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A NOVEL FRAMEWORK FOR ASSESSING MULTI-HAZARD RISK AND RESILIENCE IN A CHANGING WORLD

Catalina GONZÁLEZ-DUEÑAS[1], Gemma CREMEN[2] & Carmine GALASSO[3]

Abstract: *The world's changing climate and rapidly evolving societies are exacerbating the risk posed by natural hazards (such as earthquakes) to infrastructure and communities in general. The dynamic interdependencies of built, natural, and social systems and the potential hazard interactions amplified by climate change also add important challenges to evaluating built-natural-social system resilience. Yet, there is a lack of tools available in the literature for comprehensively assessing (and supporting related decision-making on) the performance of the built environment under multi-hazard conditions, considering climate change impacts and the cascading effects caused by system interdependencies. This paper aims to fill this gap by proposing a novel dynamic multi-hazard risk modelling framework to support decision-making under deep uncertainty, accounting for climate change effects in hazard interactions (including earthquakes), cascading consequences of system disruptions, and the multidimensional impacts of natural-hazard-related disasters. The paper describes the framework's main modules and emphasises the key aspects to consider when implementing it in different contexts. Overall, the proposed framework advances the state-of-the-art in multi-hazard risk and resilience assessment and climate-aware decision-making to support the development of robust mitigation plans and policies under different climate and societal development scenarios.*

Introduction

The advent of climate change and its intensifying effects on some natural hazard events, as well as increasing urbanisation, population growth, and the general ageing of infrastructure systems worldwide, have emphasised the need to understand the potential amplification of disaster risk in the coming decades. Despite clear and numerous efforts to model individual risk components associated with future natural-hazard events (Heo and Manuel, 2022; Mesta et al., 2022), there remains a lack of a commonly accepted analytical framework for complete end-to-end future risk quantification (e.g., Cremen, Galasso and McCloskey, 2022b). A key challenge shared among the relatively small body of existing literature on modelling future risks from natural hazards is the deep uncertainty associated with projections of climate, future societal development (e.g., population dynamics, socioeconomic development patterns, changes in land cover/use, infrastructure development), and the changes in vulnerability of existing and future built-natural-social systems (e.g., Shepherd et al., 2018; Kopp et al., 2019; Doss-Gollin and Keller, 2022). Deep uncertainty scenarios arise when it is not possible to characterise the future using a single trajectory, and the likelihood of different trajectories and the models describing them cannot be unequivocally assigned (Brockway et al., 2022). Thus, policies and solutions (e.g., structural retrofitting and accessibility to recovery funds to vulnerable populations) to mitigate future natural-hazard risks must be robust across a set of plausible futures. In other words, they must be insensitive to both assumptions and modelling errors related to how the future will evolve. Moreover, these policies must promote people-centred strategies to ensure climate justice, equity, transparency in decision-making, and participatory risk management that promotes communities' well-being and resilience. Herein, the term 'risk' is defined as the convolution of hazard, exposure, and vulnerability (Birkmann and Welle, 2015). In line with this definition, a natural-hazard risk assessment methodology typically involves a (1) hazard definition, in which the natural hazards posing a threat to the region/community are identified and characterised; an (2) exposure characterisation, which involves the description of the systems (built, natural, and/or social) that can be potentially affected by the identified hazards; a (3) vulnerability analysis, that quantifies the potential effects of the hazard on the exposed systems through a set of impact

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[1] Postdoctoral research fellow, University College London, London, United Kingdom, c.duenas@ucl.ac.uk
[2] Lecturer, University College London, London, United Kingdom
[3] Professor, University College London, London, United Kingdom

metrics; and a (4) decision-making stage in which different mitigation policies are tested to reduce/manage the risk.

The literature on natural-hazard (including earthquake) risk modelling is heavily skewed toward single-hazard scenario analysis (Cremen et al., 2022). However, there has been a recent shift in focus to the analysis of multi-hazard conditions, driven by the significant severity of damages observed during major multi-hazard events (e.g., the great 2011 Tōhoku earthquake and tsunami, the 2023 Turkey-Siria earthquake and flash floods) and their increasing rate of occurrence (e.g., Yasuhara et al., 2012; Zaghi et al., 2016; Tilloy et al., 2019; Hart, Pitman and Byun, 2020). Natural hazard interactions can lead to compound hazards, which occur simultaneously or overlap for a period, or cascading hazards, in which there is a causal relationship among the hazards (i.e., one hazard triggers another hazard, such as in the case of an earthquake-induced landslide). When considering multi-hazard interactions in a changing climate, the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2021) states that “the probability of compound events has likely increased in the past due to human-induced climate change and will likely continue to increase with further global warming”. In line with this assessment, an increasing body of literature that models the impacts of a changing climate on multi-hazard interactions is emerging (Feng et al., 2022; Ridder et al., 2020).

To address these challenges and opportunities, this paper introduces a forward-looking multi-hazard risk assessment framework for analysing future natural-hazard risks. The proposed framework deviates from existing natural-hazard risk analysis frameworks by (1) highlighting potential trends in natural-hazard characteristics and occurrence due to climate change; (2) accounting for interactions among hazards; (3) evaluating cascading consequences of disasters due to system interdependencies; (4) proposing and evaluating novel people-centred impact metrics that encompass the multidimensional impact of natural hazards and different end-user perspectives; and (5) providing the means to analyse the impact of mitigation strategies across a range of “plausible futures” defined by different regional climate and development patterns. The next sections provide an introduction to the proposed framework along with a description of its modules. The paper finishes with a discussion of the challenges of multi-hazard risk assessment in a changing world and the novelty and contributions of the proposed framework to the field of future natural-hazard risk modelling.

Proposed framework

Managing natural-hazard risks in a changing world poses significant challenges, such as identifying potential climate-induced changes in the hazard or multi-hazard profile of a region, deciding the time horizon in which to conduct the analysis, choosing an adequate and efficient model (both from the computational and the input-output requirements) resolution, the selection of appropriate metrics to evaluate multi-hazard impacts and consequences, and accommodating different stakeholder requirements. The framework’s design is a decision-making-oriented one, and thus it is flexible enough to accommodate different analysis and stakeholder needs. The multi-hazard risk assessment is conducted at the level of interest: (1) element-level (e.g., individual asset/infrastructure component); (2) system-level (e.g., infrastructure system, built-natural-social systems), which are defined as a collection of elements, such as individual houses in the case of built systems; or at the (3) regional level, which can span different systems and it is usually delimited by geographical or political boundaries. Both scenario-based and fully probabilistic multi-hazard analyses can be conducted based on data availability and stakeholder requirements. The impacts of the hazard or multi-hazard are assessed at the smallest level of analysis (e.g., element-level, system-level) and eventually summarised at the predefined one (e.g., system-level, regional) through a set of impact metrics designed to provide meaningful information to decision makers. The framework consists of three major stages: (1) Conceptualisation of future regional pathways; (2) Impact analysis; and (3) Climate- and development-aware decision science (see Figure 1). The “Conceptualisation” stage includes four modules, in which plausible trajectories of the future are defined based on development (e.g., socioeconomic, demographic) projections and changes to the multi-hazard conditions of the region under analysis, considering future climate forecasts. The “Impact analysis” stage involves analysing the effects that future climatic, multi-hazard, and development conditions will have on the built-natural-social systems of the region and their quantification through a set of impact metrics. Finally, the “Climate and development-aware decision science” stage aims to evaluate how different strategies and policies can help to mitigate the regional natural-hazard risk for supporting climate and development-aware decision-making.

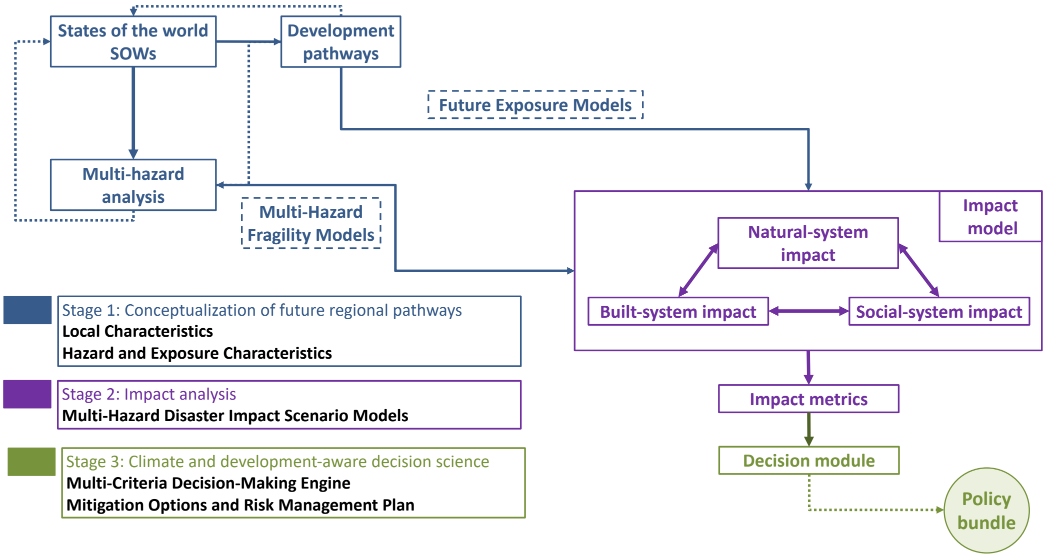

Figure 1. Proposed framework for forward-looking people-centred natural-hazard risk assessment.

Stage 1: Conceptualisation of future regional pathways

Module 1: States of the worlds (SOWs)

A key consideration when assessing risks from natural hazards in a changing world is that it is not possible to characterise hazard, exposure, and vulnerability parameters unequivocally. This is simply because we do not have certainty and, in many cases, not even a “best guess” of the future. Instead, we have what can be described as deeply uncertain situations that have significant epistemic uncertainties, meaning that there is no consensus among stakeholders on how to characterise key model parameters or the model itself (Brockway et al., 2022; Hadka et al., 2015). In climate science and decision-analysis theory, the concept of “states of the world” (or SOWs) is used when dealing with deep uncertainty. The SOWs concept aims to characterise a set of possible trajectories of the future that encompass a wide range of plausible system-state representations (e.g., Hadjimichael et al., 2020; Reed et al., 2022), embracing the idea that the future may unfold in different ways (especially on increasing timescales). These trajectories can be defined in terms of future climate, socioeconomic, or other key parameters (e.g., energy pathways, land use) projections relevant to the analysis (e.g., Doss-Gollin and Keller, 2022). Plausible futures are captured through representative “samples” that are defined based on relevant sources of uncertainty. Thus, as an output of the SOW module, key model parameters are characterised as deeply uncertain (i.e., there is no consensus on a single probability density function to represent the parameter) or as having shallow (i.e., it is possible to characterise a parameter through a likelihood or a unique probability distribution) uncertainty. For instance, when conducting a probabilistic seismic risk analysis, choosing fragility functions to model the intensity-damage probability relationship for each building archetype is critical (Gentile et al., 2022). In some cases, there is no sufficient data or models available in the literature for non-standard building archetypes or that reflect the local construction practices of the region, for which multiple fragility models can be adopted by sampling damage realisations from any of them (assuming that all of the models are equally skilful in modelling the damage behaviour). This is what is usually called deep uncertainty under competing models.

Strategies to characterise different SOWs usually rely on the objective of “learning” about the future rather than “predicting” it. Thus, the ensemble of SOWs (i.e., scenarios) chosen for the analysis will ultimately depend on the type of questions we want to answer: “*what would happen if…*”, “*how could we get to…*”, “*what are the response options we could take to…*”, “*what are the major sources of uncertainty in…*”, among others (Evans and Hausfather, 2018; Hayhoe et al., 2017). Given the diverse nature of the questions posed, several approaches have been used in the literature to characterise plausible future trajectories, such as the narrative approach, the storyline approach, and the Representative Concentration Pathway (RCP) approach. The narrative and storyline approaches share some similarities in the sense that both aim to qualitatively describe how the future may unfold. However, the former usually explores different futures based on uncertainties pertaining to human choices (e.g., economic growth, land use), while the latter tries to capture uncertainties in the physical aspects of climate change (e.g., thermodynamic vs dynamic factors) (e.g., Shepherd et al., 2018). An example of a narrative approach is the Shared Socioeconomic Pathways (SSP), in which different pathways of societal development are explored to understand how human choices might affect greenhouse emissions in the future (e.g., Hausfather, 2018). The RCP approach sets an endpoint of radiative forcing (i.e., change in the Earth's net radiative force) in the year 2100 and then works its way backwards to characterise the level of emissions that can lead to each RCP level at the end of the century (Hayhoe et al., 2017; Wuebbles et al., 2017).

An example of future pathway conceptualisation through SOWs would be leveraging the RCP and SSP approaches to explore how the risk of a region exposed to earthquakes and their cascading effects might look when considering climate change effects. This is an example of a coupled "SSPx-y" approach (adopted in the latest IPCC report; Pörtner et al., 2022), in which an RCP level is chosen and then potential narratives of socioeconomic development that could lead to this level at the end of the century are evaluated to provide annual greenhouse gas emissions that can inform Global Climate Models (GCMs) (Hayhoe et al., 2017). Regional projections of exposure (e.g., gross domestic product - GDP, land use, soil characteristics) and multi-hazard (e.g., changes in rainfall patterns affecting earthquake-induced liquefaction and landslide potential of a region) parameters can then be derived in the development pathways and dynamic multi-hazard analysis modules to evaluate changes in the risk profile of the area. Thus, the SOWs conceptualisation acts as an input for the above-mentioned modules, defining the set of modelling scenarios (SOWs) to consider. In this context, a scenario realisation corresponds to a single SOW, meaning one iteration of the analysis is obtained by sampling from the probability distribution assigned to each model parameter. Table 1 summarises the inputs and outputs of the SOWs module of the framework.

Inputs	**Relevant examples**	**Outputs**	**Relevant examples**
Questions to define and constrain the set of plausible future regional trajectories	• What are the most relevant hazards to account for in the future? • What are the most important drivers of each one of the hazards or multi-hazards identified? • How are greenhouse gas concentrations most likely to evolve given current emissions patterns? • Is climate change in the region a potential driver of migration?	Set of models and key parameters to define future regional trajectories (SOWs), along with their uncertainty characterisation (i.e., shallow or deep uncertain variable)	• Set of SSPx-y scenarios[1] (x: Shared Socioeconomic pathway, y: level of radiative forcing) • Set of alternative probability distributions to characterise a multi-hazard parameter (e.g., hazard frequency)
Data collected for the region	• Historical data of hazard occurrences in the region • Census data • Grey and green infrastructure development plans for the region	Built, natural, social, and hazard information relevant to define future regional trajectories	See Table 2 and Table 3

[1] "SSP-based scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socioeconomic Pathway describing the socioeconomic trends underlying the scenarios, and 'y' refers to the level of radiative forcing (in watts per square meter, or W m-2) resulting from the scenario in the year 2100" (Pörtner et al., 2022).

Table 1. Summary of the inputs and outputs of the "SOWs" framework module

Module 2: Development pathways

The development pathways module aims to characterise the region's future urban development, population growth, socioeconomic characteristics, infrastructure, and nature-based development based on the trajectories identified in the SOWs module. For the example presented in the previous section, the SSPx-y approach (Pörtner et al., 2022) can be used to inform future population growth and expected changes in the GDP for a particular region, which can be translated to infrastructure development and socioeconomic and demographic characteristics of the community in the development pathways module (Hauer, 2019). The development pathways module feeds into the Impact analysis stage by defining the built-natural-social systems and their evolution for a particular SOW (see Table 2). It can also modify the dynamic multi-hazard analysis module (e.g., an increase in impervious surfaces driven by an increase in grey infrastructure can affect the intensity of future flooding).

Inputs	**Relevant examples**	**Outputs**	**Relevant examples**
Set of plausible future trajectories pertinent to regional development from the SOWs module	• A set of SSP narratives • Population projections based on historical growth • Projected urban design layout based on regulatory zoning plans (e.g., code of ordinances) of a city	Set of relevant development parameters (e.g., GDP, energy supply and demand, land use) projections for each SOW for the region	• County-based projections of GDP for a particular SSPx-y trajectory • Features of the future built and natural environment based on zoning regulations (e.g., building and infrastructure locations, green infrastructure development)

Table 2. Summary of the inputs and outputs of the "Development Pathways" module in the first stage.

Module 3: Dynamic multi-hazard analysis

This module aims to (1) identify, model, and characterise the natural hazards that could potentially affect a region; (2) evaluate the effects that climate change will have on natural hazards; and (3) characterise hazard interactions and the influence of a changing climate on these interactions. Even though a direct link between climate change and earthquakes might not be evident at first glance, the Earth's system interconnectivity and system (e.g., infrastructure, social, natural) interdependencies challenge this notion. Changes in climate patterns not only exacerbate the impact of weather- and climate-induced hazards but also have the potential to create new hazard interactions due to alterations in local climate and site conditions. As the planet gets warmer, the sea level rises, and the intensity and frequency of rainfall events increase in certain areas. In turn, the potential of liquefaction in earthquake-prone areas exacerbates due to variations in groundwater levels and consequent soil saturation (Yasuhara et al., 2012). These changes can occur both inland due to heavy rains and in coastal areas due to sea level rise or compound flooding (e.g., sea level rise and rain, sea level rise, and storm surge). Earthquake-triggered landslides might also be more common and affect regions previously not considered at risk (e.g., Korup, Görüm and Hayakawa, 2012; Cloutier et al., 2017; Barth et al., 2020; Coe, 2020). Recently, some discussions on climate-related phenomena and tectonic processes have emerged in the scientific community. These include the effect of deglaciation on volcanic activity and the changes in fault stresses due to rain and snow and their effects on the microseismicity of some regions (Buis, 2019).

The hazard and multi-hazard scenarios to consider and the modelling parameters are defined based on the SOWs module. The output of this module is a hazard curve or map that quantifies the local intensity of the hazard or multi-hazard scenario for a particular region or system and a temporal-spatial description of the hazards affecting a region (see Table 3). When conducting a hazard assessment, attention must also be paid to potential hazard interactions based on their impact on the built-natural-social systems. For instance, in 2020, Tropical storm Isaias caused widespread flooding in Puerto Rico just months after a 6.4 magnitude earthquake struck the Island, causing many homes to collapse and jeopardising the community's recovery efforts (Wall, 2023). Moreover, the earthquake impacted the region when the community was still struggling to recover from the devasting effects of Hurricane Irma and Maria in 2017 (Acevedo, 2020). Here, the overlap of the two hazards depends directly on the region's recovery pace, which can vary significantly based on the community and region's political, socioeconomic, and cultural characteristics. Thus, the dynamic multi-hazard analysis module is an input to the impact analysis stage, in which the effects of the hazards on the built-natural-social systems of the region are analysed. The dynamic multi-hazard analysis module can also potentially affect the development pathways module. For instance, if compound flooding (coastal flooding and riverine flooding) is projected to affect a large proportion of a large housing development project in a city, the urban layout could be accordingly adjusted, or green infrastructure projects for flood protection could be included.

Inputs	**Relevant examples**	**Outputs**	**Relevant examples**
Set of plausible future trajectories pertinent to regional development from the SOWs module Development trajectories from the Development Pathways module	• Climate-change-induced changes in the frequency of a particular hazard • Projected interactions of weather extremes for a particular climate change projection • Projected changes to impervious surfaces in a region	• Multi-hazard or single-hazard intensity measures for the region • Temporal and spatial extent of the hazards affecting a region	• Maps of single or multiple intensity measures (e.g., flood depth, peak ground acceleration) for a region • Time-history evolution of a hazard or multi-hazard events (e.g., time-history record of flood-level variation in a region)

Table 3. Summary of the inputs and outputs of the "Dynamic Multi-Hazard Analysis" module in the first stage.

Stage 2: Impact analysis

Module 1: Built-natural-social systems impact

In this module, the hazard-induced damage and disruptions to the future built systems, natural systems, and social systems of the region are assessed (see Table 4). The multi-hazard assessment of impacts is conducted at the element level, such as individual bridges in the case of built systems or neighbourhood units in the case of social systems. It will thus depend on the system's definition (i.e., a social system's elements can be defined based on the model resolution needs at the neighbourhood or individual levels (Menteşe et al., 2023)).

Inputs	**Relevant examples**	**Outputs**	**Relevant examples**
Features of the built-natural-social systems of the region from the Development Pathways module, for each SOW considered Description of intensity measures from the Dynamic Multi-Hazard module for each scenario (i.e., SOW) considered Numerical models or mapping functions relating intensity measures with system impact Models of potential cascading impacts caused by system interdependencies	• Location and characteristics of buildings, infrastructure systems, natural features • Population centres and socioeconomic characteristics of the community • Maps of single or multiple intensity measures (e.g., flood depth, peak ground acceleration) for a region • Multi-hazard fragility functions for different built-natural systems	Impact estimates of the physical-natural-social systems of the region at the element-level (e.g., asset, neighbourhood)	• Asset-level repair costs or downtime • Household recovery time after a hazard or multi-hazard event

Table 4. Summary of the inputs and outputs of the "Built-Natural-Social Impact" module in the second stage.

Damage to built systems can be assessed by direct modelling/simulation of the multi-hazard-scenario-induced loads on the system or by empirical or data-driven relationships of hazard and damage (e.g., earthquake fragility models). Similarly, the impacts of the hazard on nature-based infrastructure or natural systems can be assessed. For example, the direct multi-hazard loading conditions and the resulting damage of trees during hurricane events have been evaluated through numerical models and experiments to evaluate vegetative debris generation (FEMA, 2012). Data-driven models have also been proposed in the literature to assess vegetative debris potential (USACE, 2017). The hazard's impact on the region's social systems should also be assessed. These impacts can directly result from the hazard or multi-hazard event (i.e., due to direct physical damage) or indirectly when the impact results from system interdependencies. A direct impact on social systems during an earthquake event is the number of people forced to displace due to seismic-induced damage/collapse of buildings. In contrast, an indirect impact can be the potential community dislocation caused by the disruption of utility services due to energy network damage. Since the hazard and development scenarios are conditioned on the SOWs defined in the first stage of the framework, the impacts are obtained at the SOW level (i.e., impact analysis per future trajectory defined as an SOW).

Module 2: Impact metrics

The objective of this module is to summarise the impact of a multi-hazard scenario for a region through a set of impact metrics. The impact metrics are computed by taking as an input the multi-hazard impacts to the built-natural-systems (see Table 5) and then aggregated at the regional level depending on the metric of choice (e.g., average losses based on building damage, ratio of displaced people with respect to the total population). These metrics need to evaluate the impacts of the disaster in the most holistic manner to support decision-making. The metrics can range from having a unidimensional perspective, such as total direct economic losses from an earthquake event, or can capture more composite information, such as the disproportionate effects of structural damage to vulnerable communities. For a compound multi-hazard event, such as the case of an earthquake event occurring while a flood event is ongoing, an appropriate composite social-built impact metric could be the cumulative well-being loss (Markhvida et al., 2020) of a household as a result of the hazard chain. This metric depends both on the physical vulnerability of the built environment (in this case, the cumulative damage on the residential building stock of the region) and on the consumption loss potential of the household unit. Another example of a composite social-built metric is the post-event accessibility of vulnerable populations to critical facilities such as hospitals. This metric depends on the vulnerability of bridges and roads to earthquake events and on the community's spatial demographic and socioeconomic patterns.

Inputs	**Relevant examples**	**Outputs**	**Relevant examples**
Multi-hazard impacts to the built-natural-social systems of the region from the System Impacts module for a specific SOW	• Expected earthquake-induced economic loss from damaged infrastructure elements • Number of people living in flood-damaged houses	Matrix of impact metrics relevant for decision-making analysis	• Earthquake-induced population dislocation disaggregated by income level • Expected annual economic loss of the housing sector due to flooding

Table 5. Summary of the inputs and outputs of the "Synthetization of Impacts" module in the second stage.

Stage 3: Climate and development-aware decision science

In this final stage, strategies and policies are proposed to mitigate the future natural hazard risks posed to the built-natural-social systems of the region under analysis. The deep uncertainties associated with how the future will evolve (as discussed in the SOWs module) mean that, given a choice, stakeholders lean more towards policies (solutions) that are robust, i.e., perform reasonably well across a set of SOWs (Brockway et al., 2022). Thus, this stage of the framework aims to propose and evaluate the robustness of different solutions in line with climate and development-aware decision science while promoting a people-centred, participatory decision-making approach to reduce any potential negative effects of climate change (i.e., maladaptation; Pörtner et al., 2022) on vulnerable and marginalised populations in particular (Brockway et al., 2022)., Techniques such as robust decision-making (RDM), scenario discovering, signpost and tipping point analysis, and participatory and scoping modeling can be implemented to propose mitigation strategies that are robust, adaptable, and engage multiple stakeholders in the decision-making process (Brockway et al., 2022). The RDM approach focuses on identifying robust solutions by evaluating the performance of the candidate solutions across the SOWs through a set of "satisficing" or "regret" criteria (Hadjimichael et al., 2020). The scenario-discovering strategy systematically develops a set of future trajectories intending to implement robust mitigation strategies (Doss-Gollin and Keller, 2022). Signpost and tipping point analysis is an adaptative planning approach that, through the continuous monitoring of some predefined indicators (tipping points), identifies the point where a mitigation policy would stop being effective (signpost) (Ramm et al., 2018). In this context, effectiveness refers to how well a proposed solution achieves its targets (i.e., fulfil its function) while considering practical aspects of its implementation (e.g., its cost and carbon footprint). For instance, a tipping point for the implementation of a floodwall as a mitigation measure can be the one associated with a maximum local water level (maximum of 6 ft) since the cost-effectiveness of this mitigation measure is usually restricted to a height of 4 to 6 ft (FEMA, 2014). Therefore, an adaptative planning approach is concerned with creating mitigation plans for the short and long term that can be modified as more evidence on the hazard (e.g., actual values of sea level rise compared to the projected ones) and its effects on the performance of the system or the proposed policy bundle is gathered. For any adopted strategy, it is also essential to facilitate the interaction of multiple stakeholders to ensure transparent communication of the mitigation policies and their outcomes, which can be actively done in a participatory modelling and scoping process (Almulla et al., 2022). Participatory modelling strategies aim to facilitate multistakeholder engagement to co-produce mitigation strategies and impact metrics, monitor the performance of the proposed solutions/policies, increase transparency in the planning process, seek active support and consensus on decisions being made, and incorporate different perspectives in the decision-making process (e.g., Brockway et al., 2022; Cremen et al., 2022).

Conclusions

This paper introduced a novel forward-looking multi-hazard risk assessment framework that explicitly accounts for multi-hazard interactions (including earthquakes and considerations related to climate change), their effects on interdependent built-natural-social systems, and their quantification through holistic impact metrics. The framework sets the basis for a decision support process in which policies can be tested across different regional climate, urban, and socioeconomic trajectories in a participatory approach, leading to the implementation of risk mitigation strategies that are robust (perform well across different future pathways) and adaptable (allowing for modifications during the time-horizon of the policy implementation, as in the case of the signpost and tipping point analysis). Practical implementations of the proposed framework would shed light on the evolving risks of different regions exposed to multi-hazard events, supporting informed risk-mitigation decision-making that accounts for critical uncertainties in built-natural-social system performance and the effects of climate change on hazard characterisation and interactions and societal development.

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References

Acevedo N (2020). Puerto Rico sees more pain and little progress three years after Hurricane Maria. Available at: https://www.nbcnews.com/news/latino/puerto-rico-sees-more-pain-little-progress-three-years-after-n1240513 (Accessed 15/04/2023)

Almulla Y, Ramirez C, Joyce B, Huber-Lee A, and Fuso-Nerini F (2022), From participatory process to robust decision-making: An Agriculture-water-energy nexus analysis for the Souss-Massa basin in Morocco, *Energy for Sustainable Development*, 70: 314–338. https://doi.org/10.1016/j.esd.2022.08.009

Barth S, Geertsema M, Bevington AR, Bird AL, Clague JJ, Millard T, Bobrowsky PT, Hasler A, and Liu H (2020), Landslide response to the 27 October 2012 earthquake (MW 7.8), southern Haida Gwaii, British Columbia, Canada. *Landslides*, 17(3): 517–526. https://doi.org/10.1007/s10346-019-01292-7

Birkmann J and Welle T (2015), Assessing the risk of loss and damage: exposure, vulnerability and risk to climate-related hazards for different country classifications, *International Journal of Global Warming*, 8(2): 191–212

Brockway AM, Wang L, Dunn LN, Callaway D, and Jones A (2022), Climate-aware decision-making: Lessons for electric grid infrastructure planning and operations, *Environmental Research Letters*, 17(7). https://doi.org/10.1088/1748-9326/ac7815

Buis A (2019). Can Climate Affect Earthquakes, Or Are the Connections Shaky? Available at: https://climate.nasa.gov/news/2926/can-climate-affect-earthquakes-or-are-the-connections-shaky/#:~:text=Scientists%20know%20earthquakes%20can%20be,studies%20have%20supported%20such%20correlations (Accessed 15/04/2023)

Cloutier C, Locat J, Geertsema M, Jakob M, and Schnorbus M (2017), *Potential impacts of climate change on landslides occurrence in Canada*, Slope safety preparedness for impact of climate change (pp. 71–104), CRC Press

Coe JA (2020), Bellwether sites for evaluating changes in landslide frequency and magnitude in cryospheric mountainous terrain: a call for systematic, long-term observations to decipher the impact of climate change, *Landslides*, 17 (11)

Cremen G, Galasso C, and McCloskey J (2022), Modelling and quantifying tomorrow's risks from natural hazards, *Science of the Total Environment*, (817). https://doi.org/10.1016/j.scitotenv.2021.152552

Doss-Gollin J and Keller K (2022), A subjective Bayesian framework for synthesizing deep uncertainty. https://doi.org/10.1002/essoar.10511798.3

Evans S and Hausfather Z (2018). How "integrated assessment models" are used to study climate change. Available at: https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change/ (Accessed 15/03/2023)

Federal Emergency Management Agency (FEMA) (2014), Homeowner's Guide to Retrofitting: Six Ways to Protect Your Home From Flooding

FEMA (2012), HAZUS-MH 2.1 hurricane model technical manual, FEMA Washington, DC.

Feng K, Ouyang M, and Lin N (2022), Tropical cyclone-blackout-heatwave compound hazard resilience in a changing climate, *Nature Communications*, 13(1). https://doi.org/10.1038/s41467-022-32018-4

Gentile R, Cremen G, Galasso C, Jenkins LT, Manandhar V, Menteşe EY, Guragain R, and McCloskey J (2022), Scoring, selecting, and developing physical impact models for multi-hazard risk assessment, *International Journal of Disaster Risk Reduction*, 82: 103365.

Hadjimichael A, Gold D, Hadka D, and Reed P (2020), Rhodium: Python library for many-objective robust decision making and exploratory modeling, *Journal of Open Research Software*, 8. https://doi.org/10.5334/JORS.293

Hadka D, Herman J, Reed P, and Keller K (2015), An open source framework for many-objective robust decision making. *Environmental Modelling and Software*, 74: 114–129. https://doi.org/10.1016/j.envsoft.2015.07.014

Hart DE, Pitman SJ, and Byun DS. (2020), Earthquakes, Coasts… and Climate Change? Multi-hazard Opportunities, Challenges and Approaches for Coastal Cities, *Journal of Coastal Research,* 95(SI): 819–823

Hauer ME (2019), Population projections for U.S. counties by age, sex, and race controlled to shared socioeconomic pathway, *Scientific Data*, 6. https://doi.org/10.1038/sdata.2019.5

Hausfather Z (2018), How "Shared Socioeconomic Pathways" explore future climate change. Available at: https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/ (Accessed 15/04/2023)

Hayhoe K, Edmonds J, Kopp R, LeGrande A, Sanderson B, Wehner M, and Wuebbles D (2017), Climate models, scenarios, and projections, *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program*

Heo T and Manuel L (2022), Greedy copula segmentation of multivariate non-stationary time series for climate change adaptation, *Progress in Disaster Science*, 14. https://doi.org/10.1016/j.pdisas.2022.100221

Kopp RE, Gilmore EA, Little CM, Lorenzo-Trueba J, Ramenzoni VC, and Sweet WV (2019), Usable Science for Managing the Risks of Sea-Level Rise, *Earth's Future*, 7(12): 1235–1269. https://doi.org/10.1029/2018EF001145

Korup O, Görüm T, and Hayakawa Y (2012), Without power? Landslide inventories in the face of climate change, *Earth Surface Processes and Landforms*, 37(1): 92–99. https://doi.org/10.1002/esp.2248

Markhvida M, Walsh B, Hallegatte S, and Baker J (2020), Quantification of disaster impacts through household well-being losses, *Nature Sustainability*, 3(7): 538–547. https://doi.org/10.1038/s41893-020-0508-7

Menteşe EY, Cremen G, Gentile R, Flippi EM, Galasso C, and McCloskey J (2023), Future exposure modelling for risk-informed decision making in urban planning, *International Journal of Disaster Risk Reduction*, 103651.

Mesta C, Cremen G, and Galasso C (2022), Urban growth modelling and social vulnerability assessment for a hazardous Kathmandu Valley, *Scientific Reports*, 12(1). https://doi.org/10.1038/s41598-022-09347-x

Pörtner HO, Roberts DC, Poloczanska ES, Mintenbeck K, Tignor M, Alegría A, Craig M, Langsdorf S, Löschke S, and Möller V (2022), IPCC, 2022: Summary for policymakers.

Ramm TD, Watson CS, and White CJ (2018), Strategic adaptation pathway planning to manage sea-level rise and changing coastal flood risk, *Environmental Science and Policy*, 87: 92–101. https://doi.org/10.1016/j.envsci.2018.06.001

Reed PM, Hadjimichael A, Malek K, Karimi T, Vernon CR, Srikrishnan V, Gupta RS, Gold DF, Lee B, and Keller K (2022), Addressing uncertainty in multisector dynamics research. Zenodo Online.

Ridder NN, Pitman AJ, Westra S, Ukkola A, Hong X, Bador M, Hirsch AL, Evans JP, Di Luca A, and Zscheischler J (2020), Global hotspots for the occurrence of compound events, *Nature Communications*, 11(1). https://doi.org/10.1038/s41467-020-19639-3

Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dessai, S., Dima-West, I. M., Fowler, H. J., James, R., Maraun, D., Martius, O., Senior, C. A., Sobel, A. H., Stainforth, D. A., Tett, S. F. B., Trenberth, K. E., van den Hurk, B. J. J. M., Watkins, N. W., Wilby, R. L., and Zenghelis, D. A. (2018). Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. Climatic Change, 151(3–4), 555–571. https://doi.org/10.1007/s10584-018-2317-9

Tilloy A, Malamud BD, Winter H, and Joly-Laugel A (2019), A review of quantification methodologies for multi-hazard interrelationships, *Earth-Science Reviews*, 196. https://doi.org/10.1016/j.earscirev.2019.102881

USACE (2017), Disaster Impact Models. Available at: https://www.usace.army.mil/Missions/Emergency-Operations/Disaster-Impact-Models/ (Accessed 15/03/2023)

Wall M (2023). Puerto Rico facing slow recovery after hurricanes, earthquakes and Covid. Available at: https://www.irishtimes.com/world/americas/2023/03/03/puerto-rico-facing-slow-recovery-after-hurricanes-earthquakes-and-covid/ (Accessed 15/03/2023)

Wuebbles D, Fahey D, Takle E, Hibbard K, Arnold J, DeAngelo B, Doherty S, Easterling D, Edmonds J, and Edmonds T (2017), Climate science special report: Fourth national climate assessment (NCA4), Volume I.

Yasuhara K, Komine H, Murakami S, Chen G, Mitani Y, and Duc DM (2012), Effects of climate change on geo-disasters in coastal zones and their adaptation, *Geotextiles and Geomembranes*, 30: 24–34. https://doi.org/10.1016/j.geotexmem.2011.01.005

Zaghi AE, Padgett JE, Bruneau M, Barbato M, Li Y, Mitrani-Reiser J, and McBride A (2016), Establishing Common Nomenclature, Characterizing the Problem, and Identifying Future Opportunities in Multihazard Design, *Journal of Structural Engineering*, 142(12). https://doi.org/10.1061/(asce)st.1943-541x.0001586