes of risk and vulnerability.
326 These are underlying factors that influence drivers of risk (Blaikie et al., 1994; Wisner et al., 2004;
327 Zebisch et al., 2023). Including them supported exploring socio-economic and political structures and
328 processes and choices that further explain why a particular community, sector, system or place is at
329 risk in the first place, and are important for designing risk management to be sustainable and lasting.
330 Both drivers of risks and root causes are often distant spatially and temporally from the system under
331 investigation (Wisner et al., 2004), they are however, highly relevant when wanting to understand
332 complex risks.
333
334 ~~Moreover, exploring socio-economic and political structures and processes and choices that further~~
335 ~~explain the root causes (i.e. underlying reasons) for risk drivers was an important reflection and~~
336 ~~learning step for us to characterise and improve our own understanding of complex risks within the~~
337 ~~systems being modelled (Blaikie et al, 1994; Wisner et al., 2004; UNDRR, 2022; UNU-EHS,~~
338 ~~2023).While drivers of risks and root causes are often distant in space and time (Wisner et al., 2004),~~
339 ~~they are relevant for multiple impacts in the model.~~
340
341 ### Connections between elements
342 Following the other conceptual modelling approaches we reviewed, we used graphical methods to show
343 connection between our chosen elements and visualise risks. We selected arrows to indicate directional
344 cause-effect relationships. Given the limitations of directed acyclic graphs used in many Bayesian Belief
345 Networks and Influence Diagrams in showing feedback effects (Bashari et al., 2016), we took an
346 approach more inspired by Causal Loop Diagrams. This meant we could better demonstrate indirect
347 effects and feedback loops (Groundstroem & Juhola., 2021), which is both more appropriate to a
348 complex risks context and helped us understand interconnectivity between elements. We used different
349 colours and dashed arrows to show connections coming from drivers of risk and root causes of risk &
350 vulnerability, compared with using black arrows for other elements in the model (see Table 2). This was
351 done so a quick and engaging visual distinction could be made for external stakeholders working with/
352 viewing the model.
353
354 ### ~~Multiple s~~Scales
355 From our review we did not find conceptual modelling approaches that were effective at demonstrating
356 risk elements and their interactions across spatial scales. For example, a critique of Impact Chains and
357 Fuzzy Cognitive mapping approaches is often that they have narrow definitions of system boundaries
358 (Petutschnig et al., 2023; Ahmed et al., 2018). For Impact Webs, we included three spatial scales in our
359 model (i.e. local, regional and global), which was intended to model globally networked risks, as well as
360 demonstrate risk drivers, root causes and impacts that are often spatially distant but have effects in the
361 local context (Helbing, 2013). As the test case study contexts where we made Impact Webs were
362 geographically diverse (see Section 2.4), there was flexibility in how the 'local' scale boundary was
363 defined. For example, for the Coxes Bazar case, the local scale was defined to inside the humanitarian

364 camp. Comparatively, Guayaquil focused on investigating the city municipality, whereas Indonesia was
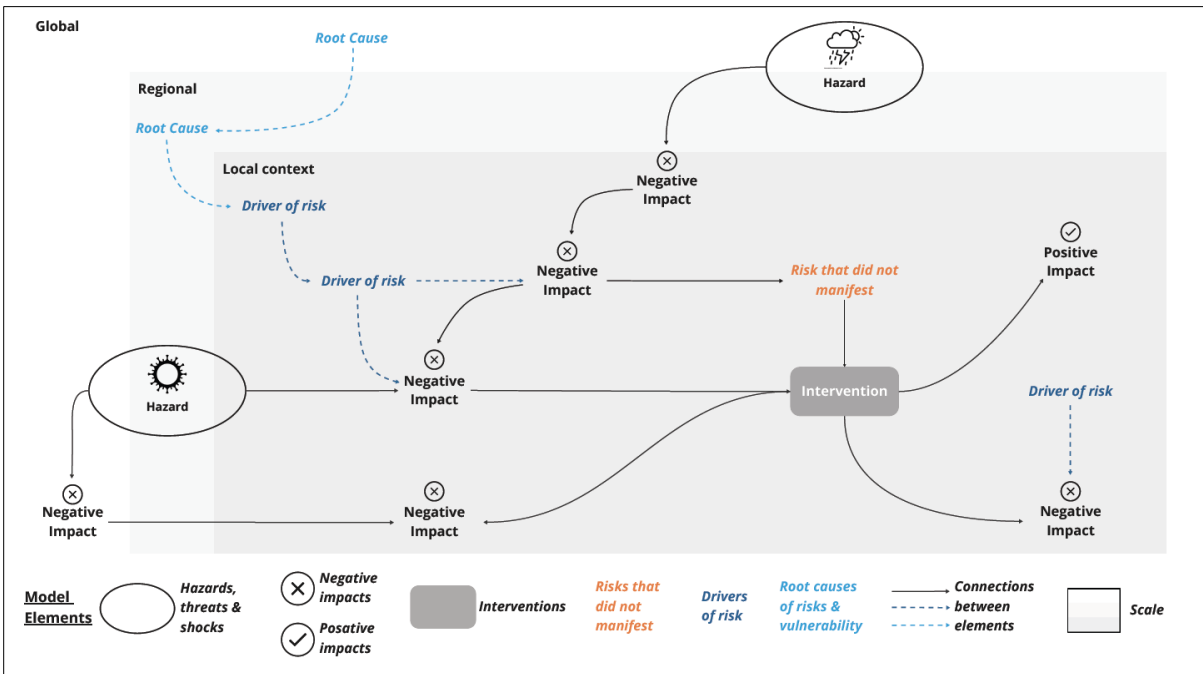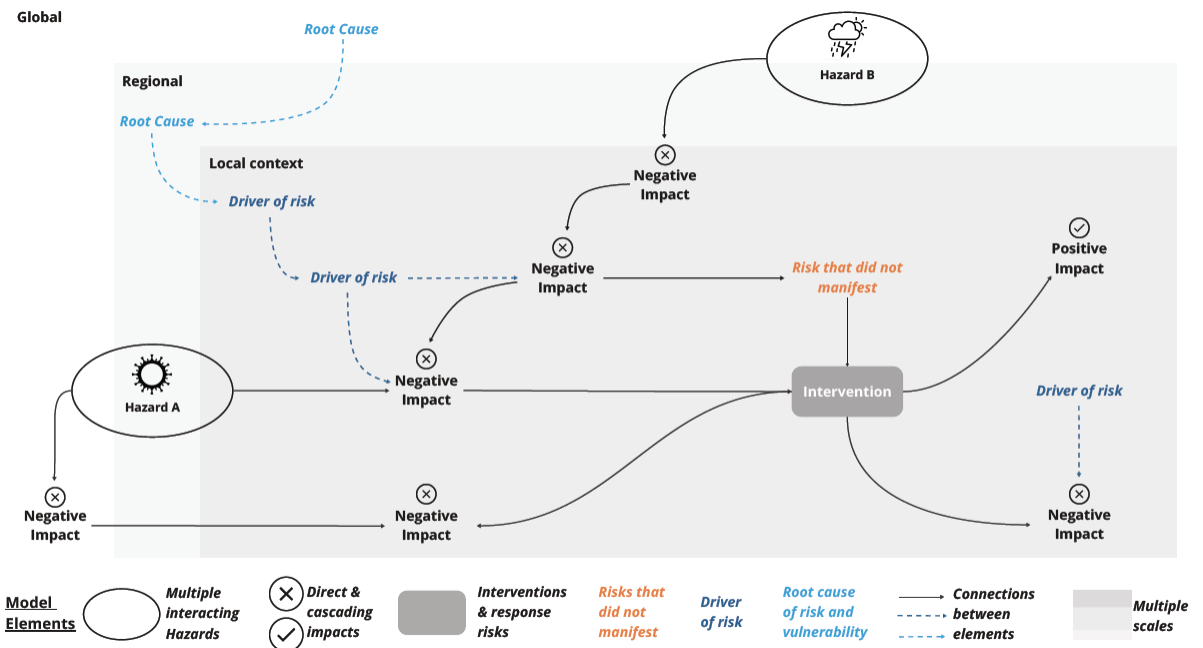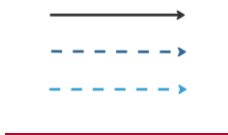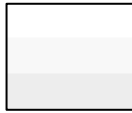365 at the national scale.
366

368
369 **Figure 1:** *Elements and possible graphical structure of an Impact Web. While here we present our*
370 *chosen graphical output of the conceptual model with computerised tools, an Impact Web could equally*
371 *be made with a pen and paper, for example if being developed in a community workshop. The model*
372 *maps the direct and cascading impacts and their interactions resulting from a biological and climate-*
373 *driven hazard. These impacts trigger an intervention, which results in further negative and positive*
374 *impacts (i.e. response risks), as well as a risk that did not manifest. Drivers of risk and root causes*
375 *linked to why impacts emerge are also included. The elements in the model are predominantly focused*
376 *on the local context, however, important regional and global interactions are included.*

377

11

378 **Table 2:** Description of the elements used in Impact Webs, including the chosen visual representation
379 in the model and examples

Element	Description	Visual representation in the model	Examples
Hazards, threats & shocks	A potentially damaging, sometimes unknown natural or human-made phenomenon, event or activity that may have adverse effects on vulnerable and exposed elements in a system. They may emerge slowly (e.g. sea level rise, droughts) or rapidly (e.g. flash flooding, earthquakes) and can be from a single phenomenon, event or activity (e.g. cyclone) or multiple interacting phenomena, events or activities (e.g. cyclone occurring during a pandemic; compounding heat and drought)	(Icons used to visually communicate hazard, threat or shock)	COVID-19, tropical cyclone, flood, drought, armed conflict
Negative impacts	Negative effects caused by one or multiple hazards, threats, shocks or policy responses to them. They can direct or indirect (i.e. cascading). A cross is placed next to the text in the model to visually communicate the impact is negative.		Increased mortality, loss of income, disruption in remittances, reduction in agricultural production, mental health effects
Positive impacts	Positive effects that occur within the system. They are often caused by interventions in response to hazards, threats or shocks. They can direct or indirect (i.e. cascading). A tick is placed next to the text in the model to visually communicate the impact is negative.		Advances in digitalization, improved early warning systems, increased risk awareness
Interventions	Actions that are taken in response to an impact, risk or hazard, threat or shock		Lockdown during a pandemic; provision of food and shelter items during a tropical cyclone; trade embargo with a country due to armed conflict; construction of a water reservoir to deal with droughts
Risks that did not manifest	Potential adverse consequences for human, technological and/or ecological systems that did not occur, often because of interventions in response to hazards, threats or shocks	*Risk that did not manifest*	Collapse of the health-care system during a pandemic, crop failure leading to food system collapse, fuel shortage crisis, economic recession
Drivers of risks	Processes or conditions that influence the level of risk by increasing levels of hazard, exposure and vulnerability	*Driver of risk*	Poverty, lack of functioning early warning systems, large informal work sector
Root causes of risks & vulnerability	Underlying factors influencing drivers of risk. They may be geographically or temporally remote as they often stem from structural as well as social, economic, cultural and political conditions that are difficult to influence directly	*Root cause of risk & vulnerability*	Regional development challenges, endemic corruption, colonial legacies

Connections between elements	Connecting arrow that indicates directional cause-effect relationships between elements in the system. The light blue dashed arrow is used to illustrate connections from a root causes of risk & vulnerability. The dark blue dashed arrow is used to illustrate connections from drivers of risk. The back arrow is used for all other connections. Different colours are used to make a visual distinction between the influence of drivers of risk and root causes of risk & vulnerability and other elements in the model		An increase in COVID-19 cases leading to a
Scale	The geographic scale at which the system interaction is occurring		Local, municipal, river catchment, county, national, regional, continental, global (in Figure 1, we show local context, regional and global as an example)

380

2.3. **Steps for constructing an Impact Web**

382 Here we present the steps that we followed to construct an Impact Web in the test cases (see Section
383 2.4 for more detail on the cases), drawing from the lessons we learned in the scoping review from
384 previous experiences among the research team.

385

Step 1: Scoping

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

401

Step 2: Identifying and mapping a preliminary number of elements

403 While there are not restrictions in terms of the order for selecting the elements in an Impact Web, we
404 found it was preferable to start from a limited number of key elements that you want to better understand
405 and then progressively build up the causal connections. In our test cases, we wanted to understand
406 multi-hazard interaction of COVID-19 and concurrent hazards, threats and shocks, therefore COVID-
407 19 was the logical entry point. This perspective acknowledged that the systems complex relationships
408 emerge more clearly when under stress, i.e. when direct and cascading impacts occur, the connections
409 between them and hazards become more visible and therefore easier to observe. In this sense, the first
410 number of elements functioned as "seeds" for the identification of the systems interdependencies. We
411 found building from key hazards, threats and shocks as the 'seed' elements facilitated following a more
412 simplistic cause-effect chain at the start of construction, i.e., direct impacts arising from each of the

413   hazards, threats or shocks. From direct impacts, cascading impacts then interventions and response
414   risks, and finally drivers of risks and root causes followed. While Impact Webs eventually aim to map
415   risk complexity, we found it difficult to start from the more complex interactions (i.e. feedback effects).
416   Rather, starting with more simple connections is easier for the modeller and stakeholders to begin with,
417   and the more complex interactions will emerge later as system understanding improves with desk study
418   and futher stakeholder interactions.

419

420   ***Step 3: Workshops and stakeholder participation***
421   Nearly all conceptual models that we reviewed integrated some form of stakeholder input, which was
422   variable depending on the decision context and complexity of the method chosen. ~~Participatory Systems~~
423   ~~Mapping~~ Causal Loop Diagrams (e.g. Coletta et al., 2024) and Impact Chains (e.g. Sett et al., 2024)
424   for example, generally elicit the integration of more stakeholder input than Influence Diagrams (e.g.
425   Mühlhofer et al., 2023), which have a strong quantitative component. A key step in our approach was to
426   draw on diverse knowledge from a range of expertise, which we did through application in ~~across the~~
427   test cases. This way, the Impact Web would be co-created to develop a mutually agreed upon visual
428   output of complex risks, as well as a shared heuristic of the system. Building on the preliminary number
429   of mapped elements in Step 2, we held two workshops in each test case. The workshops were done
430   with range of different stakeholders from communities, policy, practice, civil society, academia and
431   governments. These stakeholders were identified in the scoping (Step 1). Workshop 1 focused on
432   identifying new elements for the Impact Web, as well as reviewing the ones that had already been
433   identified and mapped from the desk review (Step 2). After workshop 1, we included the new elements
434   into the model, and held a second workshop to re-validate the logic and elements, as well as look at
435   entry points for risk management. This stakeholder backstopping provided better understanding of
436   otherwise unknown or missed model elements and their connections, and helped to characterised the
437   complex risk characteristics that could not be captured through desk study alone.

438

439   ~~from communities, policy, practice, civil society, academia and governments that were identified in~~
440   ~~the scoping in Step 1. The first workshop focused on identifying new elements for the Impact Web, as~~
441   ~~well as reviewing the ones that had already been identified and mapped in Step 2. We then included~~
442   ~~these inputs into the model, and held a second workshop to re-validate the logic and elements, as~~
443   ~~well as look at entry points for risk management. This stakeholder backstopping provided better~~
444   ~~understanding of otherwise unknown or missed model elements and their connections, and helped to~~
445   ~~characterised the complex risk characteristics that could not be captured through desk study alone.~~

446

447   ***Step 4: Review of model and visualisation***
448   After collecting stakeholder inputs across the five test cases, an important step was to review the model
449   within the research team. This included in-depth structuring of the information gathered in the
450   workshops and cross referencing it from available literature sources gathered in the desk study. Where
451   possible, we also refined the number of elements, for example by clustering two elements that
452   represented the same issues. This was done to reduce the model's complexity and ensure the final
453   visual could be an effective communication tool. We also reviewed causal connections and logic behind
454   them, reflecting to understand what this meant in a systems context, thus enhancing our own
455   understanding of complex risks. We then reworked the graphical design to create a visual and causal
456   connections which could be simpler to follow.

457

458   ***Step 5: Drafting narrative storyline***
459   As a final step to accompany the Impact Web model, a narrative risk storyline was drafted for each test
460   case that described the model and its connections in a narrative format. This helped to communicate in
461   a descriptive and engaging manner the complex model output that results from following the previous
462   steps, making it more engaging and useful to direct risk management decisions for both experts and
463   non-experts (van den Hurk et al., 2023). The storylines were drafted by the research team, explaining
464   the key aspects in the Impact Web and findings from the complex risk assessment. This was done after
465   the research team had completed the desk review, stakeholder workshops and reviewed the model.
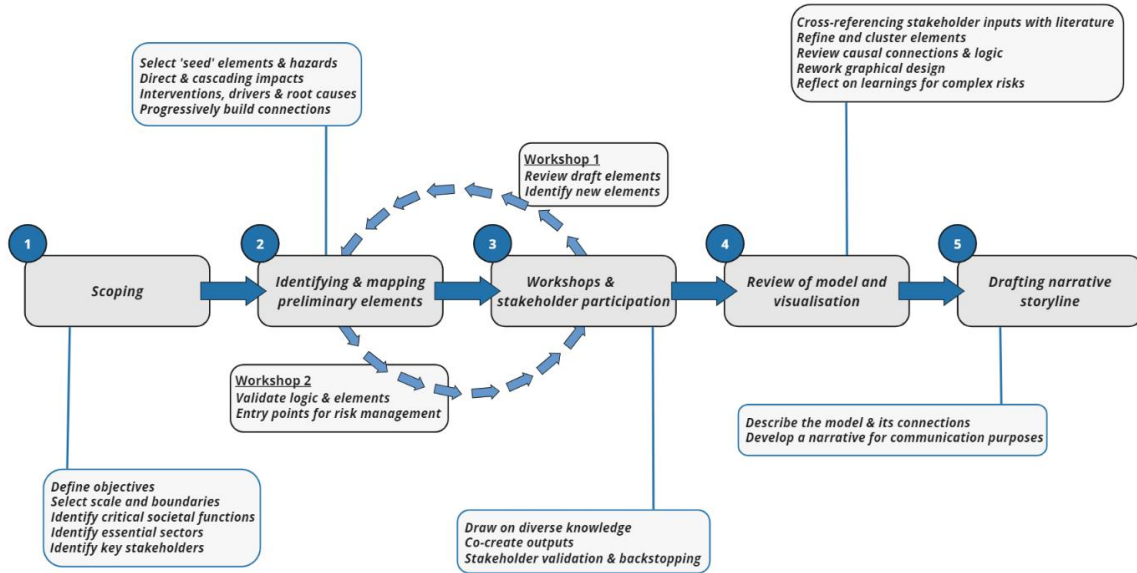
Figure 2: *Workflow of the steps that were followed for constructing an Impact Web. We trailed the approach in 5 test cases, which allowed for adjustment and improvement of the methodology as well as stakeholder feedback. The workflow followed a flexible stepwise methodology in five steps (scoping, identifying & 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.*

2.4.   Trail in test cases

Impact Webs were made in five 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 in the steps for construction and improvement of the methodology through stakeholder feedback. Second, we could test Impact Webs across different locations each with their own with unique challenges and characteristics, 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 to learn how they would engage with developing such a model. and get their input. We trailed the methodology in the cases between June and September 2021, Each case took using COVID-19 as the entry 'seed' element, building from there and adding additional elements to populate the model using desk study and stakeholder workshops. COVID-19 was selected as the first hazard to start build the model around as the pandemic had been a situation that challenged conventional risk and hazard settings, and was therefore a unique event in which to test a new complex risk assessment methodology. 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. The test cases were as follows:

- Coxes Bazar humanitarian camp (Bangladesh): Showcased COVID-19 and pre-existing social inequity in a challenging and fragile setting. It highlighted characteristics of vulnerable people and communities living in highly dependent systems.

- Sundarbans region (India): Encompassed a strong multi-hazard perspective, demonstrating the concurrence of COVID-19 with tropical cyclone Amphan. The case exhibited the dynamic nature of complex risks by exploring the delay between the cause and effect of impacts.

15

- National scale (Indonesia): Highlighted how COVID-19 and other hazards led to interconnected challenges on all fronts. The case had a special focus on the role of social protection.

- Maritime region (Togo): Focused on the rural-urban and national-international interlinkages of systems and how they were affected by COVID-19 and concurrent hazards in a regional Sub-Saharan context with high levels of poverty.

- Guayaquil (Ecuador): Gave specific insights into how COVID-19 and other hazards overwhelmed a densely populated, overcrowded urban setting. The case presented characteristics of tipping points and how system dependencies from global to local scales created and reinforced vulnerabilities (see section 3 for more).

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).

3. Results: proof of concept

Here we present the our 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 our proof of concept detailing the final output of an Impact Web and narrative storyline from the Guayaquil, Ecuador test case. Below we elaborate on why Guayaquil was chosen for our proof of concept in this paper.

3.1. 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).

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.
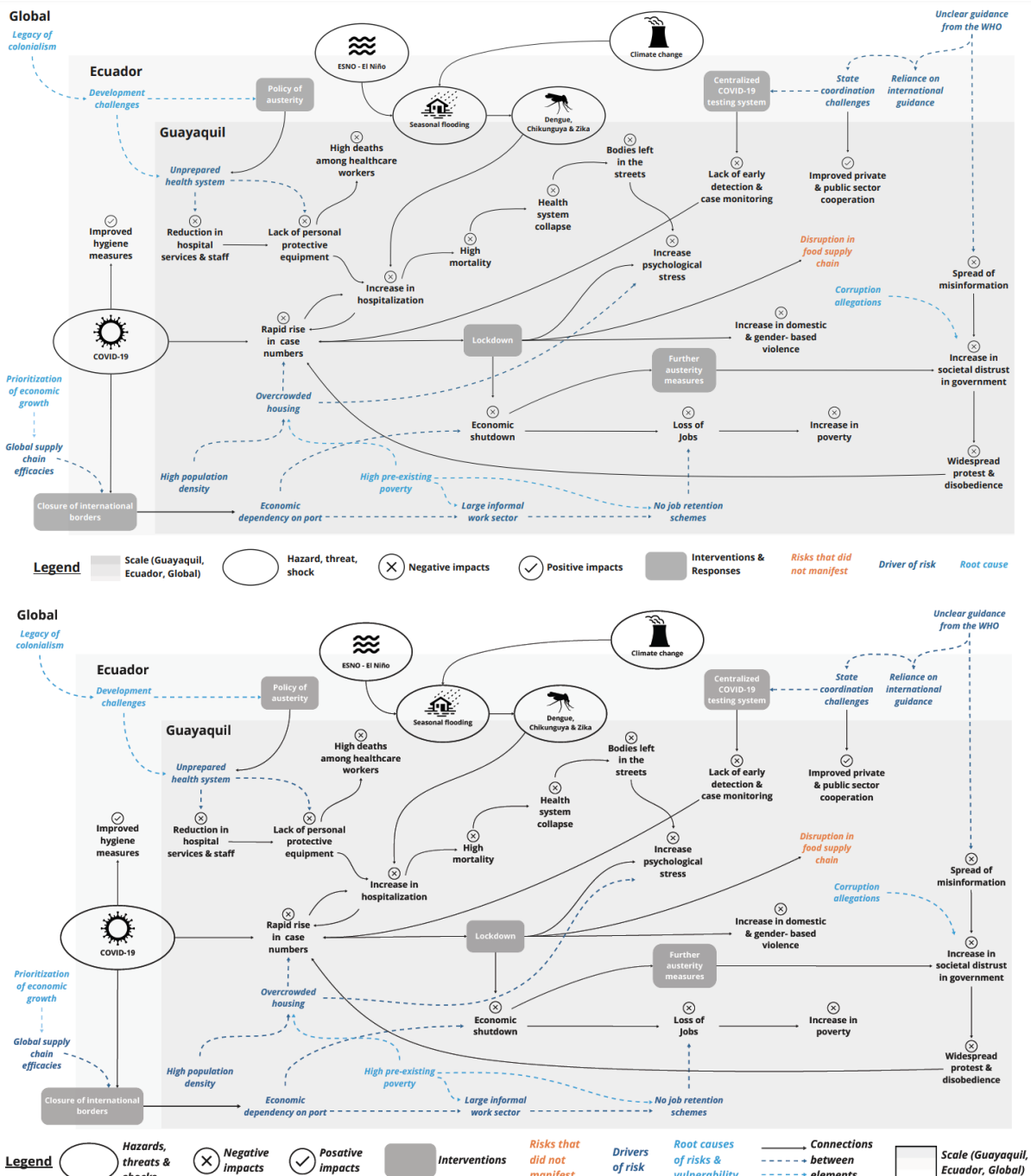

Figure 3: *Impact Web for the test case of Guayaquil, Ecuador. The conceptual model visualises complex risks and impacts linked to the COVID-19 pandemic, concurring hazards and the responses to it, as well as interconnections between system elements and drivers and root causes of risks.*

Step 5: Narrative storyline for Guayaquil, Ecuador

17

570   *The first confirmed case of COVID-19 in Guayaquil was 29 February, 2020. Driven by the city's high*
571   *population density, challenges with overcrowded housing and unpreparedness in the health system,*
572   *there was a rapid rise in cases and hospitalizations. Governmental policies of austerity in the five years*
573   *prior to the pandemic meant that hospitals and healthcare facilities were understaffed and under*
574   *equipped. The lack of personal protective equipment resulted in a high number of cases and deaths*
575   *among healthcare workers, which put further pressure on a health system that was already burdened*
576   *by increases in vector borne diseases due to seasonal flooding exacerbated by climate change. From*
577   *the compounding effects of multiple hazards and cascading impacts that emerged, the health system*
578   *reached a tipping point and collapsed, tragically resulting in a large number of bodies being left in the*
579   *streets, hospitals and care homes. This significantly increased psychological stress for the city's*
580   *residents. In March of 2020, Guayaquil had an excess mortality rate five times that of the same month*
581   *in the previous year and the highest COVID-19 mortality rate of any Latin-American city.*
582
583   *Economic disruptions from the intervention to close international borders were particularly severe in*
584   *Guayaquil due to the city's high dependency on the port. The closing of borders triggered economic*
585   *shutdown, with widespread adverse effects on employment and livelihoods. Due to the lack of job*
586   *retention schemes, many citizens, a lot of whom were already living in poverty before the pandemic,*
587   *were left without income generating opportunities. These impacts were exacerbated for the large*
588   *informal employment sector in Guayaquil. Due to the limited availability of space per person driven by*
589   *the high population density and overcrowded housing, lockdown interventions and social distancing*
590   *were difficult to follow for a large segment of the population. As seen in many places, there were also*
591   *sharp increases in domestic and gender-based violence during lockdown. As Guayaquil is a food-*
592   *producing country, one risk that did not manifest as a result of lockdowns was disruption in the food*
593   *supply chain and food shortages that were prevalent in some other countries in the region.*
594   *State coordination challenges and reliance on international guidance, which was unclear and*
595   *contradictory in the early stages of the pandemic, meant there was a lack of an integrated, cross-*
596   *sectoral and multi-scale response between Guayaquil's and Ecuador's public institutions. The national*
597   *government maintained a centralised COVID-19 testing system, which hindered the effectiveness of*
598   *city institutions to set up early-detection and monitoring systems such as contact-tracing and testing*
599   *facilities. The unclear guidance from the World Health Organisation resulted in the output of unclear*
600   *information and the national level, which was one of the factors that contributed to the spreading of*
601   *misinformation throughout digital networks. One positive impact that arose from state coordination*
602   *challenges was the strengthening of public and private sector cooperation.*
603   *In response to the economic disruptions, the government of Ecuador brought in more austerity*
604   *measures. Furthermore, corruption allegations were brought against some city and state-level actors*
605   *for capitalising on the emergency healthcare situation. These factors saw increasing societal distrust in*
606   *the government, which was already underlying. This came to fruition in Guayaquil when a societal*
607   *tipping point was reached in May of 2020, resulting in widespread protest and civil disobedience.*
608   *~~The application of the Impact Web approach in Guayaquil highlights how COVID-19 and concurrent~~*
609   *~~hazards have compounded to create cascading impacts across sectors.~~ Key risk drivers identified*
610   *included initial unpreparedness in the health system, high population density and overcrowded housing,*
611   *economic dependency on the port and state coordination challenges linked to reliance on international*
612   *guidance among others. These risk drivers influenced ~~The~~ cascading ~~nature of~~ response risks, ~~are also~~*
613   *~~characterised through the Impact Web, such as the~~ including widespread negative economic effects of*
614   *lockdown and closures of international borders, ~~or the~~and an increase in societal distrust and*
615   *subsequent protest and civil disobedience, which were in part due to further austerity interventions in*
616   *response.*
617   *A number of considerations for risk management emerged from developing the Impact Web for*
618   *Guayaquil. These include focusing attention, resources and efforts towards multi-sectoral and multi-*

619 *scale coordination across public and private institutions, as well as ensuring strong reach and*
620 *availability of social protection mechanisms and investment in risk monitoring and data systems. The*
621 *case also highlights that clear guidance and risk communication are key to building societal trust during*
622 *times of crisis.*

4. Discussion

625 With Impact Webs, we integrated Climate Impact Chains with aspects of system mapping approaches.
626 Doing this aimed to close gaps in current conceptual models of risks, through characterising dynamic
627 interactions between hazards, exposure, vulnerability, response risks drivers and root causes (IPCC,
628 2023), improving our understanding of complex risks through following a flexible stepwise
629 methodology. In the discussion we reflect on strengths and limitations of making Impact Webs. While
630 in this paper we only present one test case, our discussion reflects on lessons we learned through the
631 process of developing the methodology and from across all of the cases. We also~~, and~~ provide future
632 research directions.

4.1. Strengths

635 The application of the Impact Web methodology in case studies showed that the approach is useful to
636 conceptualise, identify and visualise networks of interconnected elements across different systems and
637 sectors. The conceptual model's suitability to map the interactions of multiple, concurrent hazards with
638 multiple pre-existing drivers of risk and root cases helps to uncover underlying societal vulnerabilities,
639 and is useful to derive storylines of how interconnected risks and impacts emerge from a hazard or
640 shock events. In the context of Guayaquil, the Impact Web and narrative storyline characterises how
641 COVID-19 revealed vulnerability in the health system, resulting in lockdowns that subsequently affected
642 many other systems and exacerbated already existing economic, domestic, governance challenges in
643 the city and country. Taking COVID-19 as the 'seed' element for our Impact Web resulted in constructing
644 a more simplistic cause-effect chain at the beginning of the modelling exercise, which can be useful for
645 replicability. Given the models effectiveness for mapping ~~the complexity of~~ an event as complex as ~~such~~
646 ~~as~~ COVID-19 suggests that you could equally develop an Impact Web to understand ~~the complexity of~~
647 ~~complex~~ climate change risks. Moreover, modelling five test cases with a flexible approach towards the
648 'local scale' (e.g. a humanitarian camp in Coxes Bazar, a city scale in Gauaquil, a regional focus in
649 Togo and the Indian Sundarbans and a national scale in Indonesa) suggests that you could create an
650 Impact Web to meet needs for a variety of decision contexts. For example, one could create the model
651 to assess complex risks for a river basin, town, or even a specific community.

653 Applying a systems lens towards analysis and mapping elements in the conceptual model, the
654 developer of an Impact Web as well as the stakeholders engaged gain a more comprehensive overview
655 of complex risks in the system they are mapping. While the final visual and the narrative storyline is the
656 output, it is the process of developing an Impact Web that stimulates critical reflection in the modeller
657 and involved stakeholders. ~~, thus enhancing understanding of complex risks, which is the key outcome~~.
658 In each of the test cases, stakeholders often entered the workshops with expertise in one sector or to
659 share their own lived experience. However, after collaboratively working on the model, participants
660 would learn from other and understand impacts and drivers outside of their expertise, thus enhancing
661 understanding of complex risks, which is the key outcome. Moreover, ~~i~~nvolving stakeholders
662 throughout the modelling process can help identify key agents who can act as a catalyst for change
663 (Renn et al., 2022; Özesmi and Özesmi., 2004). These can be, for example, stakeholders who perceive
664 more causal relationships or options to change the system. Working with stakeholders to co-create the
665 model can widen the lens for identifying critical elements, such as feedback effects and trade-offs, which
666 can then be further analysed. Additionally, taking a participatory or bottom up approach for the risk
667 assessment brings in perspectives that can influence top-down decision making.

669 As the conceptual model not only accounts for negative impacts, but also how policy responses and
670 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. ,They are additionally and are effective for pre-intervention evaluation and for communication purposes (Termeer et al., 2017; Wiebe et al., 2018).

4.2 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 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 vague, and which elements are selected for the model depending 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 sectoral 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

720 number of modelling considerations remain to be explored that are important for disaster risk
721 management, such as temporal dimensions, critical vulnerability moments (de Ruiter & van Loon, 2022)
722 and system tipping points (Lenton et al., 2023). Bridging conceptual models ~~of complex risks~~ with ~~data-~~
723 ~~driven~~ quantitative modelling approaches, as well incorporating lessons from methods that tackle
724 different aspects of complex risks in more depth such as vulnerability dynamics (e.g. Albulescu and
725 Armaș, 2024) would be useful in this ~~regard.~~regard. Additionally, while the model is affective for
726 assessing risks and trade-offs of interventions, a more structured, decision focused approach and
727 methodology to see how Impact Webs can provide comprehensive entry points for disaster risk
728 management and climate change adaptation would be useful. For example, pathways methodologies
729 have been applied to evaluate risk management decisions in complex systems (Schlumberger, et al.,
730 2024; Haasnoot et al., 2013, Werners et al., 2021). Thus, integrating conceptual risk modelling with a
731 pathways approach is one avenue that warrants further exploration. Understanding and mapping risk
732 complexity is only useful if cascading effects and systemic risks can be minimised, for example through
733 decoupling unnecessary connections across sectors. Moving from complex risk assessment to complex
734 risk management needs further attention in order strengthen the resilience of systems.

5. **Conclusions**

736 This paper ~~has presented~~ offers a new ~~novel~~ conceptual modelling approach called Impact Webs which
737 identifies, characterises, and maps complex risks. The inadequacy of single-hazard and single-risk
738 approaches in the face of global challenges like COVID-19 and climate change emphasizes the need
739 for comprehensive risk assessment that account for interconnectivity. Impact Webs are one such
740 methodology in an emerging field of research that do this. Their application in test cases identified
741 critical links between multiple hazards, responses to them, drivers of risk, root causes as well as pre-
742 existing societal vulnerabilities. The conceptual model provides a more nuanced understanding of how
743 risks propagate through systems, offering valuable insights into potential feedback effects, trade-offs,
744 and key agents that can act as catalysis of change and influence risks in a system. While the approach
745 contributes to improving complex risk assessment, a number of future research directions presented in
746 this article would further advance the methodology. These include bridging the conceptual model with
747 data-driven approaches and transitioning from complex risk assessment to complex risk management
748 that strengthens systemic resilience. In the evolving and interconnected landscape of communities and
749 societies, disaster risk reduction and climate change adaptation must account for complexity. The
750 Impact Webs approach stands as one valuable contribution to realise this, offering a system-wide
751 perspective for complex risk assessment.

770   region") projects. Views and opinions expressed are those of the authors only and do not necessarily
771   reflect those of UNDRR, GIZ or BMZ.
772
778
779   **Review statement.**
780

781   **References**
782   Ahmed, A., Woulds, C., Drake, F., & Nawaz, R. (2018). Beyond the tradition: Using Fuzzy Cognitive
783   Maps to elicit expert views on coastal susceptibility to erosion in Bangladesh. *CATENA*, *170*,
784   36–50. https://doi.org/10.1016/j.catena.2018.06.003
785   Albulescu, A.-C., & Armas, I. (2024). An impact-chain-based exploration of multi-hazard vulnerability
786   dynamics: the multi-hazard of floods and the COVID-19 pandemic in Romania. *Natural
787   Hazards and Earth System Sciences*, *24*(8), 2895–2922. https://doi.org/10.5194/nhess-24-
788   2895-2024
789   Ara Begum, R., R. Lempert, E., Ali, T., Benjaminsen, T., Bernauer, W., Cramer, X., Cui, K., Mach, G.,
790   Nagy, N. C., Stenseth, R., & Sukumar, P. (2022). *Point of Departure and Key Concepts. In:
791   Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group
792   II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.*
793   Intergovernmental Panel on Climate Change.
794   https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_Chapter01.pdf
795   Bashari, H., Naghipour, A. A., Khajeddin, S. J., Sangoony, H., & Tahmasebi, P. (2016). Risk of fire
796   occurrence in arid and semi-arid ecosystems of Iran: An investigation using Bayesian belief
797   networks. *Environmental Monitoring and Assessment*, *188*(9), 531.
798   https://doi.org/10.1007/s10661-016-5532-8
799   Blaikie, P., Cannon, T., Davis, I., & Wisner, B. (1994). *At Risk: Natural Hazards, People's
800   Vulnerability, and Disasters* (1st ed.). Routledge.
801   de Brito, M., Sodoge, J., Fekete, A., Hagenlocher, M., Koks, E., Kuhlicke, C., Messori, G.,
802   Ruiter, M. de, Schweizer, P.-J., & Ward, P. J. (2024). Uncovering the Dynamics of Multi-
803   Sector Impacts of Hydrological Extremes: A Methods Overview. *Earth's Future*, *12*(1), Article
804   e2023EF003906. https://doi.org/10.1029/2023EF003906
805   Carter, T. R., Benzie, M., Campiglio, E., Carlsen, H., Fronzek, S., Hildén, M., Reyer, C. P., & West, C.
806   (2021). A conceptual framework for cross-border impacts of climate change. *Global
807   Environmental Change*, *69*, 102307. https://doi.org/10.1016/j.gloenvcha.2021.102307
808   Chandra, A., & Gaganis, P. (2016). Deconstructing vulnerability and adaptation in a coastal river basin
809   ecosystem: a participatory analysis of flood risk in Nadi, Fiji Islands. *Climate and
810   Development*, *8*(3), 256–269. https://doi.org/10.1080/17565529.2015.1016884
811   Coletta, V. R., Pagano, A., Pluchinotta, I., Zimmermann, N., Davies, M., Butler, A., Fratino, U., &
812   Giordano, R. (2024). Participatory Causal Loop Diagrams Building for Supporting Decision-
813   Makers Integrating Flood Risk Management in an Urban Regeneration Process. *Earth's
814   Future*, *12*(1), e2023EF003659. https://doi.org/10.1029/2023EF003659
815   Cui, L., Yue, S., Nghiem, X.-H., & Duan, M. (2023). Exploring the risk and economic vulnerability of
816   global energy supply chain interruption in the context of Russo-Ukrainian war. *Resources
817   Policy*, *81*, 103373. https://doi.org/10.1016/j.resourpol.2023.103373
818   Delgado, A., Peek, O., & d'Auria, V. (2020). *The Routledge Handbook on Informal Urbanization*.
819   Routledge.
820   Dianat, H., Wilkinson, S., Williams, P., & Khatibi, H. (2021). Planning the resilient city: Investigations
821   into using "causal loop diagram" in combination with "UNISDR scorecard" for making cities
822   more resilient. *International Journal of Disaster Risk Reduction*, *65*, 102561.
823   https://doi.org/10.1016/j.ijdrr.2021.102561

824 Eberle, C., O'Connor, J., Narvaez, L., Mena Benavides, M., & Sebesvari, Z. (2023). *Interconnected*
825   *Disaster Risks 2023: Risk Tipping Points.* United Nations University - Institute for Environment
826   and Human Security (UNU-EHS). https://doi.org/10.53324/WTWN2495
827 ElSawah, S., McLucas, A., & Mazanov, J. (2015). Communicating About Water Issues in Australia.
828   *Simulation & Gaming*, *46*(6), 713–741. https://doi.org/10.1177/1046878115580410
829 ElSawah, S., Pierce, S. A., Hamilton, S. H., van Delden, H., Haase, D., Elmahdi, A., & Jakeman, A. J.
830   (2017). An overview of the system dynamics process for integrated modelling of socio-
831   ecological systems: Lessons on good modelling practice from five case studies.
832   *Environmental Modelling & Software*, *93*, 127–145.
833   https://doi.org/10.1016/j.envsoft.2017.03.001
834 Giordano, R., Preziosi, E., & Romano, E. (2013). Integration of local and scientific knowledge to
835   support drought impact monitoring: some hints from an Italian case study. *Natural Hazards*,
836   *69*(1), 523–544. https://doi.org/10.1007/s11069-013-0724-9
837 Gómez Martín, E., Giordano, R., Pagano, A., van der Keur, P., & Máñez Costa, M. (2020). Using a
838   system thinking approach to assess the contribution of nature based solutions to sustainable
839   development goals. *The Science of the Total Environment*, *738*, 139693.
840   https://doi.org/10.1016/j.scitotenv.2020.139693
841 Groundstroem, F., & Juhola, S. (2021). Using systems thinking and causal loop diagrams to identify
842   cascading climate change impacts on bioenergy supply systems. *Mitigation and Adaptation*
843   *Strategies for Global Change*, *26*(7), 29. https://doi.org/10.1007/s11027-021-09967-0
844 Haasnoot, M., Kwakkel, J. H., Walker, W. E., & Maat, J. ter (2013). Dynamic adaptive policy
845   pathways: A method for crafting robust decisions for a deeply uncertain world. *Global*
846   *Environmental Change*, *23*(2), 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006
847 Hagenlocher, M., Naumann, G., Meza, I., Blauhut, V., Cotti, D., Döll, P., Ehlert, K., Gaupp, F., van
848   Loon, A. F., Marengo, J. A., Rossi, L., Sabino Siemons, A. S., Siebert, S., Tsehayu, A. T.,
849   Toreti, A., Tsegai, D., Vera, C., Vogt, J., & Wens, M. (2023). Tackling Growing Drought
850   Risks—The Need for a Systemic Perspective. *Earth's Future*, *11*(9), Article e2023EF003857.
851   https://doi.org/10.1029/2023EF003857
852 Hagenlocher, M., Banerjee, S., Bermudez-Zambrano, D. A., Cotti, D., Hassel, J., Masys, A. J.,
853   Nawawi, Y. E. P., Rana, S., Rimmert, M., Roy, P., Schütze, S., Shekhar, H., Sodogas, V.,
854   Sparkes, E., Ketut Surtiari, A., Valdiviezo-Ajila, A., & Werners, S. E. (2022). *Understanding*
855   *and managing cascading and systemic risks: lessons from COVID-19.* UNDRR & UNU-EHS.
856 Hagenlocher, M., Schneiderbauer, S., Sebesvari, Z., Bertram, M., Renner, K., Renaud, F., Wiley, H.,
857   & Zebisch, M. (2018). *Climate Risk Assessment for Ecosystem-based Adaptation – A*
858   *guidebook for planners and practitioners.* https://www.adaptationcommunity.net/wp-
859   content/uploads/2018/06/giz-eurac-unu-2018-en-guidebook-climate-risk-asessment-eba.pdf
860 Hallegatte, S., Green, C., Nicholls, R. J., & Corfee-Morlot, J. (2013). Future flood losses in major
861   coastal cities. *Nature Climate Change*, *3*(9), 802–806. https://doi.org/10.1038/nclimate1979
862 Harris, K., Lager, F., Jansen, M. K., & Benzie, M. (2022). Rising to a New Challenge: A Protocol for
863   Case-Study Research on Transboundary Climate Risk. *Weather, Climate, and Society*, *14*(3),
864   755–768. https://doi.org/10.1175/WCAS-D-21-0022.1
865 Helbing, D. (2013). Globally networked risks and how to respond. *Nature*, *497*(7447), 51–59.
866   https://doi.org/10.1038/nature12047
867 IPCC. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability Working Group II*
868   *Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate*
869   *Change.* Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ ar5/wg2/
870 IPCC. (2023). *Synthesis report of the IPCC Sixth Assessment Report (AR6).* Intergovernmental Panel
871   on Climate Change. https://www.ipcc.ch/report/sixth-assessment-report-cycle/
872 Lawrence, J., Blackett, P., & Cradock-Henry, N. A. (2020). Cascading climate change impacts and
873   implications. *Climate Risk Management*, *29*, 100234.
874   https://doi.org/10.1016/j.crm.2020.100234
875 Lenton, T. M., Armstrong McKay, D. I., Loriani, S., Abrams, J. F., Lade, S. J., Donges, J. F.,
876   Milkoreit, M., Powell, T., Smith, S. R., Zimm, C., Buxton, J. E., Bailey, E., Laybourn, L.,
877   Ghadiali, A., & Dyke J.G. (2023). *The Global Tipping Points Report 2023.* https://global-
878   tipping-points.org/

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

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

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

889 Munn, Z., Pollock, D., Khalil, H., Alexander, L., McInerney, P., Godfrey, C. M., Peters, M., &
890   Tricco, A. C. (2022). What are scoping reviews? Providing a formal definition of scoping
891   reviews as a type of evidence synthesis. *JBI Evidence Synthesis*, *20*(4), 950–952.
892   https://doi.org/10.11124/JBIES-21-00483

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

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

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

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

908 Rehman, J., Sohaib, O., Asif, M., & Pradhan, B. (2019). Applying systems thinking to flood disaster
909   management for a sustainable development. *International Journal of Disaster Risk Reduction*,
910   *36*, 101101. https://doi.org/10.1016/j.ijdrr.2019.101101

911 Renn, O., Laubichler, M., Lucas, K., Kröger, W., Schanze, J., Scholz, R. W., & Schweizer, P.-J.
912   (2022). Systemic Risks from Different Perspectives. *Risk Analysis : An Official Publication of*
913   *the Society for Risk Analysis*, *42*(9), 1902–1920. https://doi.org/10.1111/risa.13657

914 Ruiter, M. C. de, Couasnon, A., van den Homberg, M. J. C., Daniell, J. E., Gill, J. C., & Ward, P. J.
915   (2020). Why We Can No Longer Ignore Consecutive Disasters. *Earth's Future*, *8*(3), Article
916   e2019EF001425. https://doi.org/10.1029/2019EF001425

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

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

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

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

931 Sett, D., Trinh, T. P., Wasim, T., Ortiz-Vargas, A., Nguyen, D. G. C., Büche, K., Assmann, A.,
932   Nguyen, H. K. L., Walz, Y., Souvignet, M., Bachofer, F., Vu, T. B., Garschagen, M., &
933   Hagenlocher, M. (2024). Advancing understanding of the complex nature of flood risks to
934   inform comprehensive risk management: Findings from an urban region in Central Vietnam.

935   *International Journal of Disaster Risk Reduction*, *110*, 104652.
936   https://doi.org/10.1016/j.ijdrr.2024.104652

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

940 Simpson, N. P., Mach, K. J., Constable, A., Hess, J., Hogarth, R., Howden, M., Lawrence, J.,
941   Lempert, R. J., Muccione, V., Mackey, B., New, M. G., O'Neill, B., Otto, F., Pörtner, H.-O.,
942   Reisinger, A., Roberts, D., Schmidt, D. N., Seneviratne, S., Strongin, S., . . . Trisos, C. H.
943   (2021). A framework for complex climate change risk assessment. *One Earth*, *4*(4), 489–501.
944   https://doi.org/10.1016/j.oneear.2021.03.005

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

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

953 Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R.,
954   Carpenter, S. R., Vries, W. de, Wit, C. A. de, Folke, C., Gerten, D., Heinke, J., Mace, G. M.,
955   Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Sustainability. Planetary
956   boundaries: Guiding human development on a changing planet. *Science (New York, N.Y.)*,
957   *347*(6223), 1259855. https://doi.org/10.1126/science.1259855

958 ~~Suriya, S., & Mudgal, B. V. (2013). Soft systems methodology and integrated flood management: a~~
959   ~~study of the A dayar watershed, C hennai, I ndia. *Water and Environment Journal*, 27(4),~~
960   ~~462 473. https://doi.org/10.1111/j.1747-6593.2012.00365.x~~

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

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

968 van den Hurk, B. J., Baldissera Pacchetti, M., Boere, E., Ciullo, A., Coulter, L., Dessai, S., Ercin, E.,
969   Goulart, H. M., Hamed, R., Hochrainer-Stigler, S., Koks, E., Kubiczek, P., Levermann, A.,
970   Mechler, R., van Meersbergen, M., Mester, B., Middelanis, R., Minderhoud, K., Mysiak, J.,
971   Witpas, K. (2023). Climate impact storylines for assessing socio-economic responses to
972   remote events. *Climate Risk Management*, *40*, 100500.
973   https://doi.org/10.1016/j.crm.2023.100500

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

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

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

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

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

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