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Natural Hazards and Earth System Sciences
Discussions

Between global risk reduction goals, scientific-technical capabilities and local realities: a novel modular approach for multi-risk assessment

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Abstract. We live in a rapidly changing and globalized society. The increasing connectivity of our economic, social and technical systems, growing urbanization and the consequences of climate change might lead to more complex risks and multi-dimensional vulnerability. The complex relationships between multiple and consecutive natural hazards, exposed population and built environment result in a variety of cascading effects which, if are often not considered appropriately by decision makers, can result to inadequate or even misleading risk management strategies. Thus, hindering efficient prevention and mitigation measures, and ultimately undermining the resilience of societies. International efforts to identify global risks such as within the Sustainable Development Goals, the Sendai Framework for Disaster Risk Reduction 2015-2030 or the Paris Agreement help to raise awareness, set priorities and face such global problems. However, even if the formulated goals for risk reduction are comprehensible in their abstraction, decision-makers still face major challenges when it comes to local implementation. In this paper, we present a conceptual approach for multi-risk assessment which was designed to serve potential users like disaster risk managers, urban planners or operators of critical infrastructures to increase their capabilities. Based on recent scientific and technical capabilities, we developed a tool through an iterative participative approach which has allowed users to explore various scenarios of multiple hazards, cascading effects and their impacts. As an illustrative example, the experiences during this stimulating process are documented for Lima Metropolitan area (Peru), a megacity exposed to various natural hazards, among them, earthquakes and tsunamis. We believe that such an approach for exploring, describing and quantifying different *What-if scenarios* can constitute a valuable approach for understanding complex multi-risk processes, preparing for such situations, and serving as a good practice that can be replicated for other areas of interest in the future.

1 Introduction

In this article, we provide a brief introduction on the paradigm shift from managing disasters to managing risks, followed by single-hazard to multi-hazard risk assessment. We highlight four global strategies that address disaster risk reduction and call for action. In these introductory sections, we note the need to bridge the gap between these global goals and specific tools for implementation.

1.1 From managing disasters to managing risks

A disaster as defined by the UNISDR is "*a serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceed the ability of the affected community or society to cope using its own resources*" (UNISDR, 2009, p. 9). Among all disasters those caused by natural hazards claim the greatest number of victims per year. Especially climate induced hazards have increased in frequency and intensity of events (EEA, 2021; WMO, 2021). In 2021 global losses from disasters induced by the interplay of natural hazards and vulnerabilities added up to US$ 280bn (Munich RE, 2022). Population growth, rapid urbanization and concentration of people, assets and economic activities in hazardous areas raised during the past decades (Pesaresi et al., 2017). Inadequate or unplanned socioeconomic development in places exposed to a variety of hazards increases the vulnerability of societies (UNEP, 2016).

In addition to immediate crisis management and rapid response during and after a disaster, disaster preparedness is becoming increasingly important (Strunz et al., 2022). The shift from managing disasters to managing risk is articulated in the Sendai Framework for Disaster Risk Reduction 2015-2030 which was adopted at the Third UN World Conference in Sendai, Japan, on March 18, 2015 (UNISDR, 2015a). The Sendai Framework for Action's priority one is "*understanding disaster risk*" (UNISDR, 2015a). This priority describes that "*policies and practices for disaster risk management should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment*" (UNISDR, 2015a, p. 14). The demand to consider and to understand all dimensions of risk is a basic requirement, but at the same time an enormous challenge taking into consideration multi-hazard and multi-risk situations with all the interdependencies during such events. The paradigm shift was taken up by UNDRR in the Global Assessment Report on Disaster Risk Reduction (GAR) in 2019 stating that this shift is "*seeking to redress practice that has for many years seen ex ante action articulating the complex risk drivers from which disasters materialize eclipsed by action responding to the manifestation of disasters*" (UNDRR, 2019, chapter 15, p. 403). In 2022 UNDRR stresses that "*scientific risk assessments by experts are essential in designing strategies for reducing risk and future losses from extreme events.*" (UNDRR, 2022a, chapter 8, p. 111). It is further stated that scientific results are in demand to assist key decision makers, and that information needs to be communicated clearly and transparently.

1.2 From single-hazard to multi-hazard risk assessment

An increasing number of people worldwide are exposed to natural hazards, particularly in poorly planned urbanisations (Pesaresi et al., 2017; Hossain et al., 2017; UNDRR, 2023). Effective prevention and risk management can save lives and reduce all kinds of losses. However, meaningful risk management strategies are complex, since hazards effects are multidimensional and beyond this rarely isolated. An earthquake can trigger a tsunami, soil liquefaction and/or landslides. The hazard interactions are manifold (Gill and Malamud, 2014) and become even more complex as they can further affect critical infrastructures (Barquet et al., 2023). UNDRR (2019) calls for "*information on the nature and extent of hazards, vulnerabilities, and the magnitude and likelihood of potential damage and loss needs to expand from single-hazard to multi-risk assessments to capture the range of intersecting threats.*" (UNDRR, 2019, chapter 12.3.3, p. 346).

First studies on *multi-hazards* and *multi-hazard risk* are documented by the mid-1980s (e.g., Fitz Simons, 1986; Chiu and Chock, 1998; Granger et al., 1999). Fitz Simons (1986) discusses different hazard forces and agents to which buildings, and in particular historic architectures and museums, are exposed. However, the interdependencies of hazards were not studied. Chiu and Chock (1998) presented a proposal for "*multi-hazard performance-based building design criteria*" addressing wind and earthquake hazards. They conclude that due to limited desktop computational power handling of multi-hazard design criteria was not possible in previous years. Granger et al. (1999) performed a provisional *multi-hazard risk assessment* of Cairns, Australia. Five hazards types, i.e. earthquakes, landslides, floods, destructive winds and storm tides, were analysed. The exposure to the hazard and related vulnerability was considered while cascading effects and interdependencies were not considered in detail.

While single-hazard oriented research dominated the past, studies on multi-hazards and multi-hazard risk analysis came more into the focus shortly after the turn of the millennium. Marzocchi et al. (2009) define the purpose of multi-risk analyses "*to establish a ranking of the different types of risk taking into account possible cascade effects i.e. the situation for which an adverse event triggers one or more sequential events (synergistic event).*" Approaches for identifying and characterizing hazard interactions are for example laid out in Taubenböck et al., (2009; 2013), Mignan et al. (2014), Gill and Malamud (2014; 2016; 2017), Liu et al. (2015) and Tilloy et al. (2019). A detailed review is not provided in our article, but refers to selected publications as follows. Kappes et al. (2012) focused in a review on the challenges of analysing multi-hazard risks whereas Komendantova et al. (2014) analysed the feedback from civil protection stakeholders on two multi-hazard and multi-risk decision support tools which reveal that interest is high, but hampered due to the underlying complexity. Gallina et al. (2016) published a review of multi-risk methodologies for natural hazards concluding that most of the approaches rely on the analysis of static vulnerability. A comprehensive review of multi-hazards research and risk assessment was published by Ciurean et al. (2018). The authors provide various observations among others that methodologies in real case study examples was (at the time of publication) still limited. Gill et al. (2020) analysed seven regional multi-hazard interaction frameworks (Tarvainen et al., 2006; De Pippo et al., 2008; Kappes et al., 2010; van Westen et al., 2014; Neri et al., 2008, Neri et al., 2013; Liu et al., 2016) and presented a scalable interaction framework approach with different resolutions of information using Guatemala as an example. Ward et al. (2020) provide a review of global risk studies across different hazards. They list similarities and differences between the approaches taken within and across the different hazards. The need to model multiple hazards is addressed in the review published by Cremen et al. (2022). This is supported by the systematic and scientometric review on multi-hazard risk assessment performed by Owolabi and Sajjad (2023) where they conclude, among others, on emphasizing on cascading and interrelated relationships among multiple hazards. Most recently, Hochrainer-Stigler et al. (2023) proposed a framework to guide the analysis of multi- and systemic risk which however has not yet been tested in real case studies.

1.3 From global risk reduction goals to local impacts

In addition to the scientific work, the importance of risk assessment and its challenges are addressed in global strategies, among others:

(1) The *Sustainable Development Goals (SDGs)* proposed by the United Nations in 2015 with its 17 goals for improving human society, ecological sustainability and the quality of life (United Nations, 2015a) are aiming to contribute to the global risk reduction agenda. The 17 SDGs have 169 underlying targets and 232 approved indicators. In a reflection paper UNISDR (2015b) identifies 25 targets related to disaster risk reduction in 10 of the 17 SDGs. Among others, the objective of reducing the in number of deaths and people affected as well as decrease of economic losses caused by disasters is addressed in goal 11 "*make cities and human settlements inclusive, safe, resilient and sustainable*".

(2) As it was introduced in Sect. 1.1, the *Sendai Framework for Disaster Risk Reduction 2015-2030* articulates the "*understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment*" as priority 1 of the four priorities for action (UNISDR, 2015a, p. 14). Next to the development of science-based methodologies, UNISDR (2015a) also advocates for the development of user-friendly systems and services. Thereby the needs of different categories of users should be considered.

(3) In addition, the *Paris Agreement,* an international treaty on climate change, calls for reducing vulnerability to climate change in article 7.1 (United Nations, 2015b, p. 9) and on minimizing the risk of loss and damage with the adverse effects of climate change in article 8.1 (United Nations, 2015b, p. 12).

(4) With the increase in urbanization, more people are living in areas at risk (cf., Geiß et al., 2019a). The *New Urban Agenda* (United Nations, 2017) addresses various field of action and call for strengthening resilience in the event of disasters. It envisages cities and human settlements that "*adopt and implement disaster risk reduction and management, reduce vulnerability, build resilience and responsiveness to natural and human-made hazards and foster mitigation of and adaptation to climate change*" (United Nations, 2017, p. 7).

As briefly outlined above, global goals are set to mitigate risks and damage from disasters. In parallel, risk situations are spatially heterogeneous, (often very) local and they are getting more complex due to dynamic changes in society and the exposed built landscape. Pittore et al. (2017) discussed the challenge of implementing an exposure model suitable for different hazards. The aim is not to stop at theory and research, but to offer practical solutions via tools and applications. There are databases, applications and platforms existing which support or directly target to model risks, as also recently outlined by Negulescu et al. (2023). Among them, we mention a few, like the initiatives PAGER (Wald et al., 2011) and ShakeCast (Wald and Lin, 2007),

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and further focusing on multiple hazards, e.g., HAZUS-MH (FEMA, 2004); CAPRA (Cardona et al., 2012); RiskCity and WebRiskCity (Frigerio and Westen, 2010); PREVIEW (Giuliani and Peduzzi, 2011); RiskChanges (van Westen et al., 2014; van Westen et al., 2022); WESR (UNEP, 2022, 2023); DRMKC (Marin Ferrer et al., 2019; Joint Research Centre (European Commission) et al., 2020); RiskScape (Paulik et al., 2022); CLIMADA (Kropf et al., 2022); IN-CORE (van de Lindt et al. 2023); VIGIRISKS (Negulescu et al., 2023). However, the design of information systems or tools that are capable to analyse interactively multi-hazard risk situations, and in particular dynamically updating the damage on exposed elements due to various hazards with cascading effects remain challenging (cf., Cremen, et al., 2022; Paulik et al., 2022). Therefore, we seek to address this challenge by presenting a conceptual approach that allows users to analyze the impact of various natural hazards.

Following this introduction, Sect. 2 presents the conceptual approach to developing a scenario-based multi-risk assessment tool. Subsequently, Sect. 3 describes the results and steps evolved to achieve this goal. The discussions and conclusions are outlined in Sect. 4.

2 Conceptual approach

The global risk reduction goals, as presented in Sect. 1.3, are comprehensible in their abstraction. Local risk situations and the challenges for decision makers to pursue these goals in practice can be very different across the globe. Thus, there is a gap between scientific and technical possibilities (i.e., the knowledge created by them and concrete fact-based decisions in the planning or political field). It is therefore imperative to create an interface between the actors and disciplines coming from research. We believe that an information system for multi-risk assessment can be this interface.

Considering the aforementioned guidelines and strategies in the context of disaster risk reduction (DRR) and disaster risk management (DRM) as well as the outlined research needs, we present a generic framework developed within the research projects RIESGOS and its successor RIESGOS 2.0 (Schoepfer et al., 2018). The projects focused on the development of innovative scientific methods for the *assessment of multi-risk situations* with the aim of designing an approach that meets the needs of users at the local level. In addition to the German team coming from various disciplines, the project collaborated with a variety of research institutions and public authorities in Chile, Peru and Ecuador. The conceptualization of this overall approach is visualized in Fig. 1. We argue that the starting point of our conceptual approach is a context and stakeholder analysis (Sect. 2.1) to understand the organizational environment and underlying structures. Later, we present a framework to design a multi-risk information system (Sect. 2.2). We selected a story-based concept that allows the description of a specific multi-risk situation and its representation through multiple scenarios (Sect. 2.2.1). As input, the elements of risk (hazard, exposure, and vulnerability) and their impacts on critical infrastructure are assessed, novel scientific and technical approaches developed and considered in terms of their potential implementation (Sect. 2.2.2). During these two steps, we involved users in the process from the beginning to ensure that the designed tool their requirements and needs (Sect. 2.2.3). For the demonstrator we chose a decentralized system architecture approach built on distributed web services, with a graphical user interface as the frontend (Sect. 2.2.4). We are convinced that such an approach for exploring, describing and quantifying different *What-if scenarios* can constitute a valuable tool for understanding complex multi-risk situations and to prepare for such situations.

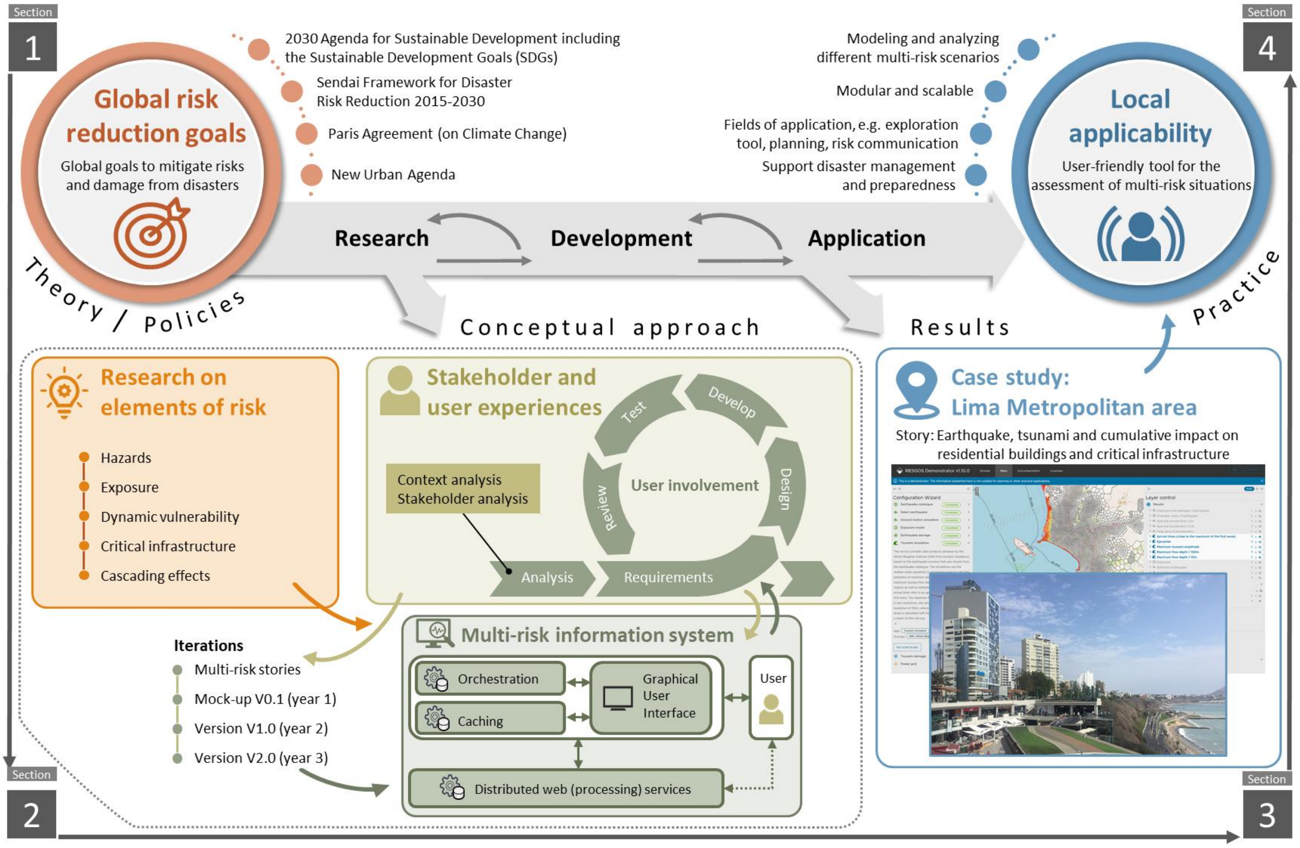

Figure 1. Conceptualization and workflow of the development of an analysis tool aiming at the implementation of global risk reduction goals (from theory / policies) on local level (to practice). The numbers in the boxes indicate the corresponding sections of the paper (Sect. 1-4). Photograph taken by Elisabeth Schoepfer (2019); screenshot of the tool (map data © OpenStreetMap contributors and available from https://www.openstreetmap.org).

2.1 Context and stakeholder analysis

Before starting the design of a tool or system, it is crucial to understand the context in which it is aimed to be used. A *context analysis* aims to understand the environment the work is placed in (Meaux and Osofisan, 2016). To do so, we first defined the thematic context, i.e. here the disaster risk reduction (DRR) and disaster risk management (DRM) domains and the assessment of the risk profiles of the location or country. We started with the identification of disasters that have occurred in the country and their ranking according to frequency and impact by consulting existing and open geo-data sets (e.g., World Bank Open Knowledge Repository (World Bank Group, 2021); DRMKC INFORM (European Commission, 2023)). In doing so, we collected the information on historical disaster events with the aim of providing deeper insights on the dynamics of possible hazard scenarios. Thereby we focused on complex situations where some hazardous events were observed to have interacted and caused cascading effects in the past, and that due to the increasingly exposed people and infrastructure can caused more damage and losses if they occurred again (Sect. 2.2.1). Secondly, a detailed analysis of the DRM policies, structures, strategies, and plans was conducted. This included the documentation of frameworks and regulations in the DRM domain as well as the respective mechanisms for coordination and cooperation in the corresponding country. Next to the country-specific instruments also activities in international cooperation were considered.

A *stakeholder analysis* has been done to identify relevant actors involved in the DRM context, describing their roles, responsibilities, relationships, interests, and relative influence / power. Naturally, the stakeholders belong to different sectors. The categories (1) universities and scientific research institutes (research community), (2) institutions operating information systems, (3) institutions operating monitoring systems, (4) non-governmental organizations, and (5) end users were used for systematization. Key stakeholders per group were identified and described in detail on different levels ranging from national and regional to local level covering their specific objectives and tasks in the working contexts.

2.2 Framework to design a multi-risk information system

As briefly outlined in Sect. 1, although there are several approaches on how to address multi-hazard risk situations, they are often not sufficient for a practical application. The development of support tools adapted for a wide range of stakeholders, the consideration of multiple hazards and dynamic aspects as well as adequate communication of results are among others topics which were suggested for future studies within the research community (e.g., Curt, 2021; Cremen et al., 2022). These tools should enable the analysis of escalation effects and multi-level scenarios. After reviewing the current research landscape and following the recommendations, our overall objective was to develop such a multi-risk approach that considers the treatment of cascading effects and to build a tool which allows the user to simulate and analyse complex multi-risk situations from the perspective of *What-if scenarios* on a local level. With this, we aim to provide users the possibility to explore various scenarios, and not only focusing on one fixed scenario (often referred to as reference scenario). Following this deterministic approach, we decided against a probabilistic assessment where all possible scenarios are combined (OECD, 2012). During the design of the tool we involved various user groups to ensure that the tool is geared towards the needs of potential users and its practicality. Our guiding questions in the design process were:

(1) "*How can natural hazards (e.g., earthquake and tsunami) that occur in close temporal succession or that trigger each other (cascading or consecutive) be described and represented considering their combined impacts?*",

(2) "*What is the cumulative impact of such multi-hazard events and how is the impact amplified compared to single hazards, e.g., damage on residential buildings and/or critical infrastructure?*".

2.2.1 Story-based concept planning

With these objectives in mind, we followed the concept of story and scenarios in order to understand and describe possible multi-risk situations (e.g., Jarke et al., 1998; Sutcliffe, 2003). With the term *story* we refer to a "*narrative description of a situation, defining the specific involved hazards, cascading effects and impacts, looking at a specific area of interest*". These stories

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represent realistic multi-risk situations with cascading effects. A story is based on physical drivers – i.e., natural hazards, – but is not limited to their description. Instead, a story should also incorporate the aspects of damage and losses in a realistic way as well as the impact, e.g., on critical infrastructures. The term *scenario* represents for us a single (numerical) realisation or expression within a story (e.g., Li et al., 2016). Scenarios represent different intensities of the triggering natural hazards and their effects. For each chosen story, multiple scenarios are available to describe different intensities of the triggering natural hazards and their effects. It is important to note that the quantitative models in the individual scenarios do not necessarily represent the entire complexity of a story. To which degree a story agrees with realistic circumstances depends on the modelling capabilities as well as on the availability of (geo-)data. Limited reproducibility should not, however, diminish the importance of qualified stories.

2.2.2 Research on elements of risk

The story descriptions have to be matched with the scientific-technical potential of research. Research on multi-risk requires a thorough understanding of the three risk components, *hazard*, *exposure* and *vulnerability,* but mostly important, their interrelations (cf., Gill and Malamud, 2017).

Hazard is defined as "*a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation.*" (UNDRR, 2022b, p. 7). UNDRR (2022b) further differentiates between natural, anthropogenic or socio-natural hazards. Within the scope of our project we focus on *natural hazards,* in particular geophysical hazards. For instance, in the context of seismic hazard, information on the possible earthquakes that can hit a region in the future needs to be available. For that aim, existing earthquake catalogues are gathered (e.g., Nievas et al., 2020). They contain few parameters that allows to simulate the geometry and intensity of similar future earthquake ruptures. Their spatially distributed intensities (i.e., seismic ground motion fields) are typically simulated through statistical or numerical models that are constantly updated thanks to the current instrumentation initiatives (e.g. Weatherill et al., 2023). Moreover, since some earthquakes can trigger a tsunami, numerical tsunami models are typically used to determine the wave propagation and to estimate the flow depth in the inundated coastal areas (e.g., Rakowsky et al., 2013). This multi-hazard interaction of an earthquake triggering a tsunami is one example of many possible hazard interactions (cf., Gill and Malamud, 2016, Fig. 4, p. 672). Other interactions are for example volcanic activities (e.g., Plank et al., 2018), that, depending on the geographical and climatic framework, can also cause landslides, lahars and/or floods (e.g., Frimberger et al., 2021).

On the other hand, *exposure* describes all elements that can be subject to loss or damage in a hazard zone, such as people, property or critical infrastructure (UNISDR, 2009, p. 15; Geiß and Taubenböck, 2013). Often, exposure data are outdated, spatially aggregated and discontinuous, or are simply non-existent in many regions of the world. In addition, it is crucial to deal with the dynamic change processes of settlement areas induced by, for example, rapid population growth and increasing urbanization (cf., Taubenböck et al., 2012; Geiß et al., 2019b). To overcome this bottleneck, approaches have been developed in the past to combine relevant information from spatial data such as earth observation and (geo-)statistics to create detailed exposure information (e.g., Wieland et al., 2012; Geiß et al., 2014, 2015, 2017, 2022). First, the physical-structural and non-structural characteristics of buildings are identified (e.g., Geiß et al., 2017; Aravena Pelizari et al., 2021) and in the following their *vulnerabilities* are estimated (e.g., physical vulnerability, Gómez Zapata et al., 2021b, 2022a). In particular, when working with multi-hazard events *dynamically changing vulnerabilities* considering cumulative damages, e.g., on buildings caused by earthquakes and tsunamis, need to be assessed (Gómez Zapata et al., 2022b, 2023).

The negative effects of disasters may cause a failure or disruption of critical infrastructures, and they are not geographically limited to the area directly affected by the disaster. For example, in power networks a failure of one of its components can trigger a cascade of failures in other components (cf., UCTE 2004; FIUBA, 2020). Furthermore, the dependence to other critical infrastructures, such as water supply pumps, traffic signals, SCADA systems (acronym for Supervisory Control And Data Acquisition), can extend the negative effects of the disaster in unforeseeable ways (Rinaldi et al., 2001). For studying the *impacts on critical infrastructure*, different approaches analyse the fragility of infrastructure components (cf., FEMA, 2003; Pitilakis et al., 2014), simulate cascading failures (Crucitti et al., 2004; Hernandez-Fajardo and Dueñas-Osorio, 2013), assess the criticality of infrastructures (e.g., Greiving et al., 2021) and propose frameworks for probabilistic risk analysis (cf., Ferrario et al., 2022; Rosero-Velásquez and Straub, 2022).

In addition, such negative effects persist over the time until the failures and disruptions are repaired. The longer it takes to resume the normal operation of critical infrastructure, the larger the impact to the economic activity becomes. Therefore, risk is also determined by the recovery of critical infrastructure after the disaster. The study of the *resilience of critical infrastructure* combines models for simulating the impact of natural hazards and the recovery process thereafter (FEMA, 2003; Ouyang et al., 2012; Sedzro et al., 2018). It also supports a risk analysis considering not only the direct impact to the infrastructure, but also the indirect consequences to the society (Bruneau et al., 2003).

2.2.3 User involvement

For the development of the presented information system for multi-risk assessment, we choose an agile software development approach (cf., Kent et al., 2001). This methodology is based on an iterative development approach where user requirements can be updated and considered for the system development through close interaction. This allows the co-creation of a system where the role of the user shifts from consumers of information to informants for needs on how systems are developed (cf., Gomillion, 2013).

The call for user involvement is not new (Kling, 1977; Norman, 1986) and has been suggested to be treated as one of a number of means for information systems development projects to be more successful (e.g., He and King, 2008; Bano and Zowghi, 2014). Kujala (2003) conducted a review of benefits and challenges of user involvement finding that interaction with users has various positive effects, especially on user satisfaction. This was confirmed by Bano et al. (2017) who performed an empirical exploration of user involvement in software development and concluded that user satisfaction and the resulting system are mutually constituted. Being aware that user requirements can sometimes be contradictory, it was considered important for the development process to evaluate the necessity and consequences of each requirement. Accordingly, we geared our approach to the needs of potential users and its practicality (cf., user-centered design; Gould and Lewis 1985; Karat, 1997) where the users are involved throughout the design and development process (Fig. 2).

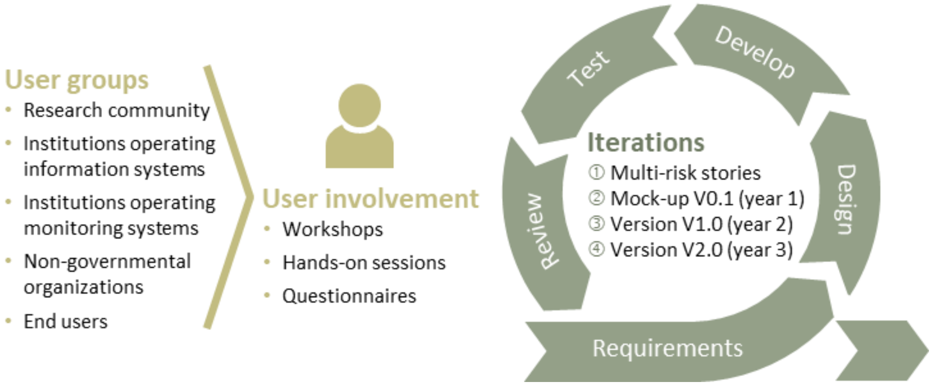

Figure 2. Detailed graphical representation of the user involvement in the design and development process (compare Fig. 1). The five different user groups were involved in the four iterations, with requirements and feedback gathered mainly through workshops and hands-on sessions, as well as questionnaires.

The development of our multi-risk assessment tool is based on a structured and systematic feedback process involving different user groups throughout the whole design and development process in various iterations to assure that requirements from the user side are considered from the very beginning (cf., Gómez Zapata et al., 2021a). For the user involvement the goal was to target various representatives from the research community (universities and scientific research institutes), institutions operating information and monitoring systems, non-governmental organizations and the so-called end users (e.g., employees of planning and disaster risk management institutions). The iterative design and development process can be broken down into four iterations, each of which was accompanied by a feedback mechanism to define further requirements and to reassess and adjust existing ones. (1) Starting point for the approach is the definition of *multi-risk stories* with the users (Sect. 2.2.1). The joint discussion with the different user groups is intended to ensure the realism and relevance of the stories, thus elaborating a common starting point that will allow structured discussions throughout the design and development process of the tool in order to capture the requirements from the user's point of view. These serve as input, definition and enhancement of the tool and its functionalities.

(2) As a second step, a *mock-up* (version V0.1) is used to visualize the envisaged tool. Therefore, we design a graphical user interface representation and visualize the possible functionalities and outputs for each step in the multi-risk chain. This allows the user to get a sense of the tool, even if the individual buttons were not yet functional. This mock-up proves particularly useful for discussing the planned features, getting feedback, and collecting requests for changes.

(3 and 4) In the following, we conduct the feedback process along the two *functional versions* of the tool, i.e. versions *V1.0* and *V2.0* (Fig. 2). Methods for assessing the requirements ranged from collaborative workshops including practical hands-on sessions to questionnaires and market research.

A set of guiding questions is developed which cover a broader spectrum of aspects regarding (1) information content, (2) user interface and (3) usability and applicability in order to evaluate how scientific research can be made applicable through a practical tool for the assessment of multi-risk scenarios. We collect the responses to these questions via a questionnaire, which are provided to users during workshops (*quick assessment*). While testing the tool either during practical hands-on sessions in user workshops or without guidance over a certain period of time after these workshops an additional questionnaire (*detailed assessment*) is used. When formulating the questionnaires for the different development steps of the tool, we aim to maintain key questions throughout the entire evaluation period. Other questions are changed or replaced in subsequent versions of the questionnaire as they are no longer relevant. The questionnaires cover up to 48 specific questions as well as three open questions to describe the overall satisfaction with the tool (see the Supplement). Information about the personal profile, i.e., the work area and function / role of the respondents is gathered while ensuring the data protection rights of individuals.

2.2.4 Scenario-based system development using distributed web services

We aimed for an approach that is applicable and adaptable to different multi-risk situations, geographic areas and scales. With this objective in mind, various system architectures can be considered. Here, we decided to create a system based on a decentralized service-oriented architecture (SOA) using distributed web services. Among other factors we selected this approach because of the following three reasons: (1) Web services can be combined to form a chain representing different multi-risk situations leading to modularity, flexibility, and scalability, (2) exchange of models / data between institutions are facilitated as data do not need to be handed over ensuring that expertise remains with the experts, and (3) the data and models are up-to-date as they remain at specialized institutions. A key element of this system approach is the use of independent web services which allow to visualize the results coming from various models from research (Sect. 2.2.2). We designed a tool which consists of (i) distributed web (processing) services, (ii) a workflow control (orchestration and caching) that links the web services into value chains to map complex multi-risk scenarios, and (iii) a graphical user interface (GUI) that allows users to interactively run various scenarios (Fig. 3).

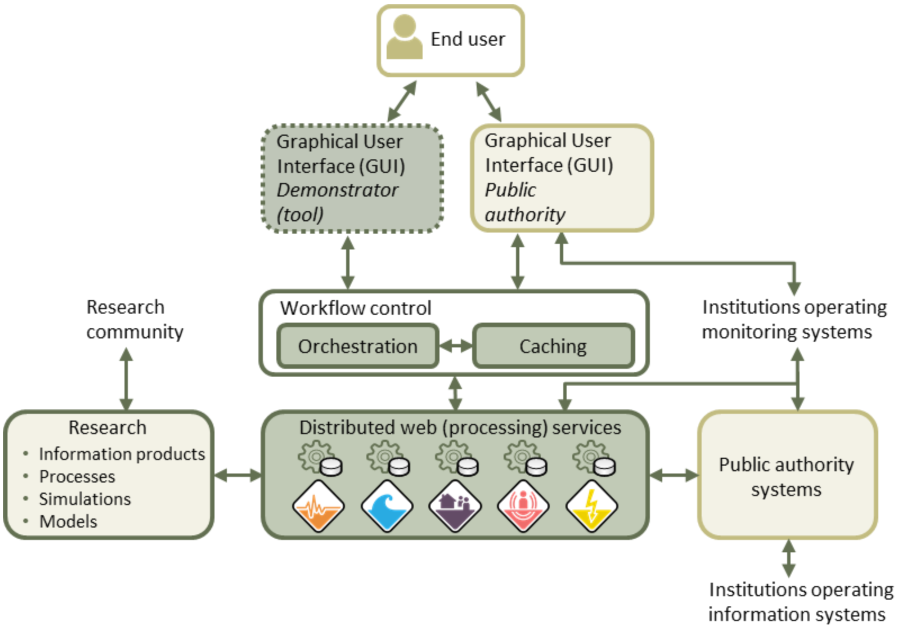

Figure 3. Elements and actors involved in the design and development of the multi-risk information system. The dotted line of the GUI of the Demonstrator (tool) indicates its provisional character, serving for demonstration purposes only.

The interaction between the loosely coupled web services is achieved by the use of Web Processing Service (WPS) interface standard directives published of the Open Geospatial Consortium (OGC; WPS, 2018). WPS are implemented in a flexible and scalable architecture based on Docker containers that encapsulate the running processes (Brinckmann et al., 2020). The interoperability between the different services is ensured by thorough harmonization of input and output formats and the use of on-the-fly converters. Dedicated WPS create simulations of intensity maps for specific hazards, either on the fly (e.g., for earthquake ground motion simulation) or by querying a list of pre-simulated events (e.g., for tsunami inundation maps) (Pittore et al., 2020).

For the graphical user interface (frontend) we created a web-based application (accessible via a web browser) with the aim (1) to allow users to specify the inputs to a model, trigger its execution and display the results of the models; (2) to chain a set of models into a scenario that represents the multitude of processes describing a complex risk situation (e.g., earthquake causing damage in buildings and triggering a tsunami) and (3) facilitating the user's exploration of the range of impacts that one or more natural hazards may have. In addition to the control layer, which orchestrates the various web services, browser caching and WebGL-rendering were introduced as another cross-cutting functionality of the tool to speed up the display of large amounts of data in the browser.

3 Results and experiences using the example of Lima Metropolitan area, Peru

3.1 Study area

Peru is highly exposed to natural hazards such as earthquakes, tsunamis, floods, mass movements (e.g., landslides, avalanches), strong winds, heavy rains, fires and low temperatures (INDECI, 2020). The implementation of our approach is shown for the example of Lima Metropolitan area, Peru. Together with the adjacent port city of Callao, the capital city of Peru, Lima, has nearly 11 million inhabitants representing approximately one-third of Peru's total population (INEI, 2022) (Fig. 4). This region is threatened by strong earthquakes and tsunamis originated from the Andean subduction zone, one of the longest continuous subduction zones on earth (cf., Rodríguez et al., 2020). In the past, the capital city of Peru was hit by significant earthquakes causing tsunami run-ups over 24 meters, e.g. in 1586 (Mw 8.1), and 1746 (Mw 8.6) (Kulikov et al., 2005; Olarte et al., 2008). Notably, a major part of the road network runs along the tsunami-prone coast. The same applies for the main port of Callao and the nearby Jorge Chavez International Airport (CENEPRED, 2017). Lima Metropolitan area is further exposed to critical infrastructures, such as water supply, wastewater disposal, IT and telecommunication, or electricity whereas a failure of electricity supply has the quickest negative impact on other sectors (cf., Greiving et al., 2021).

Figure 4. Multispectral satellite image (left) of the study area of Lima Metropolitan area, Peru, showing the expected tsunami inundation from a Mw 8.9 earthquake (generated with TsunAWI; Harig et al., 2008) and contemporary coastal features such as the harbour in Callao (upper right) and the coastal highway in Miraflores (lower right). Photographs taken by (A) Torsten Riedlinger (2018) and (B) Elisabeth Schoepfer (2019). Map data © Copernicus Sentinel data 2022, processed by ESA; © DLR, EOC Basemap Map Service 2023.

3.2 Story-based concept design

Following the story-based concept design (Sect. 2.2.1) we characterized the various elements composing the multi-risk situation. Considering a reference (worst-case) scenario of an 8.8 Mw earthquake off coast of Lima Metropolitan area as documented by INDECI (2017), we defined the following story: "*Strong shaking occurs in Lima Metropolitan area, Peru, during the day time. There are severe damages on buildings and infrastructure, many people are directly affected by building collapses. As the earthquake has the potential to trigger a tsunami, a tsunami warning is issued and evacuation to safe areas is announced. Coastal roads and roads to highlands become progressively congested. In the following a first tsunami wave impacts the coast and starts inundating parts of the harbour area in Callao. Because of the numerous building collapses, city roads become less suitable for prompt evacuation.*"

Based on this reference scenario and consultations with Peruvian stakeholders, the elements of the multi-risk story, which should be addressed by the project were identified. Accordingly, a flow chart (Fig. 5) was created conceptualizing the main logic, its components and information flows.

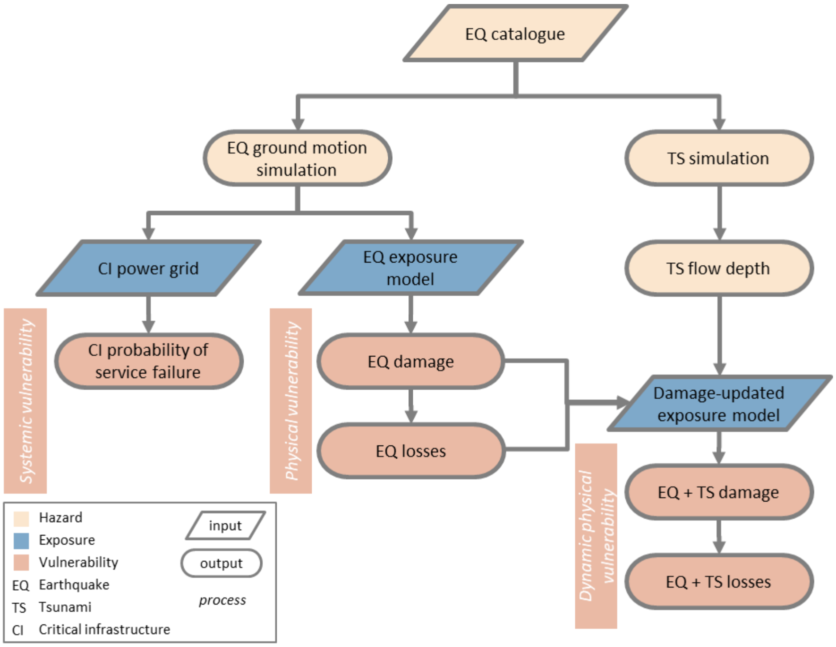

Figure 5. Flowchart of the multi-risk story for an earthquake / tsunami (Harig and Rakowsky, 2021) event affecting housing and the critical infrastructure power grid.

3.3 Demonstrator for a multi-risk information system

3.3.1 Web services and workflow control

Each step in the flowchart (Fig. 5) is represented by one or more models offered as web services with corresponding digital object identifiers (DOI). In the multi-risk story exemplified in the study area of Lima Metropolitan area, the starting point for the hazard

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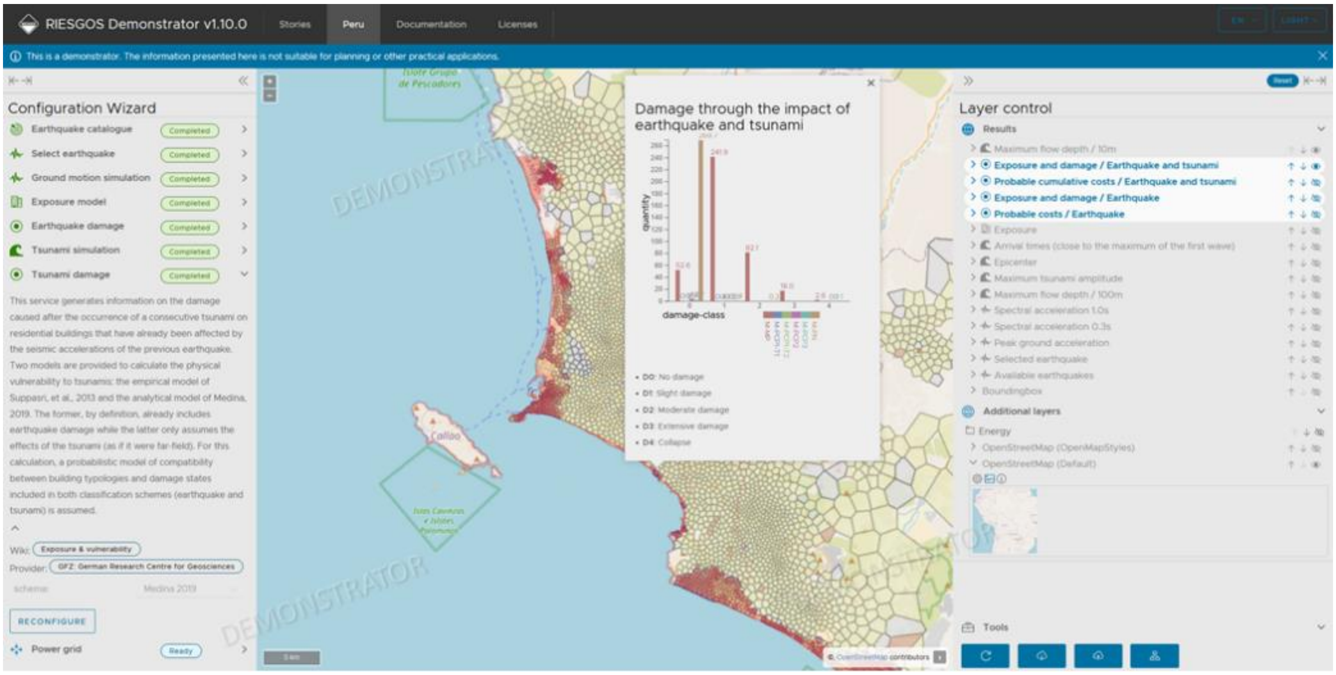
is an earthquake catalogue (Pittore et al., 2021a) where the user can choose between different scenarios, including historical and observed (compiled by project by the Global Earthquake Model (GEM) Foundation in the framework of the SARA project (i.e., SARA, 2016a; 2016b; CERESIS, 1995; Tavera et al., 2001; Leyton et al., 2009) and stochastically earthquakes (i.e., followed the approach outlined in Aristizábal et al., 2018) earthquakes. A single event within the catalogue form an earthquake scenario that is compatible with the probabilistic seismic hazard model proposed for the study area. It is described through basic parameters, such as the epicenter location (longitude, latitude) together with hypocenter depth (in kilometres), moment magnitude (Mw), and rake, dip, and strike angles, that together are used to model finite earthquake ruptures using some openly available tools of the OpenQuake Engine (Pagani et al., 2014). The user can select one of these available earthquakes which in the following triggers the subsequent web service. To do so, we have decided to simulate its correspondent seismic ground motion fields through the adoption of suitable GMPEs (ground motion prediction equations) for the specific tectonic context of the subduction inter-face tectonic regime. These spatially distributed seismic ground motion fields are simulated for the selected earthquake scenario. They are generated through the Shakyground webservice (Weatherill et al., 2021), that for case of Lima Metropolitan area, uses the Montalva et al. (2017) GMPE in terms of expected accelerations (i.e., peak ground acceleration (PGA) and spectral periods (SA) 0.3, and 1.0 seconds). This web service was constructed based on the QuakeML data formats (Schorlemmer et al., 2011) and the OpenQuake Engine (Pagani et al., 2014). Examples of these scenario-based ground motion fields are available in Gómez Zapata et al. (2021c). For those earthquakes which can potentially trigger a tsunami, another web service is introduced which provides access to pre-calculated numerical tsunami simulations. The simulations were generated using the physical generation and propagation model TsunAWI (Harig et al., 2008), which accounts for a triangular mesh with variable resolution as proposed by Harig et al. (2020). The available outputs including the maximum tsunami amplitude, arrival times and tsunami inundation depth are displayed (Rakowsky et al., 2013; Androsov et al., 2023). Some of these scenario-based tsunami inundation maps are available in Harig and Rakowsky (2021), respectively.

In order to assess the exposed elements of interest (e.g. residential buildings), exposure models are constructed. They provide information on the location, spatial aggregation and typologies of the residential building stock of Lima Metropolitan area (Yepes-Estrada et al., 2017). Each building typology has associated a fragility function (Villar-Vega et al., 2017) for both hazard-vulnerability schemes (earthquake and tsunami), as documented in Gómez Zapata et al. (2021b). The demonstrator is able to serve these exposure and fragility models through the scripts Assetmaster and Modelprop (Pittore et al., 2021b), which are used as two web services. In order to assess the damage states of the residential buildings and losses after the occurrence of the selected earthquake the so-called damage exposure update (web) service DEUS is triggered (Brinckmann et al., 2021). Using an updated exposure model that includes earthquake-induced damages, and simulations of tsunami inundation depth as inputs, once again the DEUS web services is initiated in order to approximate the expected cumulative damage and disaggregate the losses per hazard event (Gómez Zapata et al., 2023). This methodology makes use of inter-scheme damage compatibility matrices, that can be consulted in Gómez Zapata et al. (2022c); and a set of state-dependent tsunami fragility functions (Gómez Zapata et al., 2022d), that for the case of Lima Metropolitan area were constructed after having modified the analytically derived ones originally proposed in Medina (2019).

Finally, the user can also receive information on the vulnerability of the power network showing a spatially distributed probability of service disruption in the affected area (Rosero-Velásquez et al., 2022). That probability is computed based on a Monte Carlo simulation of cascading failures within the network, using the algorithm presented in Crucitti et al. (2004) and Hernandez-Fajardo et al. (2013).

3.3.2 Graphical user interface (GUI)

A graphical user interface (GUI) allows the user to independently explore the different risk scenarios making use of the aforementioned web services. The designed GUI is divided into three main display areas: the map window in the centre, the configuration wizard that controls each web service on the left, and the results panel on the right (Fig. 6). In the configuration wizard, the user is guided through the multi-risk story where he can select different parameters according to his specific interests. In the layer control panel, the user can examine and view the processed results and gets more information about the outputs (e.g., legends, detailed descriptions). In order to maintain a solid overview, only the parameters relevant for the currently selected step are highlighted as active which enables intuitive control. In this way, the user does not lose track of the current step in the multi-risk chain, even with a long and complex multi-risk story.



This is a demonstrator. The information presented here is not suitable for planning or other practical applications.

This service generates information on the damage caused after the occurrence of a consecutive tsunami on residential buildings that have already been affected by the seismic accelerations of the previous earthquake. Two models are provided to calculate the physical vulnerability to tsunamis: the empirical model of Suppasri, et al., 2013 and the analytical model of Medina, 2019. The former, by definition, already includes earthquake damage while the latter only assumes the effects of the tsunami (as if it were far-field). For this calculation, a probabilistic model of compatibility between building typologies and damage states included in both classification schemes (earthquake and tsunami) is assumed.

scheme: Medina 2019

Figure 6. Graphical User Interface (GUI) of the information system (demonstrator) exemplified for the study area of Lima Metropolitan area, Peru (as of November 2022). Map data © OpenStreetMap contributors and available from https://www.openstreetmap.org.

3.4 User feedback

User feedback was obtained throughout the four iterations, i.e. development stages (Fig. 2) and was mainly facilitated through joint workshops and practical hands-on sessions involving all five user groups (Sect. 2.2.3). The number and diversity of

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participants in user feedback was high throughout the process, which spanned several years. Although we tried to target the questionnaires to the same users, there were fluctuations due to job changes and responsibilities of the respective stakeholders. Furthermore, it should be noted that the responses to the questionnaires depend very much on the professional background and daily work tasks of the respondents. The following results reflect the obtained feedback from the respective participating user group representatives, but do not meet any requirements for statistical representativeness. The first step in the iterative development process was to define a *multi-risk story* describing the different elements to be analysed in the multi-risk situation (Fig. 2, iteration 1). During the joint discussion between scientists, technicians, professionals and users, a compromise had to be found between the requirements of the users and the technical possibilities of modelling certain processes. In the end, a set of elements was agreed upon that was judged to be the most realistic and at the same time feasible in terms of data, technology and science. This discussion took place in a workshop held in Lima on 20 April 2018.

Building on this, the users were involved in the three development iterations of the tool which included a first trial version V0.1 (*mock-up*) that was not yet functional (November 2018), followed by two functional *versions* V1.0 (November 2019) and V2.0 (November 2020) (Fig. 2, iterations 2 to 4). All three versions were presented and discussed during joint workshops. For the case study in Peru, the first two workshops took place in Lima (*mock-up* V0.1: 4 December 2018; *version* V1.0: 19 November 2019) while the third workshop was held online due to the global pandemic travel restrictions (*version* V2.0: 9 February 2021). Next to open feedback rounds, feedback was additionally collected via questionnaires. During this process, we experienced that complementary practical hands-on session (V1.0: 19 November 2019; V2.0: 10 February 2021) with the tool increased significantly the quality of feedback as one can in particular document the user experience in action. It is worth noting that direct interaction with the users during these hands-on sessions supported to gain a better understanding and to avoid misinterpretations of articulated requirements or feedback. In addition, these hands-on sessions allowed many suggestions for improvement regarding the practical handling of the user interface as well as the visual and descriptive presentation of the results. These included comments on the visualization of damage grades, both on colours used and number of grades. Probably the most controversial response was regarding descriptions. Some users wanted commonly used terms, while others voted to use international standards (e.g., the Tsunami Glossary (2019) published by the Intergovernmental Oceanographic Commission). There were also opposing opinions on technical functionalities. While some users liked to use the option of moving layers independently between levels, other users were irritated by this option. From this we have learned that it is important to always explain well the advantages and disadvantages of the embedded functions.

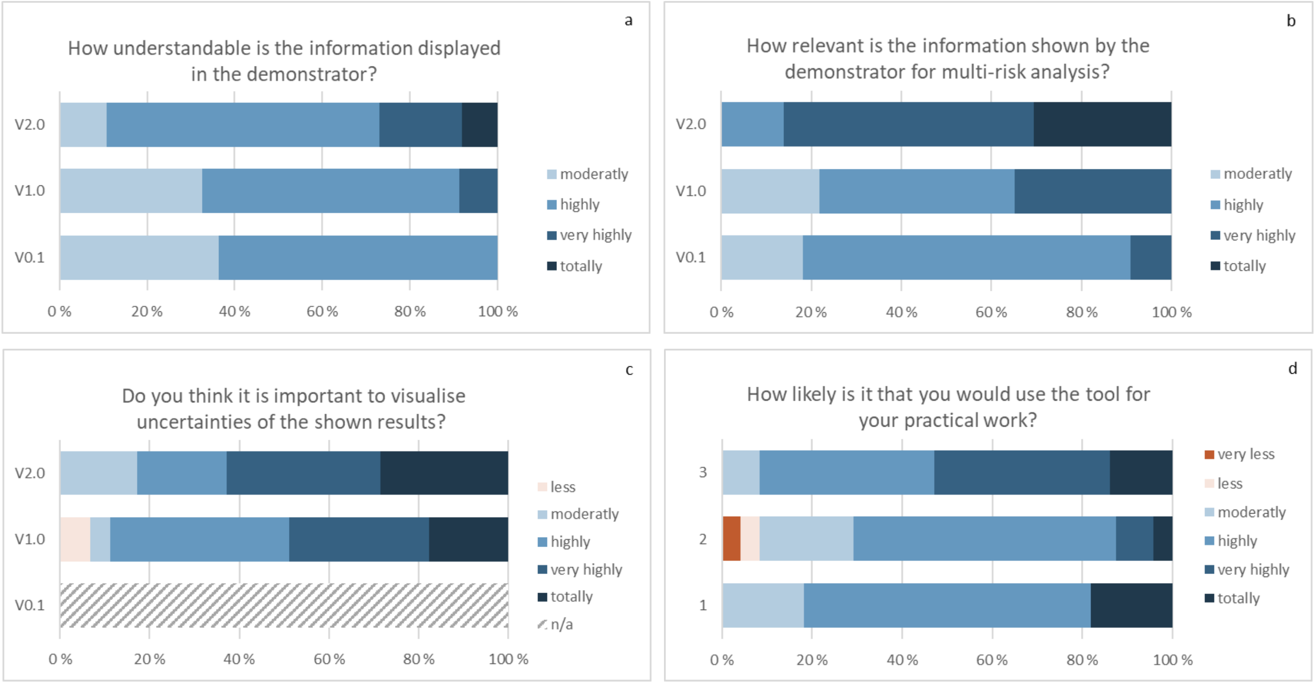
In the following, we further highlight the main findings related to the understandability and relevance of the information generated, and the practical applicability of the tool. Comparing the appreciation of the understandability of the information visualized in the tool over the three development stages, a steady increase can be observed, which can be attributed to the improvements made through the systematic integration of the feedback. While in year 1 (V0.1) the information displayed was rated with 36 % as moderately understandable and highly by 64 %, for the adapted version in year 2 (V1.0) users responded that the understandability was moderate (32 %) to high (59 %) and 9 % even said it was very high. In year 3 (V2.0), the majority of all respondents (89 %) agreed that the clarity of the information displayed in the demonstrator was highly (62 %), very highly

(19 %) or even totally understandable (8 %) (Fig. 7a). When asked about the reasons for lack of clarity, the main concerns of users were related to missing explanations of the underlying processes, concepts and variables, but also data quality seemed to play a role. The feedback was addressed by setting up a wiki to provide further details on the information presented. It also became clear that the majority of potential end users have little or no experience of using more complex risk analysis tools and interpreting scientific map products. This led to the proposal to introduce two user modes, where less experienced users are guided through the analysis process using pre-set default parameters ("*basic user mode*"), while more experienced users can freely use all configuration options ("*advanced user mode*").

The increase in understandability seems to goes along with a more positive assessment of the relevance attributed to the information. In year 1 (V0.1), 18 % of the users replied that the shown information is moderately relevant whereas the majority of 73 % rated the relevance as high, and even 9 % as very high relevant. In year 2 (V1.0), already 35 % of the users said that the relevance of the information was very high, while in year 3 (V2.0) an overwhelming majority (55 %) rated it as very highly and 31 % as even totally relevant (Fig. 7b). Users also suggested greater consideration of critical infrastructure such as gas networks, ports, bridges, water supply network, healthcare facilities and communication networks. Of particular interest were the range of possible power network system failures, the assessment of the recovery time of partial or full system functions and the minimum supply to the population.

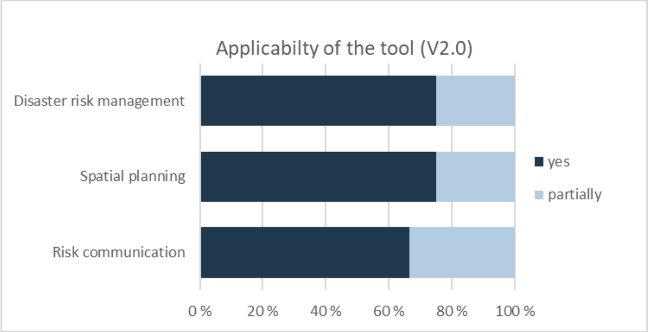
When working with scenarios, models and data, the topic of uncertainty cannot be neglected. With version V1.0 in year 2, we asked users if they thought it was important to visualise the uncertainty of the results shown in the demonstrator. While the researchers are aware that the data and model results included in the system are subject to epistemic and aleatory uncertainties, the results of the user feedback process left the impression that the issue of uncertainty receives little attention in the practice of users involved in planning or disaster risk management. In year 2, out of all responses only 7 % of users replied that is less important to visualize these uncertainties, 4 % rated it as moderately important, 40 % as highly and 31 % as very highly important. 18 % agreed that it is totally important to visualise uncertainties. The discussion on uncertainties during the joint workshops in year 3 seems to have increased the awareness on the topic, as 29 % of users confirmed that is totally important to visualise uncertainties, in addition with 34 % rating it as very highly important. Another 20 % rated it as moderately important and only 17 % as less important (Fig. 7c).

With regard to possible practical applicability, the question was asked how likely it is that users would use the tool for their practical work. For the V0.1 version presented in year 1, 18 % of the users rated the possibility of using such a tool as moderate, 64 % as very high and 18 % as totally. In year 2 (version V1.0) users responded that it is very less (4 %) and less (4 %) likely of using the tool in their practical work. The majority of users rated the likelihood of using the tool as moderate at 21 % and high with 59 %. While 8 % of users considered this to be very high, 4 % answered that they totally would use such a tool. The practical applicability of version V2.0 in year 3 compared to very V1.0 increased significantly. 8 % of users said they would be moderately likely using the tool, while 39 % said they would be highly likely and 39 % very high likely would use it. Finally, 14 % of users said that they totally likely would use the tool if it was available (Fig. 7d).



495 **Figure 7.** User feedback obtained during the three development stages (mock-up V0.1, versions V1.0 und V2.0) of the demonstrator for a multi-risk information system for years 1 (V0.1), 2 (V1.0) and 3 (V2.0). The diagrams represent four selected questions (out of a total of 45) on the information content (Fig. 7a-c) and applicability of the tool (Fig. 7d) asked to users in Lima.

As part of the user feedback process, we discussed with the workshop participants potential fields of application. The majority of respondents saw great potential in the fields of disaster risk management, spatial planning and risk communication (Fig. 8).



500 **Figure 8.** User feedback on the potential of practical applicability obtained in workshops with users in Lima during the development process of the demonstrator for a multi-risk information system in year 3 (V2.0).

During specific end user workshops, we further assessed the usefulness of the tool for local disaster risk management and spatial planning in the study area. It was found that the multi-scenario approach provided by the demonstrator has limited relevance to current disaster risk management and spatial planning, as these processes in Peru need to be based on a fixed reference scenario with clear specifications of data and methods provided by national authorities and are already supported by existing GIS tools. However, it has also been recognised as an interactive tool for gaining a better understanding of complex risk situations. It can therefore be used as a complementary tool to existing information systems. In addition to the three topics described above, the areas of policy-making (e.g., investment planning) and disaster risk response have been identified as further fields of application. Even though the tool is having its main application field in the disaster risk reduction, users in Lima also expressed the potential to use the tool for the initial assessment of the situation in the aftermath of a disaster from complex multi-hazard risk situations and cascading effects. In this case the architecture of the tool would have to be adapted to the requirements in the response phase after a disaster. Since it is reasonable to assume that communications and internet connections could be interrupted during a disaster, the tool would need to operate locally without depending on an internet connection. For applications in the prevention and preparedness phase, it is desirable to have a decentralized architecture like the one in the demonstrator, allowing the connection of servers that store various data that can be updated regularly.

4 Discussion and conclusions

In this paper, we presented one (of many possible) approach(es) how a novel approach to multi-risk analysis can make a practical contribution to the implementation of global risk reduction goals. With the presented information system for multi-risk assessment, we prove that such a system is able to reconcile scientific research with its corresponding data and models with user requirements for describing different scenarios of a complex multi-risk situation and to support decision-making. In the following, we like to discuss various aspects, including limitations.

i. *Relevance and acceptance*: Users have recognized the relevance of the topic right from the beginning and have expressed a high demand. This is certainly also due to the fact that the topic of multi-risk is becoming increasingly relevant in practice and that there are still few practical options available for dealing with these new challenges. Various stakeholders wanted to use the tool directly in its first version as they recognized great potential in communicating scientific results to decision makers.

ii. *Story-based scenario approach*: The story-based approach enables users to simulate various scenarios in one defined multi-risk situation (*story*) and to compare the results accordingly. The multi-scenario approach may be interesting for the development of strategies to strengthen or develop resilience strategies or to check the robustness of planned or already implemented measures (e.g., with reference scenarios) under different hazard scenarios ("*stress test*") or to changing conditions. However, the multi-scenario approach has limitations in some applications, especially when there are mandatory requirements to use a predefined reference scenario for practical planning processes. This is especially the case for local DRM planning.

iii. *Complexity*: Multi-risk situations can become very complex. Obviously, models and scenarios are always incomplete as they approximate complex real situations. The analytical process of the interactions of elements in scenarios is furthermore confined to selected processes. In our approach we focused on the physical elements of vulnerability (buildings, critical infrastructure), but neglected the economic, environmental, political, social and societal aspects of vulnerability. This resulted in a considerable limited representation of what would actually happen in a real disaster situation.

iv. *Uncertainties*: We presented an approach which is based on multi-risk stories and scenarios, which implies a variety of uncertainties throughout the analytical process. A first dimension of uncertainty derives from the selection of the elements to consider in the *stories* and the description of interactions among them; followed by further uncertainties, e.g., due to lack of knowledge (epistemic uncertainties) or due to the inherent variation associated with the environment under consideration (aleatory uncertainty) (e.g., Oberkampf et al., 2002). Moreover, uncertainties are interlinked along a multi-risk chain and can not only add up but ultimately reinforce each other. We call for the inclusion of mechanisms to visualize the uncertainties of the risk assessment, preferably in graphical form and without the use of technical jargon, so as to allow appropriate communication with end users about the respective level of uncertainty.

v. *Practical applicability*: The experience throughout the development process showed that the modelling of complex multi-risk situations is challenging and subject to limitations in representing what actually can happen (see point iii) as well as to significant uncertainties (see point iv). This leads to the conclusion that the results generated by the tool have rather an orienting character and that the main purpose of the tool is mainly being an exploration tool to better understand complex risk situations. It should therefore be understood as an instrument that complements already existing information systems and planning tools in the different fields of applications.

vi. *Decentralized architecture*: The selected decentralized architecture certainly has advantages ranging from (1) updated information, as the data and models in the specialized institutions are usually refreshed on a regular basis, (2) modularity, flexibility, scalability of multi-risk situations to (3) easier data exchange between institutions as data remain at their point of origin / host. However, despite the use of international standards such as the geospatial WPS defined by the OGC, the integration of new web services into the tool requires adaptations of the underlying orchestration structure. Thus, the (re-)combination of web services to form a new multi-risk chain calls for in-depth knowledge. We recommend to analyse if other stories, e.g., landslides after an earthquake, failure of drinking water infrastructure, evacuation of the affected population, are suitable following the proposed approach.

vii. *Operational system*: Users showed strong interest in the presented tool. However, the transfer from a demonstrator system to an operational service requires further efforts along with a clear commitment and solid institutional embedding. We recommend a partnership between research institutions, public authorities and service providers whereas one key authority should act as the hosting institution to integrate the tool. The integration process itself requires profound knowledge both, in the models and IT programming (both backend services and frontend development), which needs the interaction of different specialized institutions and professional support from IT experts.

viii. *Co-creation with users*: Collaboration between researchers, software developers and different user groups definitely helps to develop a tool that is useful in practice. However, collaboration requires a strong engagement from all sides. It requires a moderated process which allows that user demands can be communicated to the researchers and developers. At the same time, the involved user must be aware and able to cope with trade-offs and compromises, as they might not benefit directly from the tool while it is still under development or in a demonstrator stage. To avoid false expectations and misunderstandings, we emphasize that transparency and clear statements are most important throughout the user involvement process.

In conclusion, we have demonstrated that the tool is capable of calculating and visualizing the cumulative effects of successive hazard events. Despite some limitations, in particular with regard to already standardized planning processes and the exploratory nature of the tool, users see great potential for different fields of application and a high expectation was expressed, especially from the user side in the local pilot area, that the developed tool would be available and applicable locally. Based on these findings, it appears reasonable that the research community continues working with users on the ground. Our findings also support the call to science to contribute to an evidence-based policy. At a next step, the impact of such a system in terms of cost-benefit would be interesting to evaluate. After all, the future will tell us how much such a tool can help in planning for catastrophic events and what, in the end, can technologically not be controlled but is simply fate.

Code and data availability

Repositories of the projects RIESGOS and RIESGOS 2.0 are provided as open source code on GitHub at https://github.com/riesgos and https://github.com/gfzriesgos (last access: 26 July 2023). DOI-referenced data from the RIESGOS and RIESGOS 2.0 project are hosted at GFZ German Research Centre for Geosciences at: https://dataservices.gfz-potsdam.de/portal/?q=riesgos* (last access: 26 July 2023).

Supplement

The questionnaire is provided as a supplement to this manuscript.

Author contributions

The paper was conceptualized by ES, JL, TR, HS, GS and HT. ES coordinated the effort and prepared the original draft of the manuscript with major contributions from JL, HS, TR, and HT. JCGZ, HRV, SH and CG provided details on the study, data analysis and modelling. Technical details on software development were provided by ML and NB. Details on user involvement and feedback analysis was performed by HS with major contributions of CDL and ES. All authors contributed on previous versions of the manuscript and approved the final version.

Competing interests

ES, JL, TR and HT are guest editors of the journal. The other authors declare that they have not conflict of interest. The funders had no role in project design, data collection and analysis, decision to publish, or preparation of the manuscript.

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