

Invited Perspectives: Science for Comprehensive Disaster and Climate Risk Management

Philip J. Ward^{1,2}, Marleen C. de Ruiter¹, Kees Boersma¹, Tomris Cesuroglu³, Nathan Clark¹, Tina Comes^{4,5}, Ashok Dahal⁶, Sonja Fransen⁷, Jasper Verschuur⁵, Carmen Anthonj⁶, Srijith Balakrishnan⁵,
5 Jens de Bruijn¹, Eefje Hendriks⁶, Rodrigo Mena Fluhmann⁷, Goda Perlaviciute⁸, Linda Steg⁸, Marc van den Homberg^{6,9}, Cees van Westen⁶, Funda Atun⁶, Anja Schreijer³, Nicole van Maanen¹

¹Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1111, 1081 HV Amsterdam, the Netherlands

²Deltares, Boussinesqweg 1, 2629 HV Delft, the Netherlands

10 ³Pandemic and Disaster Preparedness Center, Erasmus Medical Center, Dr. Molewaterplein 40, 3015 GD Rotterdam, the Netherlands

⁴DLR Institute for the Protection of Terrestrial Infrastructures, 53757 Sankt Augustin, Germany

⁵Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2628BX, Delft, the Netherlands

15 ⁶Faculty of Geo-Information Science and Earth Observation/ITC, University of Twente, 7522 NH, Enschede, the Netherlands

⁷International Institute of Social Studies, Erasmus University, Kortenaerkade 12, 2518 AX The Hague, the Netherlands

⁸Faculty of Behavioural and Social Sciences, University of Groningen, 9712 TS Groningen, the Netherlands

⁹The Netherlands Red Cross data and digital unit 510, 2593HT, The Hague, the Netherlands

20 *Correspondence to:* Philip J. Ward (philip.ward@vu.nl) and Jasper Verschuur (j.verschuur@tudelft.nl)

Abstract. In this paper, we explore five core challenges that need to be addressed in order to move towards the Comprehensive Disaster and Climate Risk Management approach, which has been proposed within the newly emerging paradigm of a more holistic approach to managing the risks associated with climatic and/or non-climatic hazards and non-climatic risk drivers across varied time scales and levels. These five challenges relate to the following points. First, we have
25 a lack of comprehensive and high quality data for observing how society is impacted by, prepares for, and responds to multi-risks. Second, as a result we have a limited understanding of why individuals, communities, and other decision-makers (fail to) prepare for complex multi-risks in the way they do, and how that affects their responses. Third, our capacity to simulate how current and future risk could be effectively reduced is hampered by the aforementioned lack and fragmentation of observations and understanding of multi-risk dynamics. Fourth, current governance structures often reinforce data and
30 knowledge silos. Fifth, the high complexity and wicked nature of the multi-risk problem results in barriers in knowledge exchange at the science, policy and practice interface. In this paper, we elaborate on each of these challenges, discuss why they matter for comprehensive disaster risk management, and provide ideas of how to overcome these challenges. We end the paper with a brief outlook.

1 Introduction

35 *In August 2021, Haiti's southern peninsula faced a multi-disaster scenario. A 7.2 Mw earthquake first caused widespread structural failure, destroying 137,000 homes and vital infrastructure, and causing at least 2,248 fatalities, 12,000 injuries, and 300 missing persons, while triggering landslides that cut off remote communities (CDEMA, 2021; Government of Haiti, 2021; Cabas et al., 2023). This was immediately followed by Tropical Storm Grace, whose torrential rains and flooding paralysed rescue operations and obscured the specific origins of various casualties (Cavallo et al., 2021; Reinhart and Berg,*
40 *2022). The combined impact of these events, alongside the difficulty of reaching isolated areas, delayed essential aid. Against the backdrop of a fragile state that still suffers from the repercussions of the 2010 earthquake, the long-term consequences were equally severe; the collapse of healthcare and sanitation systems precipitated a cholera outbreak by 2022, resulting in thousands of cases and over 200 deaths (IFRC, 2022). Throughout this period, the lack of secure housing left the population exposed to ongoing seismic and meteorological threats (OCHA, 2021). Moreover, at the same time the*
45 *ongoing Covid-19 pandemic was a major compounding stressor: the Government of Haiti had to cope with the combined events of the aforementioned hazard shocks at a time that the healthcare system was already severely strained by the ongoing pandemic (Government of Haiti, 2021).*

As shown by this example, many crises occur from complex risk pathways. As is now well recognised, risk itself is a function of hazard, exposure, and vulnerability (UNDRR, 2017). Traditionally, we have studied and managed these risks
50 using a 'static approach', i.e. neglecting that different hazards interact with each other (or at least underestimating the risk of these interactions) and that exposure and vulnerability change over time (De Ruiter and Van Loon, 2022).

Over the last decade, we have come to understand that different hazards interact with each other to influence the overall risk. These interactions are referred to as multi-hazards (Zschau, 2017). Early research (e.g. Kappes et al 2012; Gill et al., 2014; Zscheischler et al., 2018; Alexander and Pescaroli, 2019; De Ridder et al., 2020) concentrated on characterising and
55 visualising different kinds of interactions (e.g. triggering, amplifying, compound, consecutive), often focusing on mainly geological, meteorological, and hydrological natural hazards. Only a few studies attempt to map where and how these hazards interact in space and time. For example, De Ruiter et al. (2020) map the consecutive occurrence of tropical cyclones and earthquakes over the period 1960-2016 at the global scale, and Claassen et al. (2023) map the spatial and temporal overlap between the footprints of 11 different hazards footprints at the global scale over the period 2004-2017. Wenzel et al.
60 (2026) proposed a practical classification aid, based on type, spatial, and temporal assessment of the multi-hazard interrelations. Still, the systematic mapping of such interlinkages is scarce (Simpson et al., 2021).

Moreover, we are increasingly understanding that many hazard interlinkages also exist with biological hazards that cause infectious diseases. For example, flooding and high temperatures can create or increase breeding grounds disease-vectors like mosquitoes, thereby amplifying exposure to vector-borne diseases such as malaria and dengue fever, or can spread
65 bacteria leading to water-borne diseases such as cholera outbreaks (Bett et al., 2021). Systematic reviews have found that 58% of all known human infectious diseases, including Zika, Chikungunya, and Ebola, have been aggravated by climatic

hazards through over 1,000 unique transmission pathways (Mora et al., 2022). Alcanya et al. (2022, 2025) found higher evidence and higher agreement on the links between extreme climatic events and water-borne diseases than for vector-borne diseases.

70 Multi-risk occurs when multiple hazards interact with dynamic changes in exposure and vulnerability (Zschau, 2017). Next to being shaped by ongoing long-term (either slow or rapid) socioeconomic change, exposure and vulnerability are dynamically shaped by previous hazards. Slow-onset hazards like pandemics and droughts can change exposure through migration, and vulnerability by eroding people's financial resources, job opportunities, access to education, health and well-being, social networks, and so forth (Hagenlocher et al., 2019; Anjum and Fraser, 2021; Yamori and Goltz, 2021; De Ruiter and van Loon, 2022). These changes have been found to create long-term path dependencies, lasting for decades (Casali et al., 2024). Rapid-onset hazards (like floods, earthquakes, landslides, or heatwaves) also dynamically shape exposure and vulnerability (Sirenko et al., 2026a). For example, hazards can lead to the immediate displacement of people as well as depopulation (e.g. Farabollini et al., 2022); an individual displaced by flooding may become exposed to vector-borne diseases; or a community enduring a disease outbreak may have increased exposure due to drinking water infrastructure damage (Prades et al., 2023; Acharya and Silori, 2025). Many multi-risks exist at the interface of natural hazards and health. For example, waterborne disease transmission pathways include destruction, failure or interruptions of water and sanitation (WASH) infrastructure service delivery due to flooding, heavy rains, tropical cyclones, high temperature or drought (Howard et al., 2016). Failure of water and sanitation services under climate and disaster conditions is highly problematic, as the increased exposure to diseases often coincides with disaster-related inaccessibility or collapse of healthcare systems, creating a double health burden, and even a triple health burden when considering the often extensive mental health impacts on affected communities (North et al., 2004; Beaglehole et al., 2015; Kanehara et al., 2016; Leppold et al., 2022).

Our society is increasingly facing these kinds of complex multi-risks (Sakić Trogrlić et al., 2024; Tansel, 2025). This is partly due to increased exposure in hazard-prone areas due to population growth and (unregulated) urban development. Moreover, the frequency and severity of some hydrological and meteorological hazards are increasing due to climate change.

90 We are also seeing an increase in biological hazards that cause infectious diseases - also related to globalisation, increasing populations, and the increased interface between humans and animals (Rulli et al., 2025), with the Covid-19 pandemic clearly thrusting this issue into the public attention (Lindahl, 2015; Baker et al., 2022; Kumar Satapathy et al., 2023).

The Mid-Term Review (MTR) of the United Nations Sendai Framework for Disaster Risk Reduction (SFDRR) (UNDRR, 2023) made it crystal clear that science is falling short in terms of understanding these complex multi-risks, and the World Health Organisation (2019) underscores that biological hazards that cause infectious diseases must be considered within a broader disaster risk context. Despite our recognition of the importance of a multi-risk approach to risk assessment and management, and the recent effort of UNDRR & ISC (2025) to include the multi-hazard context in their influential Hazard Information Profiles (HIPs), as societies we remain poorly positioned to proactively prepare for, and respond to, these complex multi-risks. Reflecting this gap, UNDRR has recently highlighted the persistent disconnect between disaster risk reduction (DRR) and climate change adaptation (CCA) and introduced the concept of Comprehensive Disaster and Climate

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Risk Management (CRM) as a governance ambition to better integrate risk across hazards, sectors, and timescales (UNDRR, 2023). However, while CRM provides a clear normative direction aligned with the Sendai Framework, its operationalisation remains constrained by many of the same scientific, behavioural, modelling, and governance limitations discussed in this paper.

105 This situation is a logical outcome of the current state of our siloed science and risk governance. In this paper, we explore five core challenges that we believe need to be addressed in order to move towards this new paradigm of a more comprehensive approach to disaster risk management, as called for by the Sendai Framework MTR. In brief, these five challenges relate to the following points. First, we lack comprehensive, high-quality data for observing how society is impacted by, prepares for, and responds to multi-risks. Second, as a result, we have a limited understanding of why
110 individuals, communities, and other decision-makers (fail to) prepare for and respond to complex multi-risks in the way they do. Third, our capacity to simulate how both current and future risk could be effectively reduced is hampered by the aforementioned lack of observations and understanding of multi-risk dynamics. Fourth, current governance structures often reinforce these silos. Fifth, the high complexity and super wicked nature (Levin et al., 2012) of the multi-risk problem results in barriers in knowledge exchange at the science, policy and practice interface.

115 In the paper, we elaborate on each of these challenges, discuss why they matter for comprehensive disaster risk management, and provide ideas of how to overcome these challenges. We end the paper with a brief outlook. Our paper aims to inspire future research endeavours by bringing together key perspectives from a wide range of relevant disciplines. While this paper focuses on interactions between natural hazards and biological hazards that cause infectious diseases, we acknowledge that a broad understanding of societal resilience also needs to acknowledge all kinds of issues that can impact security, including
120 conflict, cyber-attacks, and other non- natural hazard/disease-related aspects.

2 Key challenges

In the following sub-sections, we explore each of the aforementioned five core challenges, followed by concrete suggestions on ways forward to address them. The challenges were identified using the expert judgement of the interdisciplinary author team. This team consists of experts who have been working on the topic from different angles and disciplines, including
125 climate risk, geophysical risks, biological hazards that cause infectious diseases, social and behavioural science, disaster governance, public health, development studies, crisis management, societal resilience, and climate adaptation. The challenges are by no means exhaustive. Instead, the five challenges discussed represent key challenges that we regularly face through our multi-, inter-, and transdisciplinary endeavours in different contextual settings. An overview of the challenges and our proposed ways forward are shown in graphic representation of the paper in Fig. 1.

Towards Comprehensive Disaster and Climate Risk Management (CRM)

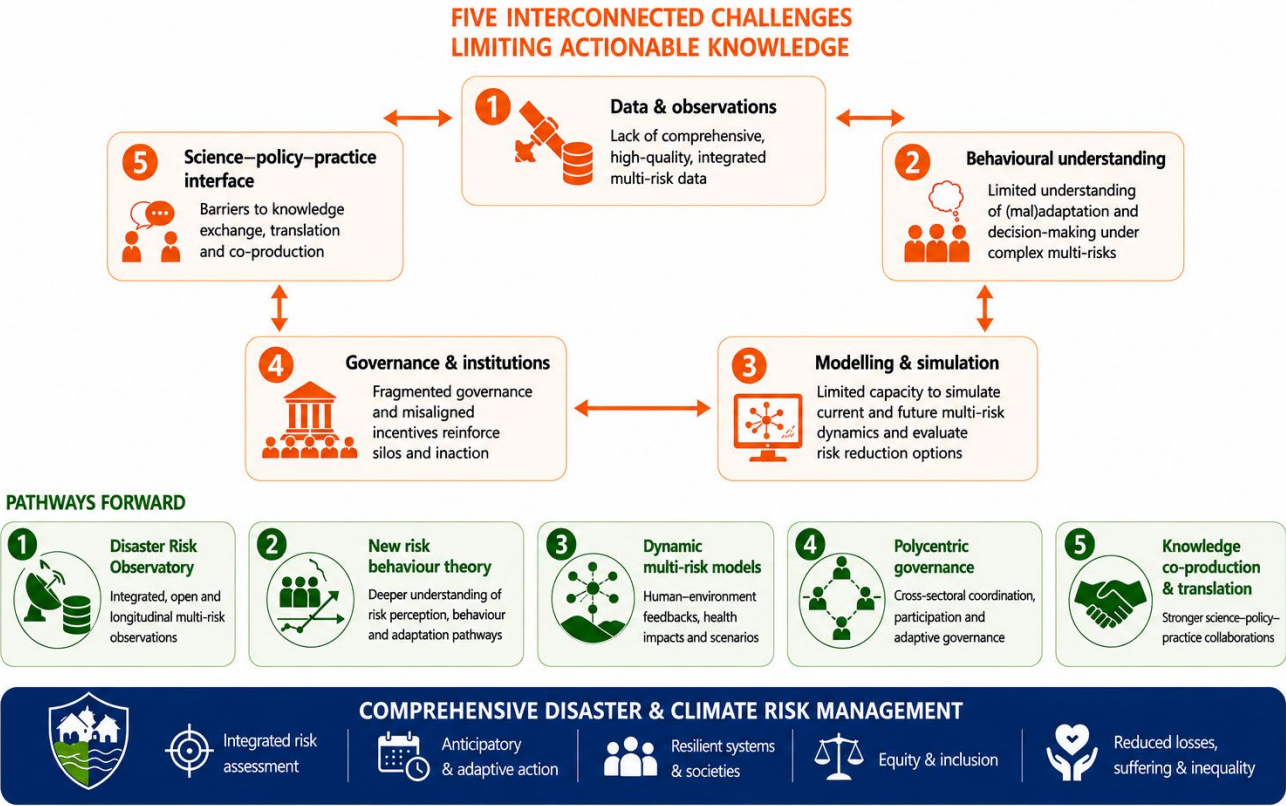


Figure 1: Graphic overview of the challenges addressed in the paper and the proposed ways forward (generated with the assistance of ChatGPT)

2.1 Observing societal impact, preparation, and response to multi-risks

Challenges

Despite the recent proliferation of data on natural hazards (especially climate data), exposure, and vulnerability, we lack comprehensive, high-quality, data for observing how society is impacted by, prepares for, and responds to multi-risks (Ward et al., 2022, 2026). For a part, this stems from the fact that data related to different aspects of disaster risk are produced and stored in disciplinary and sectoral silos. For example, health scientists collect and curate data related to biological hazards that cause infectious diseases, hydrologists collect and curate datasets related to flood and drought hazards, climate scientists collect and curate datasets related to meteorological hazards, and geologists, seismologists, and vulcanologists collect and curate data related to earthquakes and volcanoes. What is more, scientists from these disciplines often develop their own exposure and vulnerability datasets, which are also developed by social scientists (e.g., individuals' perceptions of risks and

motivation to prepare for risks), geographers, demographers, and so forth. This siloisation, and lack of data governance across disciplines and sectors, means that hazard maps, exposure databases, and vulnerability surveys cannot be easily joined or analysed together, preventing a holistic view of multi-hazard risk (Migliorini et al. 2019). Within the siloisation, there are large disparities in data quality between the Global North and Global South, due to the digital divide, chronic underinvestment in statistical and information infrastructures (such as lower densities of weather observation networks) (Dinku, 2019), institutional fragmentation, and weak data governance.

Even when data exist, their spatial and/or temporal scales may not match, obscuring local hotspots of risk. For example, urban heat islands, flash floods, or debris flows often occur at sub-city scales that global datasets or coarse hazard models cannot resolve. Likewise, social and health data are typically aggregated at the district or province level, masking intra-city or informal-settlement vulnerabilities (Lee et al., 2020; Sairam and De Ruiter, 2026). Moreover, local knowledge is not acknowledged and used enough, and we see a lack of systematic and scientific integration of citizen science into risk and resilience mapping (e.g. Albagli and Iwama, 2022).

While risk continually evolves over time, our data often do not. Climate and hazard indicators (e.g. rainfall indices, temperature anomalies) may be available from monitoring networks or reanalysis at high frequency, yet exposure and vulnerability data (like census counts or poverty surveys) are updated only rarely. In many cases, vulnerability is represented by a few ‘episodic snapshots’ (e.g. last census, last household survey) that quickly become outdated. Moreover, impact data are collected after each event, following certain data collection protocols. These protocols can differ depending on the scale of the disaster and the actors involved in the response. Also, impact data collection usually focuses on the tangible and direct losses, whereby indirect and intangible losses (e.g., mental and social health, loss of place identity, social cohesion), which are more complex to assess and measure, are overlooked (Birkmann et al., 2026). Such loss-based data also neglect the impact on communities, social fabric, or economy - and data on behavioural adaptation are often entirely missing. The dominant global disaster loss database (EM-DAT) primarily records disaster impacts that are already aggregated by its reporting sources at regional scales, making it difficult to see local variations, and so it provides little insight on trends at the finer level. Ministries of Health have health information systems to record health data; these data cannot be easily disclosed as they contain personally identifiable information. Many low- and middle-income countries are also dependent on external funding sources to maintain their so-called District Health Information Software (DHIS2) and to regularly conduct Demographic and Health Surveys. The sustainability of this data collection is under threat due to budget cuts (Khaki et al, 2025). Further, impact data often have a short-term focus (first order impacts), neglecting longer-term path-dependencies (second order impacts) that, in turn, may further amplify vulnerabilities or maladaptive policies (Sirenko et al., 2026b). As a result, adaptive or maladaptive changes may go unnoticed until a new disaster reveals them (Simpson et al., 2021; De Ruiter and van Loon, 2022). Even then, we still face challenges in learning from past disasters. Traditional disaster forensic analysis techniques (such as FORIN, PERC (Ferreira et al., 2023)) have historically emphasised examining a single focal event and its immediate drivers, rather than fully unpacking cascading, compound, or interacting events over extended temporal and spatial scales. Each disaster produces rich data (satellite imagery, sensor records, official reports, social media, etc.). AI-

techniques, such as deep learning, can be used to extract damage data from remote sensing data (Valentijn et al., 2020), and LLMs to extract impact data from newspapers (Sodoge et al., 2023). But this information, extracted from one big data type, is seldom systematically and holistically codified for future use (Feng et al., 2022; van Maanen et al 2025). As a result, valuable insights about cascading impacts, the performance of risk reduction measures, or unexpected vulnerabilities are left unobserved.

Why does it matter for CRM?

CRM requires understanding how risks evolve, interact, and cascade over time and space. In practice, siloisation, incompatible data standards, and stale information flows become ‘critical issues’ that hinder preparedness and response (Migliorini et al., 2019). For example, agencies may have detailed flood maps at high resolution but lack matching census-based data on vulnerable populations in the same area, so that risk drivers in one system cannot be linked to the other. Nature-based solutions aimed at reducing the risk of floods or extreme heat, such as blue and green roofs or wadis, can have opposing effects on the risk of disease outbreaks as they create breeding grounds for mosquitos carrying vector-borne diseases in cities (Boas Berg, 2018, Sikkema and Koopmans, 2026). Besides, the way people perceive risks and their motivation to mitigate and manage the risks can vary from region to region, and with different cultural contexts. The result is an evidence base that is partial and inconsistent, informing decisions in isolation rather than as interconnected pieces of risk. Additionally, spatial mismatches can lead to resource misallocation. For example, flood defences may be built based on national-scale models that overlook an informal settlement’s drainage problems, thereby increasing flood and disease risk there (Tilloy et al., 2019) or on social vulnerability indices or local values and identities (Savelberg et al., 2025). Temporal misalignment means we cannot reliably observe how risk is changing or whether resilience gains (or losses) have occurred in the past. As a result, adaptive or maladaptive changes may go unnoticed until a new disaster reveals them, leading to a lack of adaptive learning. This gap means that warning systems, design standards, and policies adapt only slowly; ‘lessons learned’ are often rediscovered after each crisis instead of being embedded in advance.

Ways forward

As emphasised by international data initiatives, such as the Strategic Framework on Geospatial Information and Services for Disasters from UN-GGIM, and the Global Disaster-Related Statistics Framework (G-DRSF), bringing disparate streams together can unlock synergies across disciplines and sectors in terms of our ability to observe changes in risk and its underlying drivers. To achieve this, integrated data platforms, such as UNDRR’s DELTA Resilience (previously Sendai Desinventar), UN OCHAs Humanitarian Data Exchange, and EUs DRKMC Risk Data Hub, and standardised data protocols are essential. By adopting common data schemas and open standards, this could allow for interoperability between different data types, such as earth-observation layers, sensor data, census records, and community surveys.

For example, addressing spatial and temporal scale mismatches can be achieved by recording new events by using WMO’s Cataloguing of Hazardous Event unique identifier, allowing close mapping with DesInventar Sendai-derived impact data structures, linking continued advances in satellite and drone mapping, with participatory mapping initiatives where communities collect data on housing quality, livelihoods, or hazard events. For example, combining frequent earth-

observation time series (e.g. satellite imagery, weather data) with routinely collected population data (mobile phone records, utility usage, social media) can provide near-real-time proxies for exposure and vulnerability. To understand how risk and its underlying drivers change over time, we need more focus on conducting longitudinal and cohort studies that track how exposure, vulnerability, and human behaviour evolve in the face of multi-hazards. For example, longitudinal studies on flood risk have helped to understand changes in risk reduction behaviour in Germany (e.g. Hudson et al., 2020), and long-term studies combining landscape level associations between birds, mosquitoes, and microclimates have allowed us to get a better understanding of the non-random spatial distribution and cascading effects of mosquito-borne disease outbreaks (Krol et al., 2024). Dedicated national, regional, and local poll data are needed to track people's risk perceptions and motivations to take measures, as well as whether they did actually take measures; perceived risk contamination and willingness to wear masks and get vaccinated throughout COVID-19 outburst is just one example - such public opinion measures would need to be done in a more structured and organised way.

Moreover, we need to better learn from multi-risk events in real-time as they unfold through forensic analyses post-event (UNDRR, 2025). By combining near-real-time remote sensing and other big data sources, such as social media, mobile operator data or emergency data, with Post-Disaster Needs Assessments and other secondary data, we can track the cascading effects of these events and monitor recovery over time. A concerted effort over time would enable the systematic analysis of trends and outliers across crises. This information could also be used to allow us to better anticipate and prepare for future crises before they happen, for example using counterfactual studies. For example, in climate sciences the concept of climate storylines has become popular over the last decade (Shepherd et al., 2018; Sillmann et al., 2021; Cocuccioni et al., 2025). Climate storylines refer to “physically self-consistent unfolding of past events, or of plausible future events or pathways” (Shepherd et al., 2018), and they have recently been extended to the multi-risk context by Crummy et al. (2025), but more exploration could unlock their potential.

To complement such probabilistic approaches, multi-hazard and multi-risk storylines offer an alternative by focusing on plausibility rather than probability, building on the concept of climate storylines (e.g. Shepherd et al., 2018; Sillmann et al., 2021). MYRIADEU has developed an approach to storylines that explores cause-and-effect relationships in multi-hazard and multi-risk systems (Crummy et al., 2025). Drawing on past events for context, MYRIAD-EU explored the application of storylines to support multi-hazard decision-making through co-creation and iterative exploration (Crummy et al., 2025; Casartelli et al., 2025b). This approach supports understanding of complex events and the development of forward-looking decision pathways in the Pilot regions (Sect. 2.4 and 2.5). The development of storylines supports a holistic examination of cascading effects, critical thresholds and emerging risks (Cocuccioni et al., 2025).

2.2 Incomplete understanding of actor decision-making within a multi-hazard context

Challenges

Despite large progress in the last few decades on the understanding of perception, evaluation, and behavioural responses to various risks, we have limited understanding on why individuals, communities, and other decision actors prepare for and

245 respond to complex multi-risks in the way they do. Across psychology, sociology, economics, policy studies, and other related fields, rich sets of theory have emerged that conceptualise people's decisions under risk and uncertainty (Kuhlicke, et al., 2023), building on seminal theories in economics and the decision and behavioural sciences developed in the early and mid-20th century, such as Expected Utility Theory (von Neumann and Morgenstern, 1947), Prospect Theory (e.g., Kahnemann and Tversky, 1979), Theory of Planned Behaviour (Ajzen, 1991) and Protection Motivation Theory (Rogers, 250 1975; Wachinger et al. 2013). Importantly, all theories stress the link between uncertain, delayed, or risky information and behaviour or action. More recent extensions stress the links of informational and social networks (Kim and Hastak, 2018). Empirical work has further complemented these theoretical and conceptual developments with meta-analyses, surveys, and field experiments (van Valkengoed and Steg, 2019, Noll et al, 2022, Noll et al., 2023). In parallel, a proliferation of digital and simulation methods increasingly use these theoretical and conceptual developments to analyse long-term dynamics of 255 actors exposed to a specific risk, including the behavioural choices that shape their resilience (Haer et al., 2019, Taberna et al., 2023a, Sauer et al., 2025).

However, existing theoretical and conceptual developments fall short in three ways. First, theories have often been developed within single-hazard landscapes. Existing theories typically focus on one-time choices (e.g. Protection Motivation Theory). Yet, decision-making processes may differ for a single versus multi-hazard risk context. This may result in 260 suboptimal (or even maladaptive) behaviour (Magnan et al. 2016, Eusse-Villa et al., 2024, Sirenko et al., 2026a). For instance, if households are exposed to frequent floods (with lower impact) as well as infrequent earthquakes (with higher impacts), they may be biased towards using their scarce resources to cope with and prepare for flood impacts, rather than earthquakes. However, experiences with one risk may also raise awareness about the other types of risks (see e.g. Sullivan-Wiley and Gianotti, 2017). For instance, households that are well adjusted to one type of risk (e.g., extreme rainfall), may be 265 better prepared for other lower probability risks (e.g., cyclones). In a similar fashion, people, firms and other actors are increasingly exposed to indirect risk impact channels, so-called systemic risks. For example, droughts elsewhere may affect food prices, affecting the purchasing power of households (Hill and Porter, 2017), flooding of firms may impact the supply of goods to firms downstream in the supply-chain (Koks et al., 2019), and flood-induced disease outbreaks and associated breakdown of health systems can significantly impact health outcomes (Leppold et al., 2022, Sairam and De Ruiter, 2026). 270 How actors perceive such risks and form expectations about their impacts is likely different from risks materialising locally (Miller et al., 2024). This may introduce perception bias and reduced salience to address such risks. Taken together, how well existing theories and conceptual understandings 'perform' within multi-risk and systemic risk contexts remains unclear. Second, the empirical grounding of aforementioned theories and conceptual framework across different geographical and cultural contexts has been limited within a multi-risk context, with little systematic comparative research across different 275 settings (Noll et al, 2021). As a result, it remains unclear which behavioural responses are context-specific and which reflect more general drivers, constraining the transferability and robustness of existing theories. For instance, risk theories increasingly recognise that actors do not make decisions in isolation, but form expectations about the behaviour of others and adjust their own actions accordingly (MacGillivray, 2018, van Valkengoed and Steg, 2019, Choquette-Levy et al., 2024, Hao

and Peng, 2026). This points to the importance of prevailing social networks and social norms (MacGillivray 2018). Yet, there is limited theoretical understanding of how expectations about the behaviour of institutions, organisations, and actors beyond the local community shape individual and collective risk behaviour over time (Taberna et al., 2023b), especially in a multi-risk context.

Third, while most theoretical frameworks acknowledge the importance of long-term feedback loops and learning processes (Kuhlicke, et al., 2023), most empirical analyses often only capture a single snapshot moment. As a result, existing analyses provide limited insight into how learning from risk unfolds unevenly across social groups (Arcaya et al., 2020), and how repeated exposure to changing hazards and differential access to information, resources, and influence shape divergent risk trajectories over time (Sauer et al., 2025). It also neglects important feedback loops between behaviour and risk perception; for example, in theory, high risk perception may encourage adaptive responses, and resulting protective behaviour may result in lower risk perception, and one could theorise more such feedback loops based on models that exist (van Valkengoed et al., 2025). Current literature is unable to verify such hypotheses, because of the lack of longitudinal data and the lack of theoretical and empirical base on long-term development and interactions between the key constructs related to risk perceptions and behaviours. Longitudinal studies that monitor risk perception and behaviour over time are needed to identify such feedback loops.

Why does it matter for CRM?

Understanding how different actors prepare for and respond to complex multi-risks is key for CRM. However, the current theoretical limitations are increasingly problematic in contemporary risk landscapes characterised by multi-hazards, interdependencies, increasing proliferation of digital technologies, and rapid socio-environmental and political change. Actors are now routinely affected by a multitude of risks that unfold across spatial and temporal scales, involve indirect exposure, and are shaped by the behaviour of others far beyond their immediate context. As a result, there is a growing mismatch between the complexity of real-world risk environments and the conceptual and empirical assessment tools available to understand and model actor behaviour within them. Consequently, existing CRM approaches, underpinned by quantitative and qualitative assessments based on these theories, often fail to account for this complex nature of multi-risks, resulting in potentially ineffective and/or maladaptive decisions.

Ways forward

To overcome the aforementioned research gaps, we propose two ways to move the research agenda forward. First, by making use of longitudinal survey data, as also described in Sect. 2.1. Using data from high-frequency, yet longitudinal surveys could help us to better understand the dynamic feedback and learning processes, not just across contexts and hazards but also across alternative socio-behavioural assumptions. Moreover, such datasets would help test and validate how a multi-risk context shapes risk perception and decision-making processes at different levels.

Second, research must move beyond theories grounded primarily in well-resourced settings and limited hazard types. Progress requires systematic comparative studies that examine how expectations, social interdependence, power, and learning unfold across diverse hazards, institutional arrangements, and socio-economic contexts, particularly where impacts

are most severe. Linking pre-event social and institutional conditions to post-event behavioural and risk outcomes across multiple cases is essential to test mechanisms rather than assume them. Such comparative, longitudinal evidence would enable the development of generalisable theories on disaster risk decisions that distinguish context-specific dynamics from general processes shaping preparedness, coping, and long-term adaptation under unequal and repeated hazards. The importance of better understanding the root drivers by better integrating social science knowledge is being taken up by UNDRR. For example, its *Global Assessment Report Special Report 2024* (UNDRR, 2024) focused on how forensic insights from past disasters can shape future resilience. An example at project-level of bridging this divide is the UNITY project, which has the goal to develop an integrated assessment framework for pandemic preparedness and response in which biomedical, societal and economical perspectives are brought together to provide actionable, evidence-based advice for policymakers.

2.3 Simulating risk

Challenges

As a result of these multi-risk observation and understanding challenges, as well as further conceptual and computational challenges, our capacity to simulate how both current and future risk could be effectively reduced is hampered. Some advances have been made in recent years in moving from single hazard-risk simulation to multiple hazard-risk simulation, whereby the risk of a system to a range of different individual hazards is assessed (e.g. Koks et al., 2019; Verschuur et al., 2024). However, even in these cases the simulation of biological hazards that cause infectious diseases is generally missing (Tilloy et al., 2019; Mazdiyasni and AghaKouchak, 2020), despite explicit calls to include them and their impacts from UNDRR and WHO (Sairam and De Ruiter, 2025). Where multiple hazard assessments exist, they tend to focus on one impact pathway, such as direct property damages or infrastructure disruptions (e.g. Koks et al., 2019; Verschuur et al., 2024), in isolation, with limited consideration of their interactions. However, these impact pathways come together at the actor level (e.g. individuals, firms, governments, etc), where multiple impact pathways may amplify each other. However, advances towards true multi-risk simulations are limited. In particular, in recent years, international organisations such as the UNDRR and WHO have encouraged scientists to expand their disaster risk models by including disease outbreaks and health elements (Sairam and De Ruiter, 2025). Health impacts, in particular, are complex and produce heterogeneous outcomes at the individual level, necessitating risk reduction measures tailored to specific times, places, and contexts. Mental and social health outcomes are particularly difficult to capture and measure, while their effects on societies as a whole can be very damaging, adverse, and long-lived. As such, capturing and simulating these dynamics is essential for building a systemic understanding of disaster–disease outbreak interactions and their health consequences. Although the SFDRR (UNDRR, 2025) recognises the importance of health-related outcomes, they are still rarely integrated into risk simulations (Mazdiyasni and AghaKouchak, 2020; Tilloy et al., 2019).

A major gap is in our ability to incorporate vulnerability dynamics into our risk simulations (Hagenlocher et al., 2019; Simpson et al., 2021; Drakes and Tate, 2022). Here, we refer to changes in vulnerability in both space and time. Following

De Ruiter and Van Loon (2022), these could be either: (1) underlying dynamics of vulnerability; (2) changes in vulnerability during long-lasting disasters, and (3) changes in vulnerability during compounding disasters. Even for single hazard risk simulations, a review of large-scale risk models by Ward et al. (2020) showed that vulnerability was either excluded in most studies or included in a highly stylised way. Of the ~70 studies reviewed, only 2 included dynamic vulnerability. Over the last decade some advances have been made in including dynamic vulnerability at more local scales for single hazards. For example, a review of research on flood vulnerability by Schlumberger et al. (2026) finds that several studies have done this using an agent-based modelling approach, with a few others using systems dynamics modelling. However, an ongoing review being performed as part of the MYRIAD-EU project finds very little research that includes vulnerability dynamics in multi-hazard simulations. Vulnerability dynamics are difficult to capture, as vulnerability itself is often shaped by feedbacks between experience of, and adaptation to, previous hazards (De Ruiter and Van Loon, 2022). Yet, especially prolonged crises such as the Covid19 pandemic will likely lead to behavioural adaptation or maladaptation during the response (Champlin et al., 2023; Raju et al., 2024; Sirenko et al., 2026a). Also, the specific vulnerabilities between different groups in society can lead to unequal levels and pathways of impacts and recovery (Haer and De Ruiter, 2024). Moreover, socio-psychological factors are important in determining public acceptance of risk management measures (van Valkengoed et al., 2025). Nonetheless, in simulation models these aspects are ignored or represented in a highly aggregated manner, constraining the models' capacity to reflect adaptive decision-making, social heterogeneity, and feedbacks between human behaviour and the environment (Aerts et al., 2020), potentially leaving out those marginalised and vulnerable communities that face the highest risks.

A further challenge is model validation. Validation of disaster risk simulation output is still underappreciated, which is also constrained by the fact that most validation data are still collected in terms of aggregate numbers, with limited spatial detail. In reality, disasters are inherently local processes, with impacts taking place at the local scale, and therefore locally-relevant data are fundamental (Davies and Davies, 2018) for validating our models and allowing them to be used for strengthening community resilience. The lack of validation data is holding back further developments. This is particularly critical for low-probability, high-impact hazard events, which may intensify under climate change, yet lack sufficient data for accurate modelling and local-scale validation.

Why does it matter for CRM?

CRM depends on understanding how risks accumulate, interact, and evolve across hazards, space, time, and sectors. Simplified models that do not account for these complexities can under- or over-estimate multi-risk, which could potentially lead to maladaptive responses. Health impacts, in particular, are complex and produce heterogeneous outcomes at the individual level, necessitating risk reduction measures tailored to specific times, places, and contexts (Sairam and De Ruiter, 2026). Moreover, our lack of data for training and validating the results of simulations holds back our ability to trust model results. This is particularly critical for low-probability, high-impact hazard events, which may intensify under climate change (e.g. Sun et al., 2025). Without validated models that account for the complexities of multi-risk, we cannot test risk reduction strategies under compounding and cascading risks - or detect maladaptation before it locks in.

We propose a research shift towards simulations that include multiple hazards and their interactions, and also the dynamic interactions with exposure and vulnerability across time, while accounting for different societal groups. This includes broadening the scope of analysis to include dimensions such as physical vulnerability, social vulnerability, health vulnerability, and resilience, and agency/coping potential. This would require merging data from multiple sources, in order
 385 to understand how they interact in the real-world, as also discussed in Sect. 2.2. We also see opportunities for model validation by harnessing the datasets called for in Sect. 2.1.

Modelling the dynamics and feedback between hazards and humans requires approaches that explicitly simulate feedback between human decisions and changing risk. Examples include system-dynamic models that use stylised decision rules to represent adaptation over time (e.g. Barendrecht et al., 2017) or agent-based models that represent individual agents (e.g.
 390 individuals, households, firms, governments) interacting with each other and with the physical environment (e.g. Aerts et al., 2020). In these models, decision rules can be parameterised with survey data and socio-economic indicators to capture how behavioural tendencies and social constraints shape adaptation outcomes. Large advances have been made in applying ABMs to single hazard contexts in recent years (e.g. floods (see Aerts, 2020; Anshuka et al., 2022), droughts (see Alam et al., 2022; Streefkerk et al., 2023) and outbreak response (see Vermeulen et al., 2021, De la Paz-Ruiz et al., 2025), yet there
 395 has been little progress in a multi-hazard or multi-risk context. Moreover, it is important to include socio-psychological factors in these models in order to more accurately and realistically assess risk management potential (Van Valkengoed et al., 2025).

A challenge is that simulating these interlinked processes at large scales yet high granularity requires a solid empirical foundation; this applies to all of the aforementioned dimensions, including the physical and socioeconomic processes, as
 400 well as socio-psychological aspects relating to behaviour and perception. In addition, it is computationally demanding, but advances in high-performance computing (Leijnse et al., 2021) and the integration of human decision-making into hazard models are making it increasingly feasible (de Bruijn et al., 2023, Feng et al., 2020, Liang et al., 2025).

2.4 Fragmented and insufficiently adaptive governance

Challenges

405 Underlying the issues around fragmentation and actionability of multi-risk datasets, models, and theories are fundamental governance dilemmas that influence how the management of risks are understood, financed, and acted upon. The complex interdependencies arising from multi-risks amplify existing normative challenges faced by institutions (Šakić Trogrlić et al., 2024), with fragmented responsibilities making it harder to clarify ‘who is responsible’ (Padilla et al., 2021; Liu et al., 2025). In fact, different mandates may overlap, or it may not be specified which institutions are responsible when risks interact
 410 (Alcántara-Ayala, 2025). An increasingly urgent question relates to citizens’ own capacity and willingness to mitigate and deal with multi-risks, as established institutions may no longer guarantee the same security in the face of cascading risks (e.g., insurance companies stopping insuring homes in areas prone to climate change risks). Moreover, public and/or

community participation so far has limited structural and institutional embedding in multi-risk governance. Even where advisory groups (Baxter, 2019), participatory governance mechanisms (Barquet et al., 2017; Barton et al., 2020; Bierens, et al., 2020), and community-engaged risk management processes including living labs (Boersma et al., 2022) and citizen observatories (e.g. Cobweb,¹ Safecast²) have emerged, they often suffer from limitations owing to semi-formalisation, as well as administrative, financial, and sectoral barriers. Additionally, political and budgetary cycles favour short term actions making it difficult to incentivise (and hold accountable) institutions for long term multi-risk funding and planning.

At the operational level, disaster governance systems and institutions are frequently organised in isolated pillars, preventing the pooling of knowledge and resources, hindering collaboration and slowing down decision-making (Christensen et al., 2016; De Boer et al., 2025); this is worsened in the multi-risk context. This siloing results in a lack of coordination and decision-making mechanisms, both across government levels and between state and non-state actors (Lane and Hesselman, 2017; Meriläinen et al., 2020). Mechanisms of exclusion, political constraints, the absence of co-ownership, and the lack of collective sensemaking can further create constraints to collaboration (Wolbers and Boersma, 2013; Mizutori, 2020). Equally challenging is the separation between formal and informal practices, and between normative frameworks for disaster governance and everyday coping mechanisms (Hilhorst et al., 2020). More public participation in decision-making processes has been advocated in environmental governance (e.g., Beierle & Cayford, 2002) and climate policy making (e.g., Willis et al., 2022), but its role and expected impacts in risk governance in particular demands further attention. Another crucial issue is the growing need for improved data governance. As highlighted earlier in this paper, domain specific institutions and agencies are often fine-tuned to produce and use data to address specific risks/hazards, and therefore encounter political, technical and methodological, and legal barriers to accessing, using, and sharing data for creating robust multi-risk datasets (Fischer-Preßler et al., 2024; Claassen et al., 2023; Clark, 2017). This includes a lack of interconnections between actors due to the nature of the datasets (in terms of composition, storage, and usage), as well as organisational and bureaucratic constraints such as specific mandates. Other issues relate to power asymmetries, legitimacy, accountability, accessibility, sensitive information, and funding (dis-)advantages (Lentz et al., 2022). Integration of social sciences variables in datasets and models dominated by technocratic and cost-effectiveness-led approaches is urgently needed but remains challenging (Trutnevyte et al., 2019; van Valkengoed et al., 2025).

Lastly, integrating multi-risk approaches into organisational protocols and routines requires adaptive and transformative changes to the cultures and structures of disaster management authorities and institutions. Here we refer to impactful ways of learning to address the complexities of ‘wicked’ problems - that is problems with no definitive solution owing to their complex interconnected, evolving, or contested nature (Termeer et al., 2019; Van den Ende et al., 2023). This is a major challenge: on the one hand disaster management institutions are constrained by institutional norms and environments, and on the other hand they lack the capacities (e.g. time, resources, authority, knowledge, funding) to invest in learning processes

¹ <https://www.ogc.org/initiatives/cobweb/>

² <https://safecast.org/>

that lead to meaningful changes. Besides, risk mitigation and management measures can face public resistance if citizens feel that decisions are made top-down, without a real possibility for citizens to take part in decision making. Innovative forms of public engagement are increasing, with citizen climate assemblies being a prominent example (Lorenzoni et al., 2025), providing a potentially interesting test bed for engaging citizens in decisions on multi-risk governance.

Why does it matter for CRM?

CRM depends on governance systems that can anticipate interacting risks; coordinate actions across domains and levels; and learn and adapt over time. Fragmented governance leads to unclear responsibilities and accountability when risks interact, duplication of efforts and gaps in preparedness and response, and loss of trust, legitimacy, and compliance. Without adaptive and inclusive governance, even good data, understanding, and models may fail to translate into effective and equitable risk reduction. The Sendai Framework highlights the importance of strengthening disaster risk governance to manage disaster risk, with this being one of its four Priorities for Action. Recent scholarly work increasingly points to framing disaster governance as the broader framework that shapes how risk is understood, financed, and acted upon (Djalante and Lassa, 2019; Hilhorst et al., 2020; Mizutori, 2020). This is essential, as it moves beyond the traditional framing of risk around the ‘disaster cycle’, i.e. prevention and preparedness before a crisis, response once an event unfolds, and recovery and reconstruction in its aftermath (Khan et al., 2008) as it is increasingly recognised that these phases blur in practice (Sawalha, 2020; Waseem and Rana, 2025). Citizen engagement in risk governance needs to be explicitly considered and enacted in a more professional and evidence-based manner than one-off attempts without formal mandate. Engagement of local communities in decision making might not only facilitate better-quality decisions but also strengthen community identity and resilience (Davies, 2015); yet such attempts need to be better documented, and their effects better monitored and shared across sectors and disciplines.

Ways forward

A promising framework to address these governance challenges is the poly-centric governance approach (Djalante et al., 2011; Berardo et al., 2016), which emphasises the importance of interconnection among diverse stakeholders and systems in complex risk environments. It calls for adaptive, networked, and inclusive governance approaches to bridge institutional gaps, integrate diverse forms of knowledge and practice, and build trust across actors (Comfort et al., 2010). This means investigating innovative approaches for streamlining bureaucratic procedures, fostering meaningful cross-sectoral collaboration with delineations of boundaries and responsibilities, and creating hybrid governance arrangements that can function in fragile, complex, and uncertain contexts.

The poly-centric approach is also useful for understanding how participatory and net-centric (i.e. a management approach built on a robust, interconnected network of people, processes, and technology) governance principles may support coordination, information-sharing, and collective decision-making among diverse stakeholders (Carlisle and Gruby, 2019; Morrison et al., 2023). Netcentric-governance seeks to strengthen self-organising networks that are supported by shared organisational infrastructures, enabling vertical and horizontal distribution of authority across local, provincial, national, supranational, and global levels of government. As it includes state actors, established and emerging response organisations

and societal groups and grassroots movements, the approach also answers growing calls for an ‘all-of-society’ approach to disaster governance (UNDRR, 2019; Clark et al., 2025). Moreover, the net-centric dimensions of poly-centric governance emphasise the importance of supporting digital infrastructures and architectures (Jones and Thompson, 2007; Boersma et al., 2012; Wolbers, et al., 2023). Such an approach highlights both the technical requirements for data interoperability and the political, legal, and organisational dimensions of sharing information across institutional boundaries. Besides, new forms of direct public participation in decision making (e.g. citizen assemblies) and their role in multi-risk governance need to be investigated, and there is a need for a critical analysis of possible exclusion in governance of marginalised groups who may also be most vulnerable (e.g. indigenous communities). By its nature, a poly-centric governance approach requires learning across and within sectors and disciplines, which enables institutions to exchange knowledge and co-create instruments/solutions for addressing complex and wicked problems. This means investigating and investing in new methods of learning that facilitate transformational pathways towards meaningful and impactful change.

2.5 Barriers in knowledge exchange at the science, policy and practice interface

Challenges

The aforementioned science challenges reveal that the management of multi-risks is a complex problem. A further challenge focuses on how knowledge is produced, integrated, and mobilised across science, policy, and practice. Fragmentation of knowledge systems and siloed structures hinders disaster management at all phases. Advisory and response architectures are often discipline-centric and sectoral, impeding timely integration of contextual knowledge from social, economic and behavioural sciences with natural and biomedical sciences. For example, during COVID-19 in the Netherlands, biomedical expertise provided by the Outbreak Management Team dominated scientific advice in the initial phases; while social and economic perspectives were added later in parallel structures, such as the Social Impact Team. This risks reinforcing rather than resolving compartmentalisation and potentially weakening the capacity for coordinated response (Jasanoff et al., 2021; OvV, 2023).

Asymmetries of power and representation are often evident in the production and uptake of policy- and practice-relevant knowledge. Internationally visible research from WEIRD (Western, Educated, Industrialized, Rich, Democratic) (Henrich et al., 2010) contexts with quantitative evidence tends to travel more readily into policy, while locally grounded perspectives and tacit knowledge remain under-represented, reinforcing epistemic injustices (Garcia Alvarez, 2024). Along with under-representation of social sciences and humanities, these lead to blind spots, particularly on underrepresented and marginalised groups (Brown et al., 2023; Anthonj et al., 2024, 2025). Despite calls for meaningful participation and the recognition of diverse epistemologies, such as the Grand Bargain (2016) and the Disaster Studies Manifesto (2020), many study designs still default to extractive models and narrow metrics and require more inclusive approaches (Eelaferi et al., 2022a). Power imbalances also appear in research funding, where donor priorities can skew attention away from locally salient risks and under-represented voices (Eelaferi et al., 2022b, Turnhout, 2024). Under-represented voices can be captured through, for example, locally grounded accounts of hazard exposure, coping capacities, risk perceptions, lived experiences of cascading

impacts, informal support mechanisms and collective action, and community-defined priorities that are often absent from conventional datasets. Formats for expression can vary depending on the under-represented group, context and location, and could include tacit knowledge dimensions, video, photo, and visual accounts (Anthonj et al., 2025). Evaluation of data in integrated risk assessments should go beyond statistical representativeness and empirical validity. There is a need for openness, transparent, contextually relevant triangulation and transferability.

Even when relevant actors are ‘in the room’, science-policy-practice integration can falter due to limited epistemic fluency, i.e. the capacity to translate and integrate heterogeneous knowledge (Star and Griesemer, 1989; Waltz et al. 2025). Knowledge translation is often treated as linear dissemination from science to society, rather than dialogue and co-production with stakeholders. Public participation, if any, is typically restricted to information provision (e.g., from the government to citizens) and/or citizen science (citizens as data sources, not co-deciders). Moreover, co-location of disciplines does not in itself lead to knowledge integration, as institutional logics, evaluation regimes, and disciplinary norms continue to structure interaction (Silvast and Foulds, 2022). Explicit frameworks to facilitate this exchange and integrate different disciplinary perspectives to form science advice during a crisis are limited, unevenly used, and rarely evaluated within advisory routines and decision cycles. Broad evidence-to-decision frameworks such as WHO-Integrate exist (Rehfuess et al., 2019), but their use for integrating biomedical, social and economic evidence in national pandemic scenarios remains limited (Waltz et al. 2025). There is a need for systematic tools that facilitate interdisciplinary deliberation and integration of knowledge, supported by robust data infrastructures. Continuous reflection and learning need to be an inherent part of frameworks for their adaptability to the variety of multi-risk cases and contexts, to ensure their operationalisation and usefulness during time and resource constraints of crisis times.

Why does it matter for CRM?

Across cases and literatures, this fragmentation, power/representation asymmetries, limited epistemic fluency, and missing integrative frameworks interact to produce a self-reinforcing system: siloed institutions and funding logics shape what kind of knowledge is produced and heard; under-representation and data biases limit contextual fit; absence of collaborative spaces hamper shared problem framing; and the scarcity of embedded, evaluated integration tools prevents learning-by-doing. Taken together, these mechanisms constitute a coupled-systems failure: institutions ask for integrative, use-oriented knowledge while the research and innovation system is not yet organised to supply it at the right times and scales (Kok et al., 2019). CRM depends on timely, credible, and legitimate knowledge across disaster preparedness, early warning, response, and recovery; between multiple hazards; and across interacting sectors. Weak science-policy-practice linkages can lead to: delayed or unbalanced advice during crises; limited uptake of evidence in planning and adaptation; and reduced public trust and compliance. Without this effective integration, risk management may inadvertently risk reinforcing existing inequalities and blind spots.

Ways forward

Therefore, effective and comprehensive multi-risk management depends on: (1) holistic integration of knowledge from multiple scientific disciplines, and policy and practice fields; (2) sustained collaboration among science, policy, practice,

545 affected communities, and society at large; and (3) iterative learning that adapts to context and uncertainty. This is consistent with the WHO Health Emergency and Disaster Risk Management Framework and the Sendai Framework’s emphasis on multi-hazard, multisectoral and inclusive approaches where communities should be in the driving seat (WHO, 2019; UNDRR, 2023).

To achieve this requires the adoption of systems approaches for the complex problem of multi-risk management, which transform the problem and solution domains together. An important question to be addressed is how different elements in science, policy and practice are reproducing systemic persistent challenges in DRM. We also need to embed co-production and participation throughout the research and innovation cycle, fostering responsible research and innovation. This entails building upon local knowledge, which could lead to far greater insights towards solving complex problems. To achieve this it is important to address the barriers and enablers for involving citizens and other stakeholders in science for DRM, when covering different hazards and sectors.

We also need to strengthen knowledge integration and translation mechanisms. Established knowledge translation frameworks emphasise iterative engagement, contextualisation, and co-learning (Graham et al., 2006; van Kerkhoff and Lebel, 2006; Spiekermann et al., 2015), yet in practice DRM projects often underinvest in early and sustained engagement that enable shared problem framing and the use of boundary objects (e.g. participatory maps, outbreak scenarios, serious games, photovoice) that enable shared problem framing.

Finally, we need to institutionalise reflection and learning within advisory and response systems. To achieve this we need more research to understand how knowledge can be integrated for providing scientific advice during crises, including how science collaborates with policy and practice while maintaining its independence.

3 Outlook

565 The examples presented in this paper demonstrate that scientific understanding must evolve to keep pace with the complex ways in which risks interact and advance the science beyond studying multi-hazard interactions. What happened in the Haiti example in 2021, described at the start of the paper, demonstrates the need for comprehensive, high-quality data not only on multi-hazards but also on multi-risks. The data should go beyond hazards themselves and include information on how these hazards affect non-hazard drivers and how those drivers, in turn, shape preparedness and response. The challenge is not a complete absence of data; rather, the data that does exist are fragmented, inconsistent, scattered, and owned by various bodies, making it difficult to build the integrated, multi-risk analysis required. Therefore, theory development tends to follow the availability of data and is consequently constrained in scope. Modelling of the reality depends fundamentally on data quality and understanding, while data governance structures often create barriers to integrating the diverse datasets required for comprehensive analysis. The transboundary impact of such an event, like in the Haiti example, highlights challenges in multi-risk governance. System interdependencies generate forms of multi-level governance that are often weakened by limited coordination among agencies, institutions or disciplinary silos, fragmentation of responsibilities and uneven resource

allocation. As a result, governance structures struggle to address cascading and interacting risks effectively. This, in turn, draws attention to the science-policy interface, where short-term political priorities frequently conflict with the long-term path-dependent nature of development and management of risk.

580 We envisage a number of core activities that could help us to bridge these challenges, building on the ways forward discussed above.

First, we envisage a Disaster Risk Observatory, designed to integrate diverse data streams - ranging from satellite imagery and national census data to interviews and focus groups, surveys, and disaster forensics - to systematically observe and quantify the dynamics of disaster risk across both time and space. This observatory should be a living system that evolves
585 with each disaster, each data point, and each human experience it captures. Important elements include longitudinal studies that track how exposure and vulnerability change over time; and identifying and studying major disasters as they unfold globally, in order to gather a real-time stream of information allowing us to construct dynamic, spatiotemporal impact chains that not only describe what happened but also provide insight into how and why impacts unfolded the way they did.

Second, we envisage using these improved observations, complemented with the myriad of observations that we already
590 have, to better understand how and why human risk behaviour evolves in the face of spatiotemporally dynamic changes in, and interactions between, hazards, exposure, and vulnerability. This requires developing a new generation of theories for risk behaviour that draws from different disciplines and explicitly incorporates learning processes and feedback loops, interdependencies, and systemic perspectives.

Third, we envisage using these improved observations and understanding to develop novel integrative modelling frameworks
595 that allow us to capture dynamic interactions between human behaviour and their biophysical and socioeconomic environments. For this, we see a value of developing agent-based modelling approaches, which allow us to better understand how risk may change in the future and how we can reduce both current and future risk by taking DRR measures, while accounting for complex feedbacks and interactions over time, space, sectors, and different groups of society. Moreover, such models should be able to be better validated by ingesting the improved observations mentioned above. Such an integrative
600 modelling framework should be regionally applicable and globally scalable, meaning that it is optimised with local data and experiences in target regions, but can be globally scaled using global datasets.

Fourth, we envisage a poly-centric governance approach for the sharing, coordination, and use of actionable multi-risk datasets, models, and concepts, with particular attention to collective sensemaking by formal authorities, crisis managers (both from state and non-state actors), and members from affected or threatened communities. Adequate poly-centric
605 governance could support the interconnection between actors across governance levels and sectors, and foster shared cognitive understanding of risk and disaster situations. Hence, such an approach should be based on a thorough research into - and understanding of - the underlying principles for participatory, coordinated, and equitable disaster and climate governance and risk management in increasingly complex multi-risk environments.

Fifth, we envisage approaches that allow us to better understand and strengthen how scientific knowledge, data, and models
610 become actionable in multi-risk contexts, by studying the dynamics of the science-policy-practice interface itself as a

coupled-system phenomenon across hazards, scales, and case settings. This should be able to bring together the aforementioned elements, providing the connective tissue linking actionable observations, improved theoretical understanding, dynamic modelling, and adaptive governance. This includes developing protocols to stimulate the operationalisation of citizen science approaches in multi-risk research based on good practices; context specific system analysis; context specific serious games, simulations and other boundary innovations to stimulate knowledge translation; mechanisms for effective living labs / learning societies for stimulation of knowledge translation; and tools for knowledge integration across actors, disciplines, sectors, and levels, including reflection and learning to make the tools adaptable to changing contexts in time. Apart from these approaches, knowledge brokers and boundary spanners (Williams, 2011) are important. These proactive individuals can span boundaries between sectors, disciplines, and administrative or geographical borders so that actor relationships are strengthened and governance mechanisms navigated to realise joint knowledge, plans or interventions across boundaries (Cumiskey, 2020).

Finally, these challenges are mutually reinforcing: fragmented and static data constrain theory testing and model validation; incomplete behavioural foundations reduce the realism of risk models and interventions; governance fragmentation blocks coordination and trusted data-sharing; and weak science–policy–practice interfaces prevent learning loops that would improve all four. Together, they create a persistent actionability gap for CRM. Therefore, we need to ensure that these challenges are not addressed in isolation. Moreover, several themes run across the various challenges. First and foremost, the topic of siloisation and fragmentation is a persistent issue as documented in much of the multi-risk literature of the past decade. Secondly, there is a need to ensure that multi-risk research is context-specific, whilst still understanding where findings are (or indeed are not) generalisable.

Our paper aims to inspire future research endeavours by bringing together key perspectives from a wide range of relevant disciplines, rather than demonstrating the application of the various aspects. Addressing these cross-cutting challenges requires concerted efforts that go beyond the traditional 1-4 year project cycle. To achieve the paradigm shift towards comprehensive disaster risk management, research efforts require time, resources, collaboration, and the creative space required to truly bridge silos, build trust, study both context-specificity and address generalisability, and engage in a meaningful way with ongoing political agendas such as the Sendai Framework for Disaster Risk Reduction, the WHO Health Emergency and Disaster Risk Management Framework, and the climate change agendas. We call for funding mechanisms that facilitate such a concerted and needed effort.

Code, data, or code and data availability

No code or data were used in this article.

640 **Author contributions**

PJW coordinated and led the writing of the paper. PJW led Section 3 and co-led Section 1 and 2.3; NvM co-led Section 1 and 2.1 and co-led the structuring and writing of the paper; MCdR co-led Section 2.3; AD co-led Section 2.1; JV and TComes co-led Section 2.2; KB, SF, and NC co-led Section 2.4; and TCesuroglu led Section 2.5. All authors contributed to the conceptualisation of the paper, to discussions on the content, and the writing and editing of the paper.

645 **Competing interests**

Some authors are members of the editorial board of Natural Hazards and Earth System Sciences.

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