Natural Hazards Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science

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Key Points:

- Natural hazards pose risks that span across multiple sectors and spatiotemporal scales.
- Effective risk management requires integrated approaches, coordinated processes, open science, and networked efforts.
- The ICON approach brings the scientific community, stakeholders, and decision-makers together in developing equitable and inclusive risk management strategies.

Abstract

This article is composed of one integrated commentary about the state of ICON principles (Goldman et al., 2021) in natural hazards and a discussion on the opportunities and challenges of adopting them. Natural hazards pose risks to society, infrastructure, and the environment. Hazard interactions and their cascading phenomena in space and time can further intensify the impacts. Natural hazards' risks are expected to increase in the future due to climate, demographic, and socioeconomic changes. It is important to quantify and effectively communicate risks to inform the design and implementation of risk mitigation and adaptation strategies. Multihazard multisector risk management poses several nontrivial challenges, including: i) integrated risk assessment, ii) Earth system data-model fusion, iii) uncertainty quantification and communication, and iv) crossing traditional disciplinary boundaries. Here, we review these challenges, highlight current research and operational endeavors, and underscore diverse research opportunities. We emphasize the need for integrated approaches, coordinated processes, open science, and networked efforts for multihazard multisector risk management.

1 Introduction

Natural hazards drive major damages to communities, infrastructure, and ecosystems across the globe. Recent European floods (Cornwall, 2021), wildfires in the United States (Swain, 2021), and drought in South Africa (Pascale et al., 2020) highlight how human and natural systems are exposed and vulnerable to natural hazards. Between 2000 to 2019, natural hazard-related disasters caused over 2 trillion United States (U.S.) dollars in global economic losses and over 1 million deaths worldwide (United Nations Office for Disaster Risk Reduction, 2020). These impacts are expected to rise in the future with coevolving natural and human systems subject to the impacts of multiple hazards, including extreme weather events, sea-level rise, anthropogenic disturbances, and climate change. There is growing recognition of the critical need to improve the understanding and prediction of natural hazards, characterize multihazard multisector risk, and enhance the communication of risk and its associated uncertainties to inform the design of effective risk management strategies (IPCC, 2021).

Multihazard multisector risk management requires a comprehensive understanding of different interacting systems and processes, including the feedback between ecosystems, human systems, and climate systems (Byers et al., 2018; Mora et al., 2018; Piontek et al., 2014). A growing number of scientific studies (Bates et al., 2021; Cook et al., 2018; Hirabayashi et al., 2013; Strömberg, 2007) provide valuable new insights on the potential impacts of a single hazard on a specific sector and in a specific region. However, there is a lack of integrated frameworks, coordinated processes, open science, and networked efforts that can account for the complex interactions across natural and human systems in the context of multiple interacting stresses and over a wide range of spatiotemporal scales (Figure 1).

This commentary highlights the challenges and opportunities for multihazard multisector risk management, acknowledging the pressing need for integrated (I) approaches, coordinated (C) processes, open (O) science, and networked (N) efforts. We discuss the challenges and research opportunities related to i) integrated risk assessment, ii) Earth system data-model fusion, iii) crossing traditional disciplinary boundaries, and iv) uncertainty quantification and communication, and further emphasize the immediate need for ICON science (Goldman et al., 2021).

2 Challenges and Research Opportunities

2.1 Integrated risk assessment

A sound understanding of risk drivers and their dynamic interactions is critical to inform the design of risk management strategies. Quantifying multihazard multisector risk is challenging as it requires the integrated assessment of hazard probabilities, the exposure of people and assets, and the vulnerability or susceptibility to consequent damage. In addition, multihazard risks are dynamic and are modulated by several factors, including climatic conditions, demographic changes, and socioeconomic conditions. Understanding the interactions among the risk drivers is crucial to achieving a comprehensive view of the integrated system. Developing an integrated system requires a priori planning to integrate different components while ensuring open access and interoperability across data types and models.

Earth system modeling efforts are generally focused on understanding the impacts of a single hazard in isolation, emphasizing risk assessment in limited sectors. However, these individual hazards often demonstrate compounding and cascading behaviors, where the resulting multihazard multisector risk becomes increasingly more difficult to be assessed using conventional techniques. Furthermore, the conventional risk assessment techniques are mostly concentrated on predicting hazards instead of the actual risk or impacts. Risk predictability is often limited to decision-making across a range of spatiotemporal scales due to the lack of coordinated databases (Fuchs et al., 2012; Rakhal et al., 2021). Improving the risk prediction capabilities of Earth system models demands networked efforts among the scientific community, stakeholders, and agencies for database development and management with implications to inform mutually beneficial risk mitigation and adaptation strategies. For instance, tropical cyclones, flooding, and landslide risk prediction ahead of sufficient lead time allow risk managers enough time to take necessary steps for preparedness and damage mitigation; whereas the lack of predictability in earthquakes complicates the disaster mitigation and preparedness activities. Understanding the natural hazard phenomena and generation processes is critical to improve hazard and risk predictability.

The challenges outlined above raise several questions for researchers and policymakers. How can we develop an open-source integrated modeling framework that can account for complex interactions and dependencies among human and natural systems? How do the cascading hazards and associated risks change with evolving climatic conditions, socioeconomic developments, and settlement patterns? How do mitigation and adaptation strategies change risk perception? How can we upscale knowledge from basin-scale process understanding to regional-scale hazards and risks modeling, and vice versa?

The availability of high-resolution datasets and modeling resources have opened opportunities for integrated multihazard multisector risk assessment across a wide range of spatial and temporal scales. There is also an increasing acknowledgment of the need to systematically integrate risk management efforts into policy, plans, and programs for sustainable development. Strategic and integrated efforts to promote community resilience to disasters have been initiated through Hyogo Framework for Action 2005-2015 and Millennium Development Goals. The Sendai Framework for Disaster Risk Reduction (Trogrlić et al., 2017) and the 2030 United Nations Sustainable Development Goals (Desa et al., 2016) underscore the pressing need for inclusive and integrated multihazard risk management approaches. These networked efforts are designed to be mutually beneficial across multiple stakeholders.

Community risks to natural hazards are often quantified using an index such as the US National Risk Index (FEMA, 2021), and Global Climate Risk Index (Eckstein et al., 2021). Scientific communities have made substantial progress in understanding the potential impacts of multihazards on multisectors and from local to global scales (Chester et al., 2019, 2020; Koks et al., 2019; Wright et al., 2019). Furthermore, World Meteorological Organization’s guidelines have emphasized the need for multi-hazard impact-based forecast and warning services to disseminate accurate and understandable weather and climate information. Satellite remote sensing, citizen science, and low-tech sensing could be instrumental in supporting local-level risk management, particularly in the data-scare region. Additional networked initiatives such as community-based modeling and data collection that integrate traditional wisdom, indigenous knowledge, and experts' opinion have been effective for multihazard risk management (Miles, 2018; Rakhal et al., 2021; Sanders et al., 2020).

2.2 Earth System Data-Model Fusion

Recent advances in big data, high-performance computing systems, cloud computing, and community-based modeling, among others, have opened the doors for more integrated and coordinated efforts on modeling, prediction, and risk assessment of natural hazards (Emerton et al., 2016; Farahmand & AghaKouchak, 2013; Yousefi et al., 2020). There are, however, salient challenges that the modeling communities across disciplines of natural hazards have recognized. Natural hazards impact at various spatial and temporal scales, and hence a need for scalable modeling efforts. The spatial and temporal scales associated with hazards vary with their types, which are often incompatible and inconsistent with hazard models, available datasets, and decision-making scales. Data collection for large-scale (regional) hazards such as hurricanes/cyclones and droughts are easier than that of small-scale (local) hazards like riverine flooding and landslides. The integration of such datasets in multihazard models poses a particular challenge in resolving local-scale processes. Also, developing FAIR (Findable, Accessible, Interoperable, and Reusable) (Wilkinson et al., 2016) datasets with coordinated and networked approaches through interagency and intergovernmental efforts is still a challenge. FAIR data and model-based practices in publication and policy reports, for instance, provide pathways for advancing discoveries in multihazard research and decision-making through open science. Whether datasets are in-situ or remotely sensed, they are not without uncertainties, which adds further challenge to integrate with hazard models. The integration of human systems is often challenging in such hazard models (Howley, 2021; Sima, 2021), hence the lack of a comprehensive assessment of exposure and vulnerability to people and properties. Also, note that the development and maintenance of databases and integrated hazard models demand continuous computational and financial resources, and networked efforts from researchers in the community and monitoring agencies for open access to data.

The challenges outlined above suggest several questions for researchers. How can we make optimal use of sparse station networks, remotely sensed radar and satellite retrievals, numerical weather prediction products, and global climate model outputs to provide high resolution forcing to modeling integrated human and natural systems? How can the Earth system models capture both local as well as large-scale dynamics? What are the efficient ways to couple models to understand compounding and cascading hazards? What is the best choice of spatiotemporal model resolution for specific hazard and risk assessment? Can we develop a modular framework for risk assessment across spatiotemporal scales? How do we integrate human system feedback into a multihazard modeling framework?

The availability of novel observational datasets presents significant opportunities for improving our understanding, modeling, and predictions of natural hazards. Data collection has started to become coordinated through large research community networks, including the Long-Term Ecological Research, the Great Lake Ecological Observatory Network, the United States Geological Survey, the National Ecological Observatory Network, and the French network of Critical Zone Observatories, among others. However, there is a need for greater coordination within each data system to ensure internal consistency and develop crosswalk tools to enable the interoperability of data products among these efforts. Recent advances in data assimilation and machine learning techniques provide opportunities to integrate high-resolution in-situ and remote-sensing observations into hazard models. Free and open-source data and code sharing platforms like GitHub and Google Collaboratory have been effective tools for open science. Open data initiatives, including OpenDRI and DesInventar provide systematic, homogeneous, and compatible databases of natural hazards. Recent advances in high-performance computing systems such as the National Center for Atmospheric Research Cheyenne allow the wider research community to run computationally intensive computer models. In addition, cloud-based tools such as Google Earth Engine, Amazon Web Services, and EOfactory have been crucial to forging collaborations among diverse research communities worldwide.

Coordinated modeling efforts across disciplines can promote the Earth system modeling by developing, supporting, and disseminating open-source codes, documentation, and integrated software modules. Some examples include- National Center for Atmospheric Research (NCAR) community models, International Institute for Applied System Analysis' community water model, Community Surface Dynamics Modeling System (CSDMS), European Center for Medium-Range Weather Forecasts (ECMWF), European Flood Awareness System (EFAS), and Global Landslide Hazard Assessment Model (LHASA) with Global Landslide Catalog (GLC). These modeling resources can help improve the understanding of complex connections that drive the Earth system and predict high-impact hazard events to potentially inform decisions about policy and resource allocation for hazard mitigation and adaptation strategies.

2.3 Uncertainty quantification and communication

Risk communication requires a sound understanding of future risks with quantification of associated uncertainties, and a coordinated approach among disciplines (Scolobig, 2015). Natural hazard risks are dynamic and deeply uncertain. Deep uncertainty refers to a situation "where the system model and its input parameters are not known or widely agreed on by the stakeholders to the decision" (Lempert, 2002). For instance, deep uncertainty in flood risk projections arises from different system components, and propagates along the modeling chain that consists of emission scenarios, general circulation models, downscaling techniques, hydrological models, hydraulic models, and exposure and vulnerability components (Sharma et al., 2021). All components of the ICON science permeate through this modeling chain of uncertainty quantification. In addition, these uncertainties often propagate through multisector systems. For example, agricultural planning and management efficacy are subject to uncertainty propagation stemming from an integrated agricultural, atmospheric, and hydrologic modeling system. However, current approaches to estimate hazards sample only a relatively small subset of the known unknowns such as model structures and parameters while neglecting the cross-sectoral feedback mechanisms. Such assumptions ignore the impacts of key uncertainties on hazards and dynamics. This can drastically underestimate the tails of the hazard probability distribution (Wong et al., 2018). In addition, natural hazards' warnings/alerts are communicated generally through the discrete single-valued warning products. Most often, such products do not openly provide associated uncertainty measures and make them publicly available. It could be partly because different studies have highlighted "uncertainty" as a major challenge in risk communication, including the challenges associated with establishing reliable sources of warning, consistency in the communication strategies, the credibility of the source, and accuracy of the information (Carr et al., 2016). Failing to effectively communicate risk and uncertainty could lead to overconfidence in risk perception, and result in poor decisions and outcomes (Zarekarizi et al., 2020).

Key questions associated with uncertainty quantification include the following: What are the decision-relevant uncertainties driving natural hazards and risks estimates? How does uncertainty propagate along with the integrated socioeconomic, environmental, and infrastructure systems? What are the coordinated approaches for uncertainty characterization, quantification, and reduction in hazard predictions and risk assessment? Key questions associated with uncertainty communication include the following. What are the effective tools and approaches to communicate uncertain hazards and risk information? How do policymakers, decision-makers, and communities perceive uncertainty? What changes are needed to make uncertainty an integral part of risk assessment? How do risk perceptions impact mitigation, preparedness, and response behavior, and how do these change when the estimated risk accounts for uncertainty?

2.4 Crossing traditional disciplinary boundaries

Multihazard multisector risk management requires integrating multiple areas of expertise that bring together different disciplines in multi-, inter-, and/or trans-disciplinary research (Wehrden et al., 2019). Such integration can span across Earth science, engineering, social science, data science, and decision science, among others. For instance, the development of flood prediction and information dissemination systems require reliable weather predictions (atmospheric science), land surface modeling (Earth science), big data analysis (data science), high-performance computing system (computer engineering), a user-friendly web-based information portal (information science), risk communication (social science), and a continuous automated monitoring network (electrical/electronic engineering). It further demands coordinated approaches and networked efforts that are designed for mutual benefit among governmental/non-governmental institutions, industries, policymakers, decision-makers, and practitioners. However, designing, implementing, and evaluating cross-disciplinary, mutually beneficial research remains challenging. Researchers, research institutions, and funding organizations still lack a concrete framework for promoting and implementing mechanisms to foster ICON-based research collaborations. In addition, differing research methods, languages, and knowledge barriers among disciplines compound the complexity of ICON science implementation (Barringer et al., 2020; Pischke et al., 2017).

The key question is: How can we promote and strengthen ICON-based cross-disciplinary research? Scientific communities have recognized the need for cross-disciplinary research. Nonetheless, the full use of ICON principles remains nascent. The National Research Council Committee on Facilitating Interdisciplinary Research (NRC, 2005) identified key driving forces to promote interdisciplinary research: i) the inherent complexity of nature and society, ii) the desire to explore problems and questions that are not confined to a single discipline, iii) the need to solve societal problems, and iv) the power of new technologies. In addition, collaborative research proposals have been gaining increasing emphasis from funding organizations. For example, the United States National Science Foundation (NSF) adopts convergence as one of the ten Big Ideas for future NSF investments (NSF, 2021). NSF identifies convergence research as having two primary characteristics: i) research driven by a specific and compelling problem, and ii) deep integration across disciplines.

3 Call to Action

Scientific efforts, policies, and decision-making on multihazard multisector risk require a sound understanding of risk and its drivers, from local to global scales. This includes understanding how risk may change across a wide range of spatiotemporal scales and how that risk may be reduced through disaster risk reduction efforts. Such efforts may be through both structural (such as mitigation measures) and nonstructural (such as adaptation that promotes resilience) means. As we highlight in this commentary, ICON provides a unique opportunity to bring scientific communities, policymakers, decision-makers, and the public together, facilitating the development of equitable and inclusive risk management strategies. The need for ICON science permeates through multihazard risk assessment and management in terms of integrated risk assessment, data-model fusion, uncertainty quantification and communication, crossing traditional disciplinary boundaries, and gears toward developing efforts to be mutually beneficial, and beyond.

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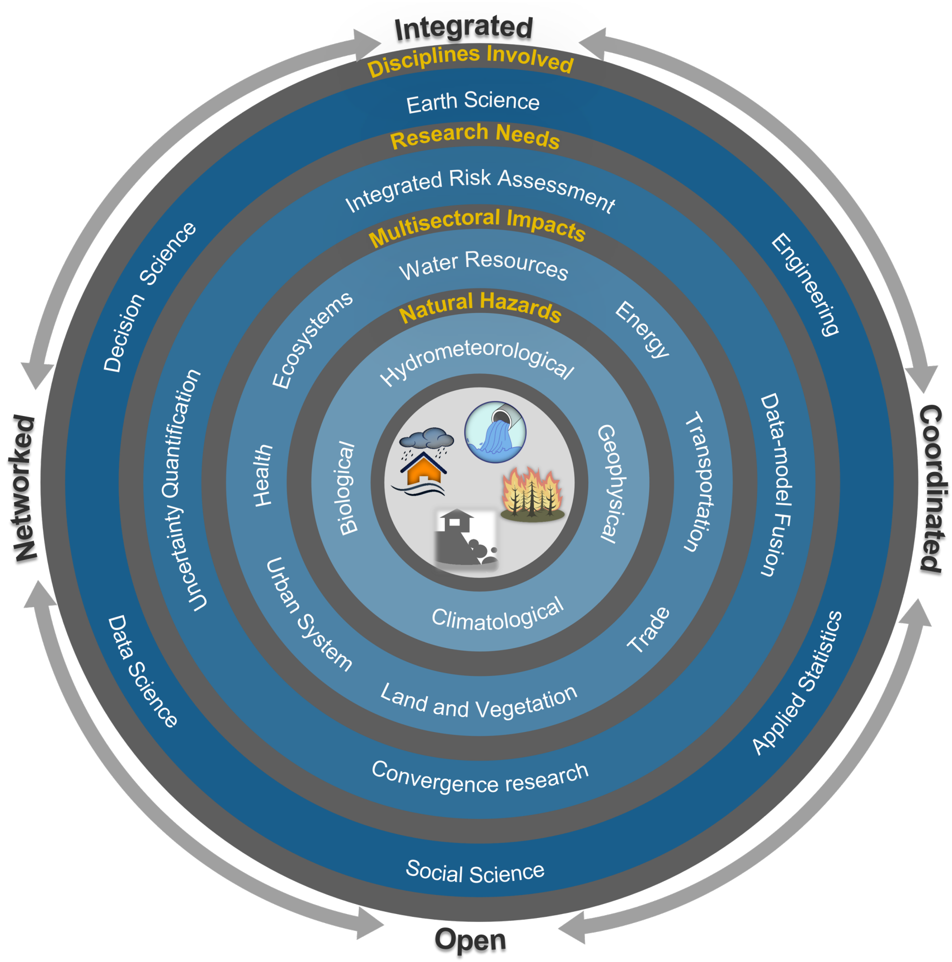

Figure 1: Multihazard multisector risk management under the Integrated, Coordinated, Open and Networked (ICON) science framework. Natural hazards can be geophysical (earthquakes, landslides, and volcano), hydrometeorological (flood and avalanches), biological (disease epidemics and animal/insect plagues) and climatological (droughts and wildfires), among others.