Deliverable D4.1

The web-based simulation and information service for multi-hazard impact chains. Design document.

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Abstract

The overall objective of the PARATUS project and the platform is the co-development of a web-based simulation and information service for first and second responders and other stakeholders to evaluate the impact chains of multi-hazard events with particular emphasis on cross-border and cascading impacts. This deliverable provides a first impression of the platform and its components. A central theme in the PARATUS project is the co-development of the tools with stakeholders. The central stakeholders within the four applications case studies are therefore full project partners. They will be directly involved in the development of the platform. We foresee that the PARATUS Platform will have two major blocks: an information service that provides static information (or regularly updated information) and simulation service, which is a dynamic component where stakeholders can interactively work with the tools in the platform.

The PARATUS will further make sure that documentation (e.g., software accompanying documentation) is also publicly available via the project website[1] and other trusted repositories.

The deliverable 4.1 was submitted to the European Commission on 31/07/2023 and is waiting for approval by the Research Executive Agency. Therefore, this current version may not represent the final version of the deliverable.

[1] https://www.paratus-project.eu/

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Document History

Version	Date	Author	Description
VI	15-05-2023	Cees van Westen	Made the concept note
VII	16-06-2023	Nadya Kommendatova, Tatiana Ermolieva (IIASA)	Provided input on systemic risk
VII	30-06-2023	Rabina Twayana (AIT), Iqra Naz, Bastian van den Bout (ITC)	Provided input on RiskChanges and FastFlood
VII	14-07-2023	Michalina Kulakowska (CRS)	Provided input on serious games
VII	20-07-2023	Funda Atun and Iqra Naz (UT); Silvia Cocuccioni (EURAC)	Provided input on stakeholders and impact chain tools
	23-07-2023	Philipp Marr (UNIVIE); Marcel Hurlimann and Pavan Kumar (UPC), Lea Schollerer (DLR)	Provided input on hazard tools and data
VII	24-07-2023	Cees van Westen, Liv Hassinger (UT)	Completion of the contributions
VII	25-07-2023	Bettina Koelle (RCCC)	Provided input on adaptation measures
VII	25-07-2023	Cees van Westen, Funda Atun (UT)	Adding missing sections
VII	26-07-2023	Gal Agmon, Bouke Ottow (NRC)	Provided input on user-centred design and on impact-based forecasting
VII	26-07-2023	Cees van Westen, Funda Atun, Iqra Naz, Irene Manzella (UT)	Completing the editing and making the deliverable ready for review
VII	26-07-2023	Irene Manzella	Internal Review
VII	29-07-2023	Christian Geiss (DLR), Bettina Koelle (RCC)	
VIII	31-07-2023	Cees van Westen, Funda Atun, Liv Hassinger (UT)	Incorporating the comments and final check
VIII	31-07-2023	Cees van Westen	Submission of the deliverable

Disclosure Statement:

About PARATUS:

The PARATUS project aims at increasing the preparedness of first and second responders in the face of multi-hazard events and to reduce the risks related to impacts on various sectors that result from complex disasters. The outcome is to develop a cloud-based Online Service Platform that offers support in reducing dynamic risk scenarios and systemic vulnerability caused by multi-hazard disasters. To achieve these objectives, the project will perform in-depth assessments of complex interactions between hazards and their resulting impacts in various sectors, as well as analyse the current risk situation and study how alternative future scenarios could change multi-hazard impact chains. Based on these analysis, scenarios of multi-hazard impacts will be co-designed with stakeholders and developed in four case study areas (including the Caribbean, Romania, Istanbul, and Alpine areas).

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List of Acronyms

Acronym	Definition
AAL	Average Annual Losses
ABM	Agent-Based Model
AIT	Asian Institute of Technology
API	Application Programming Interface
CAPRA	Comprehensive Probabilistic Risk Assessment
CEP	Citizen Engagement Platform
CMINE	Crisis Management and Innovation Network Europe
CMIP	Coupled Model Intercomparison Project
CRA	Community Risk Assessment
CVaR	Conditional Value-at-Risk
DMOP	Disaster Monitoring and Observation Portal
DSS	Decision Support System
DRM	Disaster Risk Management
ESFG	Earth System Grid Federation
ESDI	Earth System Dynamic Intelligence
EU	European Union
EURAC	EURAC Research
EWS	Early Warning Systems
FAIR	Findable, Accessible, Interoperable and Reusable data
FEMA	Federal Emergency Management Agency
FEWES	Food, Energy, Water, Environment and Social Security
GDES	Gender, Diversity, Ethics and Security
GUI	Graphical User Interface
IBF	Impact-Based Forecasting
ICRAMM	Integrated Catastrophe Risk Analysis and Management Modelling
IMHRRF	Integrated Multi-Hazard Risk and Resilience Framework
IPAI	Information Physical Artificial Intelligence
IPCC	Intergovernmental Panel on Climate Change
ITU	Istanbul Technical University
KNMI	Royal Netherlands Meteorological Institute
M	Month
MAAS	Multi-Agent Accounting System
MHRIN	Multi-Hazard Risk Intelligence Networks
PARATUS	Increasing Preparedness and Resilience of European Communities by Co-Developing Services Using Dynamic Systemic Risk Assessment
POC	Proof of Concept
PPCP	Public-Private-Civic Partnership
RAN	Resilience Advisors Network
REA	European Research Executive Agency
CLI	RiskScape Command Line Interface
SMA	Social Media Analytics
SMCE	Spatial Multi-Criteria Evaluation
SMCS	Social Media and CrowdSourcing
UNIVIE	Universität Wien
UT	University of Twente
VaR	Value-at-Risk
WP	Work Package

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Executive Summary

Currently, there are no publicly available tools for developing and quantifying impact chains for compounding multi-hazard events and their cascading impacts. The available loss assessment tools are often not within reach of first and second responders and local authorities, and their data requirements may be overly complicated for the stakeholders to obtain within the time they have to make decisions. One of the main challenges is understanding how the working process of stakeholders can be integrated into a service that is both generic enough to be usable in different settings and flexible enough to be applied to a specific situation. In this framework, the overall objective of the PARATUS project, and hence of its platform, is the co-development of a web-based simulation and information service for first and second responders and other stakeholders to evaluate the impact chains of multi-hazard events with particular emphasis on cross-border and cascading impacts. This deliverable provides a first overview of the platform and its components. A central theme in the PARATUS project is the co-development of the tools with stakeholders. The stakeholders within the four applications case studies are therefore full project partners and they are directly involved in the development of the platform. We foresee that the PARATUS Platform will have two major blocks: an information service that provides static information (regularly updated) and simulation service, which is a dynamic component where stakeholders can interactively work with the tools in the platform. The information service is expected to contain the following components: a terminology WIKI and links to other platforms developed by EU Horizon Europe projects with similar objectives; an impact chain WIKI which contains the standardized impact chains for a number of historical disasters, and which can be queried by users on several aspects; a module linking to hazard and exposure datasets and modelling results; a tool guiding users to various resources on risk reduction measures, and climate adaptations, and a tool to link to relevant datasets of the case study sites. The simulation service contains a series of tools that the users can use to develop new hazard and risk information for their own area and develop future scenarios and risk reduction alternatives. The following tools are foreseen: an impact chain builder, where users can develop their own impact chain of past events, or possible future disaster events, which is used as a basis for quantifying direct damage and prioritizing secondary losses in different sectors; the FastHazard tool which will provide fast estimations of multiple hazards and can be used as basis for risk reduction planning; the RiskChanges tool for the quantification of losses; a resilience indicator tool; a tool for developing future scenarios and risk reduction alternatives; an impact-based forecasting tool; a component for serious games for training with the other simulation tools ; and a tool for collaborative planning. The exact number of components, and the final structure of the platform will be determined iteratively through a series of stakeholder consultations, following a user-centred design. It is important to state here that the design will be a compromise between the stakeholder needs of the stakeholders involved in the PARATUS project as partners (DSU in Romania, ASFINAG in Austria, IMM in Istanbul and NRC in the Caribbean), and stakeholder requirements of the ones outside of the consortium. The platform will be designed in a flexible way to be able to cater for stakeholders that work in different sectors, geographic setting, and interacting hazards, and at the same time to address (a number of) their needs for analysing the impact of compounding and multi-hazard events, with cascading impacts.

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1. Introduction to Work Package 4 and its deliverables

Work Package 4, the User-Centred Risk Assessment and Mitigation Service, is the core of the PARATUS project, as all the information and knowledge from other work packages come together in WP4 to develop the outcome that is an open-source platform for dynamic risk assessment. The PARATUS platform will allow to analyse and evaluate multi-hazard impact chains, risk reduction measures, and disaster response scenarios in the light of systemic vulnerabilities and uncertainties. The services in the platform will be co-created with the support of various stakeholders. The objective of WP4 is fourfold: (i) design of multi-hazard impact chains and definition of the quantifiable components; (ii) model population with hazard, exposure and vulnerability data tailored to the specific user; (iii) co-development of future scenarios based on changes in causes (climate change, socio-economic changes), (iv) co-development of planning alternatives and selection of optimal risk reduction options.

The effort for WP4 contains the following five main tasks, and as outputs, we will have 8 deliverables (Table 1.1).

- Web-based simulation and information service (M06-M46);
- Cloud-based Decision tool on available methods and data sources for analysing changing risk components (M12- M36);
- Scenario formulation and selection approach and tools (M24-M44);
- Cloud-based Integration of tools for decision-making with respect to adaptation measures under possible scenarios. (M30-M46);
- Application of the tool in impact assessment for various sectors (M34-M48).

Table 1.1: Deliverables for WP4 related to the PARATUS platform

Del #	Name	Partners	Month
D4.1	The web-based simulation and information service for multi-hazard impact chains. Design document	**UT,** ASFiNAG, NRC, RCCC, RAN, IIASA, DLR, EURAC, CRS	July 2023 (M10)
D4.2	The web-based simulation and information service for multi-hazard impact chains. First version.	**UT,** ASFiNAG, NRC, RCCC, RAN, IIASA, DLR, EURAC, CRS	May 2024 (M20)
D4.3	The web-based simulation and information service for multi-hazard impact chains. Final version.	**UT,** ASFiNAG, NRC, RCCC, RAN, IIASA, DLR, EURAC, CRS	Aug 2026 (M47)
D4.4	Web-based data selection tool for multi-hazard impact chain modelling	**UT**, ASFiNAG, UPC, DLR, NRC, RCCC, RAN, IIASA	Sep 2025 (M36)
D4.5	Scenario formulation tool for selection approach and tools	**IIASA,** ASFiNAG, UT, NRC, RCCC, RAN	May 2026 (M44)
D4.6	Cloud-based Integration of tools for decision making with respect to adaptation measures under possible scenarios	**RCCC,** NRC, RAN, UT, CRS	May 2026 (M44)
D4.7	Report on the Evaluation of the tool in impact assessment for various sectors, with recommendations	**UT,** UNIVIE, ASFiNAG, KNMI, NRC, ITU, IMM, UB, DUR	July 2026 (M46)
D4.8	Report on the long-term development of the tool under CMINE and within the Red Cross Red Crescent Network	**RAN,** NRC, FI, UT, DB	Sep 2026 (M48)

The PARATUS platform combines the aspects of information provision on methods and tools, best practices, analysis tools for hazard and risk assessment, and simulation of possible scenarios and decision support tools that link the hazard, exposure, and vulnerabilities, into a simulation tool for direct loss estimation. Indirect loss assessment modules are used to either quantify the indirect impact or use semi-quantitative indicators. The system will be based on a set of open-source software scripts (e.g. Python) that can be operated by experts directly, or through a Graphical User Interface. Tools are implemented in a cloud-based environment, using open-source software components. The result will be a system for dynamic multi-hazard impact assessment, where the effect of changes in the individual components can be considered. UT and the stakeholder NRC will take the lead in the co-development of the tool with software developers. RAN will be safeguarding the role of stakeholders. DLR will link with the exposure modelling approach developed in WP1. RCCC will ensure the link with the adaptation measures developed under WP3.

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1.1 Systemic risk

People have always had to face catastrophes involving natural hazards, such as floods, droughts, hurricanes, large-scale fires, etc. However, in today's highly interconnected world losses due to natural hazards are increasing due to compound disaster events, systemic interdependencies and risks emerging within interconnected economic and environmental systems, growing population density, assets and industries concentration in catastrophe-prone areas, and environmental change due to anthropogenic impacts. Multi-hazards impact communication systems, consumption, savings, and investments, critical infrastructure, electricity supply and irrigation, affecting agricultural and energy production and provision systems, thereby undermining food, energy, water, environmental, social (FEWES) security.

The systemic risks in interlinked natural and human systems neither can be characterized and evaluated analytically by a single probability distribution, nor they can be managed in a one-by-one fashion. **Systemic risks and losses in interdependent systems can be defined as the risks of a subsystem (a part of the system) threatening the functions of other subsystems**. A shock in a peripheral subsystem or/and region can trigger systemic risks propagation with impacts, i.e., instability or even a collapse, in other systems and regions. The risks may have quite different policy-driven dependent spatial and temporal patterns. While standard risks analysis and assessment can rely on historical data, systemic cascading risks in interdependent systems are implicitly defined by the whole structure and the interactions among the systems, such as the spatio-temporal patterns of natural hazards, exposures, supply-demand relations, costs, production and processing technologies, prices, trade flows, , risk perception and risk measures, infrastructure in place, and feasible decisions of stakeholders.

Increasing interdependencies and vulnerability in complex systems raise considerable methodological challenges regarding the analysis, evaluation, and management of the interdependent systemic risks. The related decision problems under the lack and even absence of real repetitive observations restrict traditional quantitative risk assessment, prediction, and policy evaluations. The main issue in this case is robust management of the risks (Ermoliev and Hordijk, 2006), which can be achieved by equipping the systems with ex-ante precautionary mitigation and ex-post adaptive strategies enabling the systems sufficient flexibility, robustness, and resilience to maintain sustainable performance and fulfil joint security goals independently of what, where, and when the (systemic) shock occurs.

In front of severe uncertainties and dependent risks, the strategies (decisions) can be of the two main types:

1) the ex-ante strategic **precautionary mitigation anticipative actions** in the face of uncertainty before the event (shock) occurs (construction of dams, bridges, building reinforcement, resource allocation, new technologies, irrigation infrastructure, water reservoirs, grain storage, cat funds, insurance reserves);
2) the **ex-post adaptive adjustments** (reconstruction, insurance claims, reinsurance, credits, financial markets, marketing, inventory control, subsidies, prices, costs) that are made after the information about the event becomes available or the event actually occurs (after observing the event and receiving actual information about real losses, damages, failures, etc.).

A proper robust combination of ex-ante strategic mitigation and ex-post operational adaptive measures can reduce the post-event burden, relax the tightness in various systemic supply-demand relations and lessen chances of critical imbalances, exceedances of vital thresholds, which could otherwise lead to systemic failures with potential catastrophic consequences and the lack of securities. Also, the structure of the two-stage decision-making allows to minimize chances of irreversibility and lock-in situations. Thus, land use planning is often confronted with decisions which are very costly to be reversed or altered (Arrow and Fisher, 1974). Conversion of natural land for building a dike or a water reservoir on the one hand can bring big benefits and on the other, can cause a chain of cascading events in different economic systems and land use sectors making the systems exposed to even more severe events and possibly irreversible long-term systemic risks.

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For example, building a dike to protect against floods can lead to even higher disaster cost if economic activities and properties are allocated next to the dike, and the dike suddenly breaks due to the lack of proper maintenance (as in the case of New Orleans flood induced by hurricane Katrina, which is considered to be both a "human-made" *and* natural disaster).

As it is not possible to totally prevent disasters, many concerned organizations are now considering as a priority to strengthen the societal disaster resilience through various combinations of ex-ante and ex-post mitigation and adaptation measures. The resilience towards disasters can be understood as the **capacity** of a social entity (e.g., a group or community), "**the ability of individuals, communities, organizations and states to adapt to and recover from hazards, shocks or stresses without compromising long-term prospects for development**" (Combaz 2014). According to the Hyogo Framework for Action (2005), disaster resilience is determined by the degree to which individuals, communities and public and private organisations are capable of organizing themselves to learn from past disasters and reduce their risks to future ones, at international, regional, national, and local levels. Disaster resilience is part of the broader concept of **resilience** – '**the ability of individuals, communities and states and their institutions to absorb and recover from shocks, whilst positively adapting and transforming their structures and means for living in the face of long-term changes and uncertainty**' (OECD, 2013).

Societal resilience can be characterized by three main properties: **resistance, recovery, and "creativity"** (Kimhi & Shamai, 2004). Resistance relates to a community's efforts to withstand a disaster and its consequences, i.e., to be properly equipped with ex-ante precautionary mitigation and ex-post operational adaptive decisions. It can be understood in terms of the degree of disruption that can be accommodated without the community undergoing long-term change (e.g., to its social structure; (Adger, 2000). Here, resistance is the distance between the community's pre-disaster level of functioning and a threshold beyond which the community would be unable to return to its usual state. Recovery relates to a community's ability to absorb the disaster losses or 'pull through' the disaster. It is this property that refers directly to the idea of a community 'bouncing back' to its pre-disaster level of functioning (Breton, 2001). Recovery can be understood in terms of the time taken for a community to recover from a disruption. Creativity can be defined as the ability to learn from experience, perhaps, aiming to attain higher resistance and recovery capacities.

The disaster risk management can be represented by the four stages: mitigation, preparedness (which is a part of non-structural mitigation), response, and recovery. Mitigation is the general process of strengthening a community's capabilities so that it has the resilience to better cope with any future disaster. Preparedness involves anticipation of a disaster, and the creation of a response capability. This includes analysing probable threats, setting up warning and communication systems, response management structures, organizing training, and stocking supplies (Mileti, 1999). Response refers to the actions taken during and immediately after a disaster occurs. The focus here is on saving lives, minimising damage to property and minimizing disruption to the community. Recovery is the short- to long-term phase of rebuilding and restoring a community to its pre-disaster state. During this phase damage assessment is completed and used to inform the reconstruction of housing and infrastructure, and the re-establishment of community institutions.

The integrated analysis and planning of disaster mitigation, adaptation, robustness, sustainability, and resilience are embedded in the concepts of disaster risk management (DRM), notably disaster risk reduction (DRR) (Manyena, 2006; Revet, 2012).

1.2 General concept of the PARATUS platform

The envisaged PARATUS platform allows the use of multiple hazard types, which can be natural and man-made. When calculating the risk, the user must define the type of hazard interaction (independent, compounding, combined, cascading etc.), which will determine the calculation of exposure, vulnerability, and loss. Central in the analysis is the development of a **multi-hazard impact-chain-model-builder**. Users co-develop the possible combination of hazardous events that might occur, and the resulting impact chain as a flow diagram. Several

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users can collaborate on projects where different users can upload data types in various formats. The administrator can generate projects and assign users to them. Users can analyse different types of elements-at-risk in the same area. Users will decide on which components can be quantified, depending on the available data and level of uncertainty, and which can only be evaluated semi-quantitatively or qualitatively as narrative.

The service will combine **quantitative components** (e.g., mostly concerning direct exposure and loss estimation and certain components of indirect loss assessment) **and semi-qualitative approaches**.

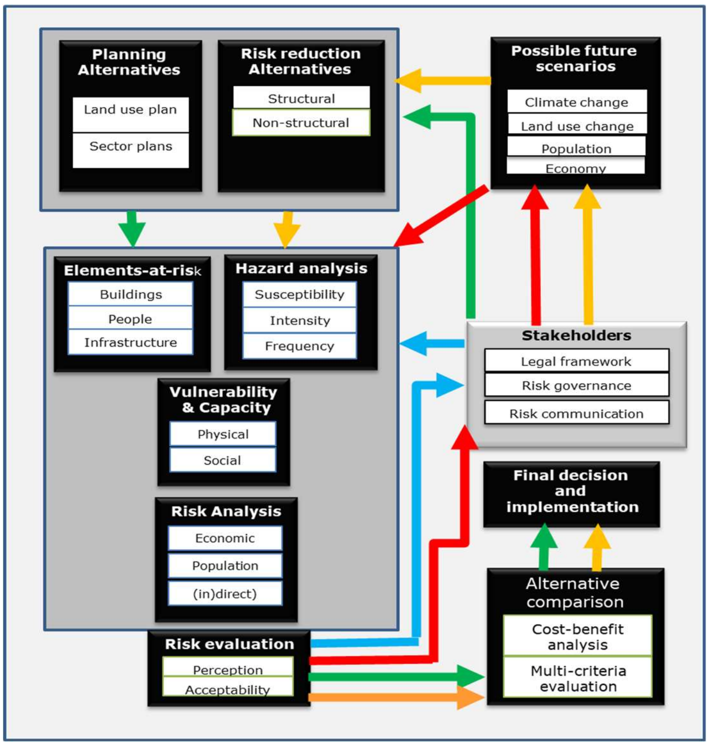

Figure 1.2.1: Dynamic risk assessment. Blue: for current situation; Green: for risk reduction alternatives; Red: for possible scenarios; orange: for alternatives under possible scenarios.

Index methods allow users to simplify complex interaction landscapes by breaking down events into a modification of one of the three dimensions and includes scenarios. For example, when analysing a climate-driven hazard occurring in a conflict situation, a currently existing conflict can be included as a modification to coping capacity (as conflict means, in essence, lack of access) while past conflicts in an area augment its vulnerability[2]. Expert information can also be layered in an index method. The 'enhanced' part of the method developed in this study resides in the inclusion of layers of interactions. Several indirect risk assessment tools will be added in the service, depending on the stakeholder and the required function. *PARATUS* will co-design the tools with stakeholders.

Risk can be calculated for the current situation (blue arrows in figure 1.2.1) as direct risk and indirect risk following the components of the model builder. Risk can also be indicated using spatial multi-criteria evaluation following a set of indicators, of which the direct hazard and exposure indicators are directly calculated, and others are used as indicator values per administrative unit. Users can co-develop risk reduction options and indicate how these will change the hazard, exposure, and vulnerability components. Risk can also be analysed for these risk reduction alternatives, and the difference in risk levels can be used in cost-benefit analysis to evaluate the optimal risk reduction alternative. RiskChanges can be analysed for possible future scenarios (red arrows in Figure) and specific future years. For these scenarios and future years, the service will contain a tool for the co-design of these scenarios. These will consider changes in hazard types, hazard interactions, hazard frequencies resulting from specific climate change scenarios. They can also be in combination with land-use change and population change scenarios, where the types, and number of exposed

[2] Wannewitz., Hagenlocher, & Garschagen, (2016)

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elements-at-risk will change. Users can define these scenarios and provide the metadata to the hazard and elements-at-risk maps/ Finally, users can define adaptation alternatives, and evaluate their effect on reducing the impact under different future scenarios. The system will be based on a series of Python scripts, which can be used directly by experienced Python users or via a Graphical User Interface (GUI) by inexperienced users. Algorithms that have been developed in earlier research initiatives can be linked to the system. Users can upload their own datasets in various forms (e.g., hazard maps, elements-at-risk maps, administrative unit maps, and vulnerability curves) and formats (points for individual objects, lines for e.g., transportation networks, building footprints, land use polygons, grids). There is also a link to data stored on Open Geospatial Consortium (OGC) compatible servers for geospatial data or to database connections.

1.3 Objectives

The overall objective of the PARATUS project and the platform is:

Co-development of a web-based simulation and information service for first and second responders and other stakeholders to evaluate the impact chains of multi-hazard events with particular emphasis on cross-border and cascading impacts.

A central theme within the PARATUS project is the co-development of the tools with stakeholders. The central stakeholders in the four application case studies are therefore full project partners. They will be directly involved in the development of the platform. Through initial workshops we have identified what the stakeholders consider relevant. We then want to develop a first idea (as presented in this document) which is discussed with the end-users in the project. This resulted in the proposal as indicated in this document. In workshops that will be organized in the period between May 2023 and May 2024 we will present and discuss the platform ideas to a range of stakeholders that participated in the initial workshops in the four application case study areas.

We will develop and implement a standardized participatory methodology and a toolbox for co-developing impact chains conceptualizing multi-hazard systemic risk for different sectors and environmental conditions. We will apply a combination of Forensic analysis approaches to a set of learning case studies (selected past disaster events) to analyse and apply the complexity of disaster impacts in different contexts, also tapping knowledge, data, and information from earlier European projects (See section 2.3). Particular attention will be devoted to the social aspects of impact chains. We will develop a WIKI for historical impact chains, using a standardized methodology and software tool. Researchers, first and second responders, and other stakeholders can contribute new impacts chains for other events. The impact chain WIKI is therefore editable and will be a central part of the PARATUS platform. The platform will allow for:

- Consult impact chains of historical events.
- Display the impact chains in an interactive manner.
- Describe the component of the impact chain and the connections using metadata, and where possible using interactive maps.
- Determine which components of the impact chain can be quantified.
- Use the library of impact chains as the starting point for generating new impact chains.
- Make a link between the impact chains component and the web-based calculation and simulation.

The PARATUS platform will consist of two main sections, each of which will house several components. The information service will provide static information related to definitions, terminology, risk assessment methods, impact chains, hazard models, adaptation measures, data sources for hazard, exposure, vulnerability, risk, scenarios, and alternatives.

The PARATUS platform will be an open-source platform for dynamic risk assessment that allows to analyse and evaluate multi-hazard impact chains, risk reduction measures, and disaster response scenarios in the light of systemic vulnerabilities and uncertainties. It will be generic, but applicable in different contexts, geographical scopes, sectors, and end-users.

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2. Earlier Work

2.1 Multi-hazard risk

Compounding and multi-hazard impacts have been studied for a span of years, after a long period where studies were mainly focused on single hazard risk. The research on multi-hazard risk has been carried out at various scales of analysis, ranging from local to regional or global. In one of the earliest global studies Dilley et al. (2005) developed a multi-hazard index, which is an illustration of the "all hazards at place method". The Global Risk Atlas and the Global Assessment Report (2021) have a similar but further quantitative methodologies. In these two approaches, average annual losses (AAL) are added to calculate cumulative AAL from various hazards, which were analysed separately through a probabilistic risk assessment. These approaches consider all hazards occurring in the same area but do not take into consideration hazard interactions. At a more local or regional scale, several spatial approaches concentrate on the homogenization of the hazard assessment, which tries to compare distinct hazards and the associated risk. Some of these approaches are qualitative based on the intensity and frequency of the hazard, while others are probabilistic.

However, the approach of interacting multi-hazard deals with methods of investigating two or more hazards and considers the hazard interactions like cascading or triggering effects (Gallina et al., 2016). Generally, it has more requirements for data and computing power than the first approach of independent multi-hazards. A qualitative procedure was proposed by Barrantes (2018) to overcome the issue of data availability in developing countries, which can simulate the spatial interactions among individual natural hazards in the context of less data availability. Numerous published articles have examined and modelled diverse combinations of natural hazards; however, they often lack systematic coverage of all potential multi-hazard scenarios (Choi et al., 2021). Furthermore, it is essential to adequately model significant interactions and cascading effects between hazards to accurately estimate the damage experienced by a target exposed to multiple, potentially coincidental natural hazards. This is crucial because losses resulting from hazard interactions can differ significantly from a mere summation of individual losses, assuming each hazard to be independent of others. Multi-hazard risk approaches incorporate the evaluation of risks stemming from multiple hazards, considering not only hazard interactions but also interactions between vulnerabilities.

Quantitative evaluation (including uncertainty) of multi-hazard risk is an emerging topic, despite significant research conducted in recent years. However, the development of mature methodologies is still in progress. Marzocchi et al. (2012) have highlighted fundamental principles for assessing multi-hazard risk, emphasizing the impact of interactions between hazardous events on the final risk estimation and providing insights into their inclusion in a multi-hazard risk assessment. Currently, the existing literature on empirical or deterministic quantitative assessment of multi-hazard risk has primarily focused on specific combinations or sets of hazards, involving experts from diverse disciplines. Examples are earthquakes and wind, earthquakes and hurricanes, wind and storm surges, and earthquakes combined with ash fall and pyroclastic flow from the volcanic eruption.

Jaimes et al., (2015) presented general quantitative criteria for the assessment of damages of a building exposed to many hazards and introduced two simplifications in the approach due to the less data availability, namely the independence of loss estimations for different hazards, and the assumption that after each instance of loss or failure, structures are restored or reconstructed, without considering any dynamic recovery process between successive hazards.

From the literature review of approaches to multi-hazard risk assessment, the following points were highlighted:

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- Most findings only concentrate on one or two groups of hazards like hydrogeological, tectonic, and a comprehensive approach of multi-hazard is often absent.
- Multi-hazard findings often do not deal with a quantitative risk assessment when modelling hazard interaction.
- Available quantitative and qualitative multi-hazard risk approaches typically do not model residual damage and recovery dynamics because of successive disasters.

2.2 Software tools

Currently, there are no publicly available tools for analysing multi-hazard risk and their use in complex impact chains. The HAZUS-MH loss estimation tool developed by FEMA in the USA is one of the best examples of a multi-hazard loss estimation tool for earthquakes, floods, and windstorms. However, the model is problematic to apply internationally due to country-specific characteristics and is limited to the modelling of hazard interactions and specific impact chains. Other tools only generate loss estimation for individual hazard types (e.g., OpenQuake for earthquakes, SaferPlaces for floods). In addition, there are proprietary risk assessment tools (e.g., from (re)insurance, consulting companies), but these are often not within reach of first and second responders and local authorities. The data requirements of such tools may also be overly complicated for the stakeholders, who may have to make decisions based on limited information. One of the main challenges is how the working process of stakeholders can be integrated into a service that is both generic and usefully applied to a specific situation. *Table 2.2.1* provides information on software tools that have been identified as important for the development of the PARATUS platform. The proposed service will be based on tools that are developed for multi-hazard risk assessments (e.g., RiskChanges[3]), and that consider future scenarios and adaptation measures (e.g., CLIMADA[4]). The tool will also build on the INFORM[5] Risk methodology, which comprises several quantitative tools for decision-support prevention, preparedness, and response phases.

Table 2.2.1: Software tools relevant for the PARATUS platform

Name	Description and relevance for PARATUS
CAPRA https://ecapra.org/	The CAPRA (Probabilistic Risk Assessment) Platform was an initiative of the World Bank GFDRR that aimed to develop a multi-hazard risk assessment tool to strengthen the institutional capacity for assessing, understanding, and communicating disaster risk, with the ultimate goal of integrating disaster risk information into development policies and programs. Under the CAPRA platform, government, institutions, private companies, and other agencies address specific development challenges and meet disaster risk information needs through specialized software applications, extensive documentation, consultancy and advisory services, hands-on practical training, and other complementary services. The CAPRA suite of standalone tools offered a range of tools for probabilistic hazard modelling, an exposure module, a vulnerability database module, and the CAPRA-GIS for probabilistic risk assessment. Unfortunately, the tools are no longer updated and many of them do no longer function. **PARATUS uses the physical vulnerability curves from the CAPRA tool, which cover different hazards and building types.**
HAZUS https://www.fema.gov/flood-maps/products-tools/hazus	HAZUS is a standardized methodology developed by the Federal Emergency Management Agency (FEMA) in the USA. The freely available software package called HAZUS-MH (for Multi-Hazard) gives users access to FEMA's models for estimating potential losses from earthquakes, floods, and hurricanes. The software package uses Geographic Information Systems (GIS) technology to estimate physical, economic, and social impacts of disasters. It graphically illustrates the limits of identified high-risk locations due to earthquake,

[3] http://riskchanges.org/
[4] https://wcr.ethz.ch/research/climada.html
[5] https://drmkc.jrc.ec.europa.eu/inform-index

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	hurricane, and floods. Users can then visualize the spatial relationships between populations and other, more permanently fixed geographic assets or resources for the specific hazard being modelled, a crucial function in the pre-disaster planning process. HAZUS-MH runs under ARCGIS
IN-CORE https://www.ncsa.illinois.edu/research/project-highlights/in-core/	By accessing the Interdependent Networked Community Resilience Modelling Environment (IN-CORE) platform, users can run analyses that model the impact of natural hazards on a particular community. In doing so, IN-CORE can gauge a community's resilience to major disasters. IN-CORE Lab, which is a customized Jupyter Lab with pyIncore installed and hosted on a cloud system provided by the National Center for Supercomputing Applications (NCSA), gives users the ability to develop, run or test their model in their own workspace. **This is a very new tool and PARATUS should further explore its use, and applicability within the project.**
RiskScape https://riskscape.org.nz/	RiskScape is an open-source spatial data processing application used for multi-hazard risk analysis. RiskScape is highly customisable, letting modellers tailor the risk analysis to suit the problem domain and input data being modelled. RiskScape provides a flexible data processing framework for building and executing geospatial risk models. RiskScape can take a variety of input layers and geospatially stitch them together. For example, RiskScape can take a building portfolio and a flood hazard map and analyse the flood depth (if any) that each building was exposed to (Paulik et al., 2022). The software requires knowledge of the RiskScape Command Line Interface (CLI). RiskScape currently does not have GUI (Graphical User Interface). It is expected that CLI users have a working knowledge of the command line for the operating system they are using. Commands and examples used in this documentation are all used from a Unix terminal and tested using Windows PowerShell. The software itself is written in Java. The system has been completely redeveloped recently.
OpenQUAKE https://www.globalquakemodel.org/openquake	The OpenQuake Engine is the Global Earthquake Model Foundation's (GEM) state-of-the-art, open-source software collaboratively developed for earthquake hazard and risk modelling. It runs on operating systems such as Linux, macOS and Windows; and can be deployed on laptops, desktops, standalone servers, and multi-node clusters. The functionality to analyse hazard and risks at specific site, city, country, or regional level makes the OpenQuake Engine a powerful and dynamic tool for assessing the potential impacts of earthquakes at any location in the world.
SaferPlaces https://saferplaces.co/	Global Platform AI-based Digital Twin Solution for Flood Risk Intelligence. Geospatial, Satellite, Climate Data and AI-based models combined into a cloud computing environment provides incredible insights in terms of flood risk intelligence. SaferPlaces leverages the increasing availability of high resolution geospatial and climate open data from Google Earth Engine (GEE), Open Street Map (OSM), Microsoft Planetary, AMAZON and Copernicus which are integrated automatically to build the different layers of the city's digital twin. This is a commercial solution, ranging between 3-20 Euro/km^2/year. **Within PARATUS we explore the use of such Cloud-based solutions.**
CLIMADA https://wcr.ethz.ch/research/climada.html	CLIMADA is a Python-based software tool that allows to estimate the expected economic damage as a measure of risk today, the incremental increase from economic growth and the further incremental increase due to climate change. CLIMADA provides global coverage of major climate-related extreme-weather hazards at high resolution via a data API, namely (i) tropical cyclones, (ii) river flood, (iii) agricultural drought and (iv) European winter storms, all at 4km spatial resolution - wildfire to be added soon. For all hazards, historic and probabilistic event sets exist, for some also under select climate forcing scenarios (RCPs) at distinct time horizons (e.g., 2040). CLIMADA is developed, maintained and available open-source in Python 3.x Free use and access under

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	GNU GPL3 GitHub made. Data freely available under CC BY 4.0 via the CLIMADA data API (application programming interface, metadata provided). **PARATUS is planning to use CLIMADA and integrate this tool in the possible tools within the PARATUS platform**.
INFORM Risk https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk/Methodology	The INFORM Risk Index is a global, open-source risk assessment for humanitarian crises and disasters. It can support decisions about prevention, preparedness, and response. INFORM has three dimensions: hazard & exposure, vulnerability, and lack of coping capacity. Each dimension encompasses different categories, which are user-driven concepts related to the needs of humanitarian and resilience actors. In order to accommodate the INFORM Risk methodology, where the vulnerability variable is split among three dimensions, the equation is updated to: Risk = Hazard & Exposure 1/3 × Vulnerability 1/3 × Lack of coping capacity 1/3. It is a multiplicative equation. A composite index is typically a compromise between a data driven and a user driven model. There are always some components which existing data cannot describe, especially if the demands for quality of data are very high. **PARATUS aims to use part of this method in the Resilience Indicator tool.**

2.3 Research projects

The PARATUS project builds on the achievement of many previous EU projects. Therefore, we have made an evaluation of which projects could be helpful for the development of the proposed methodology in PARATUS (*Table 2.3.1*). One of the useful organisations in this context is the "Societal Resilience Cluster" within the CMINE community, which was established to enable closer cooperation between the Horizon 2020 projects RESILOC, ENGAGE, BUILDERS and LINKS, joined in 2021 by RiskPACC and CORE, and in 2022 by MEDIate and PARATUS. The Cluster is hosted on the CMINE platform and is endorsed by the European Research Executive Agency (REA)[6]. CMINE was launched in 2019 to enable the project teams to interact with other resilience focused Horizon 2020 supported projects, while engaging in an open dialogue about joint cooperation. CMINE is effective in creating a baseline for closer interaction, building up on synergies and generating added value collaboration, based on the conviction that community platforms simplify communication exchange, mandate cooperation, and calibrate joint efforts in the research arena. The closer cooperation provides a window to co-create, participate in, and observe discussions on innovation. Several related projects which partly cover the same topics are listed in table 2.3.1.

Table 2.3.1: Research projects related to the topic of the PARATUS project.

Project	Description and Relation to PARATUS
ARMONIA https://cordis.europa.eu/project/id/511208 2004 - 2007	The overall aim of ARMONIA was to provide the EU with a set of harmonised methodologies for producing integrated risk maps to achieve effective spatial planning procedures in areas prone to natural disasters in Europe. It is one of the first multi-hazard risk projects.
ConHaz https://cordis.europa.eu/project/id/244159/reporting 2010-2012	Natural Hazards: direct costs and losses due to the disruption of production processes. The project aimed at compiling and synthesising current knowledge on cost assessment methods to strengthen the role of cost assessments in the development of integrated natural hazard management and adaptation planning. **PARATUS uses the knowledge from this project in terms of assessing indirect losses from natural disasters**
CHANGES http://changes-itn.eu/ 2011 -2015	The CHANGES network (Changing Hydro-meteorological Risks – as Analysed by a New Generation of European Scientists) aimed to develop an advanced understanding of how global changes (related to environmental and climate change as well as socio-economical change) will affect the temporal and spatial

[6] https://rea.ec.europa.eu/index_en

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	patterns of hydro-meteorological hazards and associated risks in Europe; how these changes can be assessed, modelled, and incorporated in sustainable risk management strategies, focusing on spatial planning, emergency preparedness and risk communication. **PARATUS builds on tools that were developed in this project**.
ANYWHERE http://anywhere-h2020.eu/ 2016 - 2019	Developed a pan-European multi-hazard platform (A4EU) which provides a better identification of the expected weather-induced impacts and their location in time and space before they occur. Seven A4EU prototypes are currently running live operational at the Civil Protection command centres of seven pilot sites, representing different climatic scenarios around Europe. The tool is not Opensource. **UPC (Barcelona) was coordinator and is also partner within PARATUS.**
C2IMPRESS https://www.c2impress.com/ 2022 - 2025	Co-Creative Improved Understanding and Awareness of Multi-Hazard Risks for Disaster Resilient Society. This project has very similar objectives as PARATUS and aims to develop a novel integrated risk and resilience framework (comprising methods, tools, and guidelines) to empower public authorities and citizens to prepare themselves for future hazards. **PARATUS is in regular contact with this project and co-organize joint seminars on specific topics.**
RASOR https://cordis.europa.eu/project/id/606888/reporting 2013 -2016	RASOR was structured along 3 tracks: a global risk assessment service, and SME-led national and local services through innovative partnering arrangements. A three-phase approach allows RASOR to: demonstrate the technological feasibility of the concept and develop a global tool and apply RASOR services to specific user segments and geographic areas. **PARATUS uses the methods developed in this project.**
TURNKEY https://cordis.europa.eu/project/id/821046 2019 -2022	The EU-funded TURNkey project developed an easy and low-cost platform in the cloud for forecasting, warning, and response to earthquakes – the operational earthquake forecasting (OEF), earthquake early warning (EEW) and the rapid response to earthquakes (RRE) system. It was demonstrated and tested in six European cities affected by high seismic activity. The project will be backed by a team of multidisciplinary experts from 10 EU Member States. **PARATUS shares several partners and one case study with this project.**
ALARM https://cordis.europa.eu/project/id/891467 2020 -2022	The EU-funded ALARM project developed a prototype global multi-hazard monitoring and early warning system. The project will use near real-time data and tailored products from ground-based and satellite systems to strengthen models of identifying and predicting the risk and displacement of particles in suspension and gas derived from natural hazards as well as extreme weather situations,
RESILOC https://www.resilocproject.eu/ 2019 -2022	The EU-funded project RESILOC aims to study and implement a holistic framework of methods and software instruments required for the assessment of resilience indicators in a community. The studies will help design and implement software to collect information on such communities. **PARATUS collaborates within the DRS Cluster of CMINE**
BUILDERS https://cordis.europa.eu/project/id/833496/reporting 2019 - 2022	BuildERS aimed to improve the resilience within European societies and communities by providing new knowledge on who are the most vulnerable and for which reasons. This was done based on the assumption that a) risk awareness, b) social capital and c) preparedness are core aspects influencing vulnerability. **PARATUS collaborates within the DRS Cluster of CMINE**
LINKS https://cordis.europa.eu/project/id/883490 2020 - 2023	LINKS sets out to create a community of stakeholders, the LINKS Community, which brings together first-responders, public authorities, civil society organizations, business communities, citizens and researchers across Europe dedicated to improving European disaster resilience through the use of social media and crowdsourcing (SMCS). **PARATUS collaborates within the DRS Cluster of CMINE**
RISKPACC https://www.riskpacc.eu/ 2020 -2024	The EU-funded RiskPACC project aims to increase disaster resilience in society by understanding and closing the risk perception action gap (RPAG) using a co-creation approach to risk communication. In doing so, the project will facilitate

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	greater interaction between citizens and civil protection agencies to collaboratively identify their needs and develop potential procedural and technical solutions to build enhanced disaster resilience. **PARATUS shares partners and collaborates within the DRS Cluster of CMINE**
MYRIAD_EU https://www.myriadproject.eu/ 2021 - 2025	MYRIAD-EU's mission is to catalyse a paradigm shift in how risks are currently assessed and managed. Instead of addressing risks and hazards one by one, leading scientists from across Europe will co-develop the first harmonised framework for multi-hazard, multi-sector, and systemic risk management. The interlinkages between the different hazards and economic sectors will be studied in 5 pilots. **PARATUS is in regular contact with this project and co-organize joint seminars on specific topics.**
CORE https://www.euproject-core.eu/ 2021 - 2024	CORE (sCience& human factOr for Resilient sociEty) is a multi-disciplinary consortium established to understand how to define common metrics with respect to the different natural and man-made disaster scenarios, and how to measure, control and mitigate the impact on the populations, particularly on vulnerable groups: disabled, elderly, poor, as well as women and children. **PARATUS collaborates within the DRS Cluster of CMINE.**
DISTENDER https://distender.eu/ 2022-2025	DISTENDER is an EU-funded project to establish new common ground for scientists and policy makers by developing actionable strategies for climate change mitigation and adaptation processes.
ICARIA https://cordis.europa.eu/project/id/101093806 2023-2025	The ICARIA (Improving ClimAte Resilience of crItical Assets) project will use asset-level modelling to understand climate-related direct and indirect impacts provoked by complex, compound and cascading disasters and the risk reduction that suitable, sustainable, and cost-effective adaptation solutions provide.
MEDIATE https://mediate-project.eu/ 2022 - 2025	MEDiate aims to develop a decision support system (DSS) for disaster risk management by considering multiple interacting natural hazards and cascading impacts using a novel resilient-informed, service-oriented, and people-centred approach that accounts for forecasted modification in the hazard and exposure. **PARATUS is in regular contact with this project and co-organize joint seminars on specific topics.**
The HuT https://thehut-nexus.eu/ 2022 - 2026	Within The HuT project, European research groups, institutions, and stakeholders will work to integrate and leverage best practices and successful multi-disciplinary experiences. The project's main ambition is to promote a set of trans-disciplinary risk management tools and approaches that could be adopted and used in as many situations as possible. Specific attention will be devoted to assessing the transferability of the developed innovations across territorial contexts and hazards. **PARATUS collaborates with this project and shares several partners.**
ENGAGE http://www.engage-climate.org/ 2023 -2025	Natural and man-made disasters remind us how the ability of societies to adapt and prosper depends on the collective action of the whole society. But the significant role citizens and communities can play at the grassroots level has been overlooked in research. ENGAGE will turn this around, showing how individuals and local practices can interrelate effectively with planned preparedness and response, practitioners, and technology. **PARATUS collaborates within the DRS Cluster of CMINE.**

2.4 Tools of PARATUS partners

The **Community Risk Assessment**[7], [8], or CRA, is a dashboard showing risk data for specific countries aiming to go up to community level. The CRA is based on the INFORM risk index categorizing risk indicators in hazard

[7] https://dashboard.510.global/#!/
[8] https://www.researchgate.net/publication/316433200_Unpacking_Data_Preparedness_from_a_humanitarian_decision_making_perspective_toward_an_assessment_framework_at_subnational_level

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exposure, vulnerability and lack of coping capacity. The data that is used is country wide but goes in to deeper admin levels. For example, for Uganda there is data on district level but also on sub-county level while some indicators go up to parish administrative areas.

The CRA gives local stakeholders like the Red Cross and Red Crescent societies insight in what areas are often exposed, are more vulnerable than others or lack the coping capacities to deal with disasters. This is used in the planning of Disaster Risk Reduction, Preparedness or Anticipatory Action projects as well as more development-oriented programmes.

The strong point of the platform is the easy to use and intuitive interface, making it easy to quickly grasp and quantify the risk in a country.

CRA is a dashboard that is designed, developed and hosted by 510, the data & digital initiative of the Netherlands Red Cross. As a partner in this project 510 brings in among others, the knowledge and experience of the CRA.

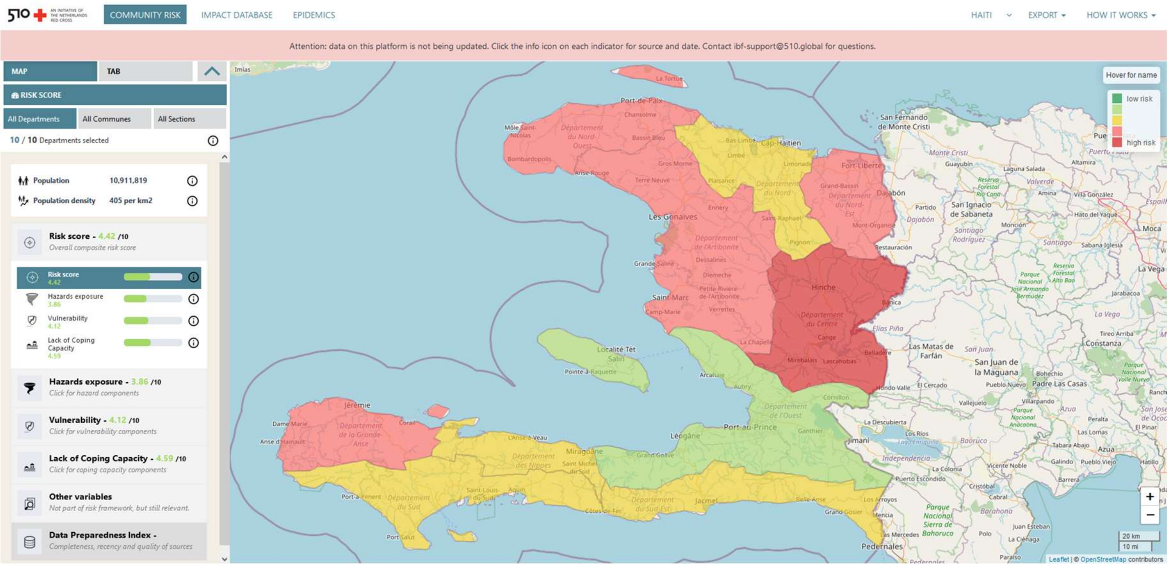

Figure 2.3.1: The CRA Dashboard for Haiti

The **Impact Based Forecasting Portal**[9] (IBF Portal) is a one stop shop for disaster managers implementing anticipatory action. Knowing the general risks in a country gives you insights in how to implement preparedness and DRR projects. But knowing when and where a specific hazard event will occur gives you the possibility to hugely lower the impact of the event. The IBF Portal makes use of state-of-the-art high skill weather and climatic forecasts to calculate the potential impact of these events on a specific area of a country. By knowing when and where and with what magnitude will happen, disaster managers can execute pre-defined actions specifically for that area and moment. These can range from evacuations to early harvests, and from targeted cash distributions to distribution of water treatment products. The IBF Portal was originally developed for floods in Zambia and is nowadays running in 9 countries on 7 different hazards (floods, flash floods, heavy rainfall, drought, tropical storms, dengue and malaria). The product is implemented together with national Red Cross / Red Crescent societies, national hydro met agencies and disaster management authorities. During the development the end user is at the centre and these past implementations have given many insights from national level actors in what they need to be able to implement early warning and early action.

IBF Portal is a product that is designed, developed and hosted by 510, the data & digital initiative of the Netherlands Red Cross. As a partner in this project 510 brings in among others, the knowledge and experience from the IBF Portal.

[9] https://ibf.510.global/login

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Riesgos [10]. Experts from different disciplines work together in the joint project RIESGOS 2.0 (Scenario-based multi-risk assessment in the Andes region) and develop innovative scientific methods for the evaluation of complex multi-risk situations with the aim to transfer the results as web services into a demonstrator for a multi-risk information system. The project RIESGOS 2.0 builds on the achievements of the predecessor project RIESGOS (Spanish for "risks"). The results from the research are transferred as web services into a demonstrator for a multi-risk information system. The demonstrator is based on a modular and scalable concept and is designed in a decentralized manner. A web platform allows users to simulate and model how various natural hazards, such as earthquakes, landslides, volcanic eruptions, floods and tsunamis, would progress and interact. It is also able to consider the impacts on critical infrastructure such as power grids. It consists of a series of independent, distributed webservices, and a user interface that accesses these services. An important added value of this modular and interoperable approach is the possibility to integrate different web services into already existing system environments.

RIESGOS 2.0 is funded by the German Federal Ministry of Education and Research (BMBF) as part of the funding measure "CLIENT II – International partnerships for sustainable innovations" of the framework programme "Research for Sustainable Development (FONA)". The project is supervised by the Project Management Jülich (PtJ). The coordination of the project is under the responsibility of the German Aerospace Center (DLR).

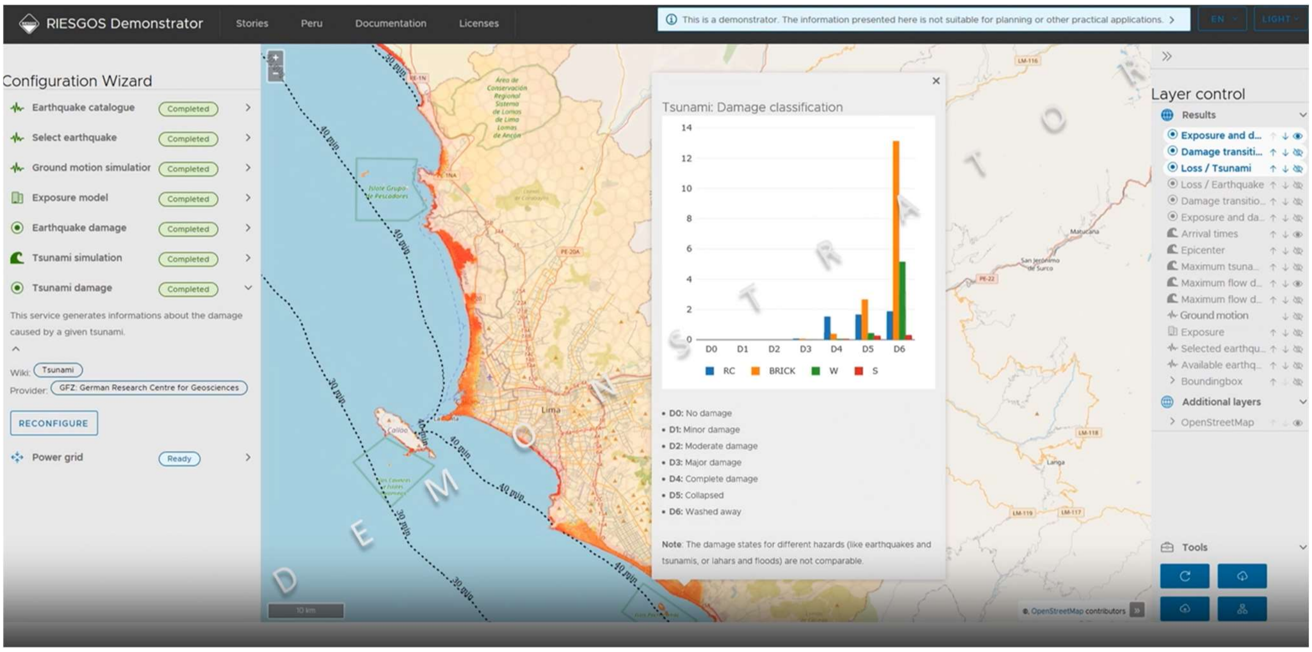

Figure 2.3.2: Example of the Web-based Demonstrator for multi-hazard risk assessment under the Riesgos project.

[10] https://www.riesgos.de/en/

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3. Stakeholders

Co-designing the PARATUS platform is one of the objectives of the project. The whole project is built upon an **inclusive approach** that aims to establish a unified PARATUS Stakeholder Hub, which gathers not only representatives from the DRM field but from a wide range of other relevant groups, sectors, and disciplines, including academia, large and SME technology providers, civil society, governmental and non-governmental organizations as well as standardization bodies and competent authorities.

The PARATUS project engages with stakeholders at different levels, depending on their characteristics, needs, interests, and relevance to the project. The project applies the five engagement levels defined by the International Association of Public Participation (IAP²) to ensure a balanced representation of all stakeholder group; these are:

- ***inform*** stakeholders with little interest, or influence in, the project results;
- ***consult*** stakeholders that are supportive of PARATUS but with little time/capacities to dedicate to the project;
- ***involve*** stakeholders that are influential and maintain periodic exchanges to adequately inform them;
- ***collaborate*** with stakeholders that are key with respect to both, interest, and influence;
- ***empower*** stakeholders through the development process and the knowledge gained, so that they can decide whether to adopt or boost the final developments and endorse the uptake of the project results.

With the start of the project, the relevant stakeholders have been defined for each of the four application case studies in the Caribbean Islands, Alps, Bucharest, and Istanbul. During the kick off meeting and the first external stakeholder workshops, their needs and requirements are analysed, and priority groups are established to effectively co-design the PARATUS platform to be used by various stakeholder groups.

Following stakeholder analysis process to identify which stakeholder groups shall be involved within the activities of the project, in parallel, together with the interested stakeholders we are building a PARATUS Stakeholder Hub. The hub is an online and offline environment to facilitate active engagement with other crisis management professionals (including first and second responders) and relevant stakeholder groups. In this way, we will create synergies with the Societal Resilience Cluster, an informal, voluntary, and free subset of the Community for European Research and Innovation for Security (CERIS) and in particular the Disaster Resilient Societies (DRS) community made-up of EU projects working on different aspects of Societal Resilience.

3.1 Co-designers and users of PARATUS platform

From the project start onwards, the PARATUS project will have a strong focus on cooperating with stakeholders from a large spectrum of areas related to Disaster Risk Management (DRM) as well as various sectors that face high risks related to impacts caused by dynamic multi-hazard events (e.g., humanitarian, transportation, communication sector etc.). Their systematic participation in all key project activities will allow the consortium to align with and follow up on relevant policies, challenges, gaps, and community needs of those stakeholder groups. This inclusive approach shall ensure that the final project results will be of high relevance and quality to efficiently address the challenges for DRM and contribute to building a society that is sustainable and resilient to compounding disasters.
The platform will offer various tools, databases, methods, toolboxes for various purposes like learning, assessing systemic risk, making decisions, increasing awareness or just to be trained. Therefore, the intended user profile covers a wide range of stakeholders, i.e., scientists, DRR specialists, planning experts, climate change modellers, participatory planning experts, hazard assessment experts, vulnerability experts, technical

staff, first and second responders, local and regional authorities, insurance companies, consultants, critical infrastructure managers, humanitarian organisations, secondary school children and university students (*Table 3.1.1*).

Table 3.1.1: Overview of potential users of the PARATUS platform, what it may offer to them and the likely impact.

User Profile	The platform will offer	Potential Impact
Scientists and technical staff working on remote sensing, GIS, and historical disaster databases from technical departments linked to first and second responders, and local and regional authorities. Insurance companies and consultants.	Multi-temporal hazard & exposure datasets tools using Remote Sensing images, Machine Learning, and crowd sourcing. Augment disaster databases with hazard inter-actions and their impact chains to better characterize compounding disasters. Methods to convey uncertainty of risk factors by decision makers.	Incorporation of historical data resulting in better understanding, leading to more effective risk reduction actions and policies. Enhanced understanding and improved knowledge and situational awareness of disaster-related risks.
Scientists from different disciplines working on hazard, vulnerability and risk and technical staff working on planning and GIS data analysis, from planning departments linked to first responders, and local and regional authorities. Insurance companies (e.g., PAID) and consultants (e.g., ADPC). Second responders (OEBB, ASFINAG, Telecommunication),	Methodology and toolbox for co-developing impact chains, open-source algorithms for (in)direct loss estimation and socio-economic indicator integration to address systemic risk. Four examples where tool is co-tested in diverse settings. E.g., migrant groups in Istanbul, and low-income groups in Romania. Implement the method in an open-source platform with training reaching a wide group of DRR practitioners that adopt it in their work.	Unified method for the assessment of systemic risk for compounding disasters. The methods are further standardized though international stakeholder communities. Standardized methods will lead to wider acceptance and implementation of DRR policies in measures in areas with conflicting interests. Enhanced sharing of knowledge and coordination regarding standardisation in crisis management.
Social scientists, DRR specialists, planning experts, climate change modellers, participatory planning experts, hazard assessment experts, vulnerability experts. Representatives of first responders, critical infrastructure managers, humanitarian organisations, local authorities. Secondary school children, university students.	Co-developed scenarios for different sectors and scales so that DRR decisions explore long term adaptation and DRR pathways. Holistic analysis of the impact of diverse extreme events, for more efficient planning of the mitigation and adaptation measures. The tools have been applied in case studies using local and regional relevant data. Serious games for the evaluation of optimal adaptation/mitigation measures for risk reduction	Wide range of stakeholders is collaborating with the tools in the platform. Expansion of stakeholder hubs to diverse communities of practice, including authorities (ISOCARP, ICLEI); less citizens in high-risk conditions. More efficient cross-sectoral, cross-disciplines, cross-border coordination.

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During the project, stakeholders will be engaged in the project to provide insights, knowledge, data, and expertise; contribute to the project with suggestions to improve and develop the platform; receive knowledge coming out of PARATUS in the form of deliverables, communication, and dissemination materials. When the platform is active, they will be able to use it to fulfil their needs.

Constant interaction with stakeholders at various levels will allow PARATUS to better tailor and develop the platform. It furthermore allows stakeholders and project partners, to exchange on best practises and lessons learnt which will also help to explore new innovative technologies and solutions supporting stakeholder operations across different countries. Those innovations need to be considered within PARATUS to ensure that the user-centred risk assessment service tool developed within the project is compatible and can be interconnected with other existing and emerging solutions.

Additionally, we develop synergies with the related cluster projects and other relevant initiatives at national and international levels will increase the outreach and multiply the impact of the PARATUS project and support the transfer of knowledge and research outputs to the PARATUS Stakeholder Community as well as the similar projects' networks.

Gaining the trust of stakeholders by involving them at all stages of the project will allow to build a network of "project ambassadors", thereby multiplying the project outreach and generating opportunities to gain endorsement from new stakeholders. This will be crucial when the project enters the final key engagement phase focusing on the uptake and sustainability of project results (see *Section 2*).

3.2 Project activities with stakeholders

Stakeholders from different groups will participate in specific activities throughout the project's duration. Initially, a list of anticipated stakeholder group activities include case study kick-off meetings, needs and requirements assessment workshops, focus group meetings, co-designing scenarios and testing the outcomes.

- **Case Study kick-off meetings** aim to inform stakeholders about the project and get them engaged, discussing potential roles and responsibilities of stakeholders as well as potential tools and legal frameworks to consider.

The work in case studies started with the kick-off meetings with the involvement of partners including end-users and subcontracted partners (e.g. ASFiNAG, BFW and Synalp in the Alps case study). In these meetings, the tasks and timeframe for deliverables were defined, and we had open discussion concerning expectations, interests, and motivation for the participation in PARATUS. Preliminary plans regarding structure and organisation for the external stakeholder workshop were collected. The focus concentrated on who to invite, which topics should be discussed and what role the external stakeholders should take.

- **Needs and Requirement Workshops** on user requirements for the services to be developed within the PARATUS project.

The overall purpose of these workshops is to co-develop the service based PARATUS platform on close interaction with its stakeholders. The PARATUS project has already conducted the first needs and requirements workshops in the application case study areas of Bucharest, Istanbul, Caribbean Islands (Sint Maarten), and the Alps (Innsbruck and Bolzano). These workshops were the first step in co-developing tools for better decision-making and minimizing the number of people affected by disasters and systemic risks. The workshops were conducted in local language with simultaneous translation to English.

During the first workshops, we discussed past natural hazards in the case study areas, the reason and impacts of these hazards, designed the preliminary impact chains, and discussed potential future events.

Additionally, we visited case study areas. During case study excursions we got a better insight into possible occurring hazards.

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The stakeholder selection was led by the local end-user. For instance, in the Alps the strategic contacts of ASFiNAG were vital to connect with key players in the region who work (in a broad sense) on hazards. During the selection process, in communication with WP5, the following groups where identified: decision makers & public bodies, practitioners, critical infrastructure, transportation, civil protection, insurance companies, society and citizens groups, and related projects.

In Bucharest the team followed a slightly different approach. The focus was evacuation, accommodation, water and food provision, and other measures. These measures are implemented in collaboration with the local authorities, which must organise areas where first responders and the population can gather. In this context, the most prominent roles belong to the Ministry of National Defence, the gendarmerie, the police, and other order enforcement personnel who oversee evacuation procedures and security in the area impacted by the hazardous event.

For a better overview of stakeholders' needs, expectations, *and* motivation, every participant had the chance to give input regarding wishes and possible contributions to PARATUS. In *Table 3.2.1* we listed the results attained from the external stakeholder workshop in Bolzano and in *Table 3.2.2* and *Table 3.2.3* one can see the interests, needs, and expectations of stakeholders in Bucharest. For more information about the results of all four case study area workshops, please see *Deliverables 6.2* and *1.1*.

Table 3.2.1: External Stakeholder workshop in Bolzano, what stakeholders want and can contribute as well as what stakeholders hope to gain through PARATUS project (Source: Deliverable 6.2)

Possible Contributions to PARATUS	**Expectations and wishes**
Expertise regarding Climate Change (geosphere)	Cross-link available data
Know-How: prediction, extreme weather	Checklists for practitioners
Data: Hazard-/ Risk-maps, Raw data (Synalp)	Cross-border collaboration in emergency response units regarding (avalanches, fires…)
Climate adapted forests, Biodiversity, Forest inventory data; Input by BFW (Vienna)	Multi-hazard platform Further development of the platform and economize it (market ready…)
Tools for process modelling (BFW); FlowPy, Avaframe	Possibility to connect in a network with certain experts.
Data contribution (Wasser Tirol?)	Practicable benefit for the Brenner region and the corridor. With a focus on seeing new hazards.
Case study data, examples (ÖBB)	Networking with Event database
Specific local / regional knowledge (Transitforum)	A closer scale modelling (smaller grid)
	Don't compromise the topics too much.

Table 3.2.2: Interests, needs and expectations of stakeholders in Bucharest Case Study (Source: D 6.2)

Organizations	**Interests and Needs**	**Expectations from PARATUS platform**
Ministry of Defence	Broad-spectrum identification of the risk elements, of their impact of military entities (personnel, military infrastructure, equipment designed for national defence)	The platform should be an instrument that supports decision-making, that allows for the identification of support tasks to be provided by the ministry to the authorities responsible for risk management. Fundamental support in the adaptation of response activities.
Prefecture	High-level collaboration between institutions	Interconnected network of experts
Gendarmerie and Police	Provides support functions, for which a clear, comprehensive picture of the first after-event measures is a pre-requisite. The first 24 h are pivotal, meaning that knowing what must be done during this narrow time frame will generate an optimal response.	May extend on two levels: 1) a set of preventive/training measures prior to disaster occurrence, with general access for the population, and 2) a set of maximum-security measures and responsibilities designed for the departments involved in response actions. The second one would be very helpful, since disaster situations do not

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		leave room for thinking and call for immediate actions.
ISUBIF	Access to the database with all elements at risk, to perform law enforcement in relation to the owners/users of these elements. This would facilitate the check-up of necessary mitigation measures, and the fulfilling of obligations regarding the elaboration of self-defence plans. Availability of economic stakeholder to provide equipment (e.g., bulldozers, excavators, trucks etc.) and staff in a timely manner for support.	The platform should include these information and databases on the types of useful and available resources in disaster situations. It should help the improvement of collaboration between institutions. The platform should make available the best European practices applied in previous disaster situations, which can be translated into the legal framework and applied in the field.
Ministry of Development	Involvement of the institutions with primary and secondary roles at both central and local level (public local authorities) in future meetings.	Prioritizing the dissemination of the project at institutional level, but also to the population.
Department for Emergency Situations DSU	Identification of risks at micro scales (increasing grain resolution), specific to each community (A group may be vulnerable in terms of location, and another group because of its socio-economic status etc.)	Continuous update of data regarding risk elements.

Table 3.2.3 Interests and platform need at decision making level in Bucharest Case Study (Source: D 6.2)

Interests	Needs
Clear, live/continuously updated information from the field during disaster	Data transformed to information required in different situations
Fast transfer of information required to allocate resources	Existing data transferred to maps
Reduction of the response time during intervention	Real time data collection from field
Immediate support from one intervention structure to the other	Assisted decisions
Even if the disaster response system is well-managed, we need to increase the effectiveness of preventive and preparation/training measures provided by other stakeholders	Helping find procedures for no procedure situations
Necessity to maintain communication in disaster situations	Updated maps
Continuously updated database concerning the building stock and population	Decision supporting tools using different possible risk and disaster scenarios
Database of all the locally- and regionally available resources in disaster situations, which can be provided by both ministries and economic stakeholders	Updated in real time or near real time information on access routes in case of disasters
Support in getting accustomed to the intervention area	Integration of dispersed databases
Reduction of communication delays in disaster situations	Support in decreasing response time
Necessity to educate the population in terms of proactive attitudes	Support in raising awareness and in educating the population in order to increase resilience
Necessity to prioritise information in disaster situations	Real time information prioritisation system
Necessity of knowledge on vulnerabilities regarding infrastructure, the building stock, the population, and on the trails and areas fit for evacuation procedures	Configuration of the platform based on information access levels
Necessity to identify hidden, indirect risks	Inclusion of hidden, indirect, hybrid and cascading risks into scenarios and into the decision-making support system
International accreditation of more intervention modules (e.g., CBRN in the process of accreditation)	Inclusion of a unitary, standardised system for the assessment of the situation in the field (in case of disasters)

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Necessity of information support in prioritising intervention information	Data and information resources well-structured in the platform, which can generate operational realities to be used in decision-making
Necessity to identify the risks for the physical integrity of rescuers	Increased levels of sensitive information security and data protection
Identification of risks at sector scale	Continuous update of data on the building stock
Identification of the vulnerability specific to each community type	Granting the population access to information which can help raise awareness in terms of danger sources, and generate adaptation strategies

- **Focus group meetings** discussing impact-chains of past events and what determined the impact chains levels and defining required information for estimating the impact chains of possible future events.

In the project we conduct two types of focus group meetings: internal focus group meetings with our end-user partners and focus group meetings with external stakeholders in the case study workshops . The focus group meetings in Bucharest are an example to the former. To identify vulnerabilities and needs in the response system, the partners agreed on grassroots, bottom-up approach. A succession of focus groups organized on the hierarchical levels of the intervention chain in Bucharest was approved, based on specific protocols and discussion guidelines. The latter is a method that we apply in our workshops to co-develop impact chains together with external stakeholders. The focus groups were designed as participative sessions to stimulate interaction between the stakeholders and to structure the discussion around predefined questions.

For instance, during the last focus group in the Caribbean Island workshop, the guiding questions were:

About past events:
- Which are the main natural hazards the area is prone to?
- What are the impacts of these hazards?
- What are the main events you experienced in your career and what was your role?
- How did past events affect different sectors?
- Where did the past events occur?

Understanding the impact chains:
- What are the main impacts based on the criteria in Impact Chain diagram?
- What are the risks related to these events?
- Which exposed systems are directly affected by the events?
- What are the indirect impacts of the event?
- What elements make the system and actors even more vulnerable?

The needs assessment:
- For your decision making – on which components of the mapping we have been doing do you need more information?
- Which tools would you need for this decision making?
- Which kind of data / information do you need for it?
- How can the platform be interactive?
- How does a user-friendly platform look like?
- In which phase of disaster management do you want to use the platform?
- What information do you need in which phase?

Stakeholders' expectations from PARATUS:
- Which of the desired tools can be used for the PARATUS platform?
- In which ways do you want to be involved in PARATUS?
- How can PARATUS involve you / your organization in the project?

- **Scenario co-design** meetings and evaluation meetings.

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Scenario co-design is another method that we use in our meetings with external stakeholders. We follow two approaches. The first, we are asking some specific questions to the stakeholders about future challenges and discuss them in groups (below please see some questions as an example).

Scenarios and future challenges:

- Which (additional) hazards do you expect to be a main challenge in the future?
- Which are the impacts you can think of regarding future challenges?
- Which tools would you need to tackle future challenges?
- For which hazards are you well prepared and which not?
- What trends do you expect in the future?
- Which underlying risk factors are potentially increasing risks, i.e., population growth, economic instability?
- How can adaptation decrease the risks?

The second, we give them some scenarios and develop together impact-chains for each scenario. For instance, in the workshop in Istanbul there were six scenarios shared with the participants. a scenario-based approach was conducted to reveal major impacts caused by an earthquake with a magnitude greater than Mw 7.0. In each scenario the size of the earthquakes were the same but temporal aspects differed from each other to delineate urban functioning and people's mobility (*Figures 3.2.1* and *3.2.2*)

Figure 3.2.1: timeline for scenarios (Source: D1.1)

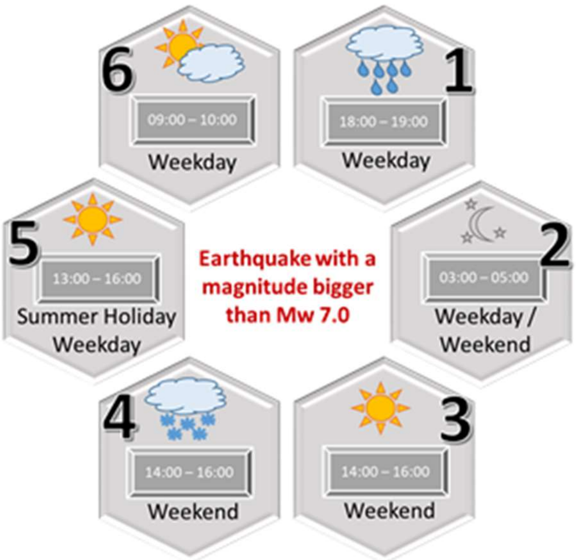

Figure 3.2.2: The six scenarios used in Istanbul Application Case Study Workshop (Source: D1.1)

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- **Testing**

Testing of the platform prototypes and evaluating modifications is done in an iterative process etc. Short cycle user testing will keep the user engaged and involved during the development of the platform, introducing innovative training elements to the platform.

- **Stress testing workshops**

The stress testing workshops will be integrated into the Learning Lab process and aims to support PARATUS partners across the various sectors in integrating climate-related risks in their projects and equip stakeholders with operational climate knowledge. These workshops address questions about what the hazards and climate projections (and uncertainties) are, what these mean for their project (impacts) and what can be done to reduce vulnerability (actions). It aims to move discussions from hazards to impacts to action. The workshop consists of interactive components about the main concepts of climate risk and regional projections, a reflection on the potential impacts of climate hazards on their respective projects and planning and joint collaborative work on a predefined case study. This approach focuses on cross sectoral learning through the exchange of challenges and solutions. Interaction, visualization, and engagement will be core focus points – drawing on the extensive experience of the Climate Centre in innovative online facilitation and creative learning.

- **Social Simulations:**

Social simulations are characterized by the social aspect of the tool in which different groups of interest interact in a fictional environment that emulates the real-world system and interlinkages between its key elements. The project will use social simulations to explore possible futures and new pathways towards risk reduction, adaptation, mitigation, and creating more resilient communities. An important element of the projects' simulation will be the social learning aspect. This will allow people to learn different perspectives and individual challenges, through narration-based gameplay and include them meaningfully in navigating future challenges and testing possible solutions. One of the most important distinctions of this social simulation is that it will be future-oriented. Seeing and experiencing the possible future outcomes of their own decisions, players will be able to confront their hidden assumptions and actively learn from their mistakes within a safe environment. This will build the capacity of stakeholders for actual disaster situations.

3.3 Questionnaire results

To conduct an inventory on types of users and existing tools we designed a questionnaire. The questionnaire helped us to find out what types of users are using what types of tools in which tasks related to DRR. The questionnaire was in the form of a Google Form and was shared with partners and stakeholders. The questionnaire was interacted with during various meetings (e.g., CERIS meeting in Toulouse) and was also made available on the PARATUS website (*Figure 3.3.1*).

The questionnaire consisted of 8 questions. Several questions were asked about the software that was used by the stakeholders for their work on DRR. The responses are summarized in *Table 3.2.1*. As can be seen from the table, these responses varied considerably, ranging from software tools for hazard assessment (e.g., FloodArea[11] for flood hazard assessment, RAMMS[12] for debris flows, RocFall)[13] to exposure analysis (e.g., BEAM[14]) to risk assessment tools (e.g., XRisk[15]). It is interesting to note that only one software for risk assessment was mentioned.

[11] https://www.geomer.de/handbuch/floodarea/en/index.html
[12] https://www.slf.ch/en/services-and-products/ramms-rapid-mass-movement-simulation.html
[13] https://www.geoengineer.org/software/rocfall
[14] https://emergency.copernicus.eu/mapping/sites/default/files/files/CEMS_IB_158_Austria_BEAM.pdf
[15] www.xrisk.fr

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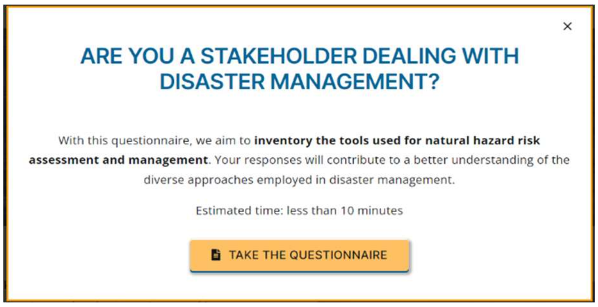
Until now, the questionnaire was answered by a limited number of stakeholders (only 13). We intend to keep the questionnaire open for several more months. The results are summarized below (Figure 3.3.1 ,3.3.2, 3.3.3 and table 3.3.1).



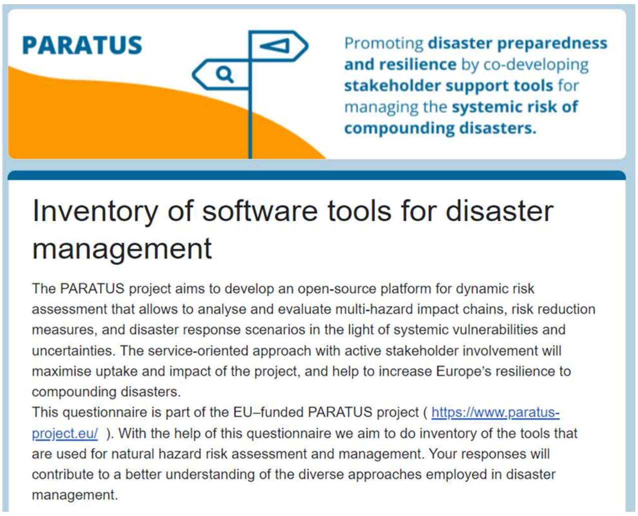


Figure 3.3.1: Left: Announcement on the PARATUS website. Right: Start of the questionnaire for stakeholders

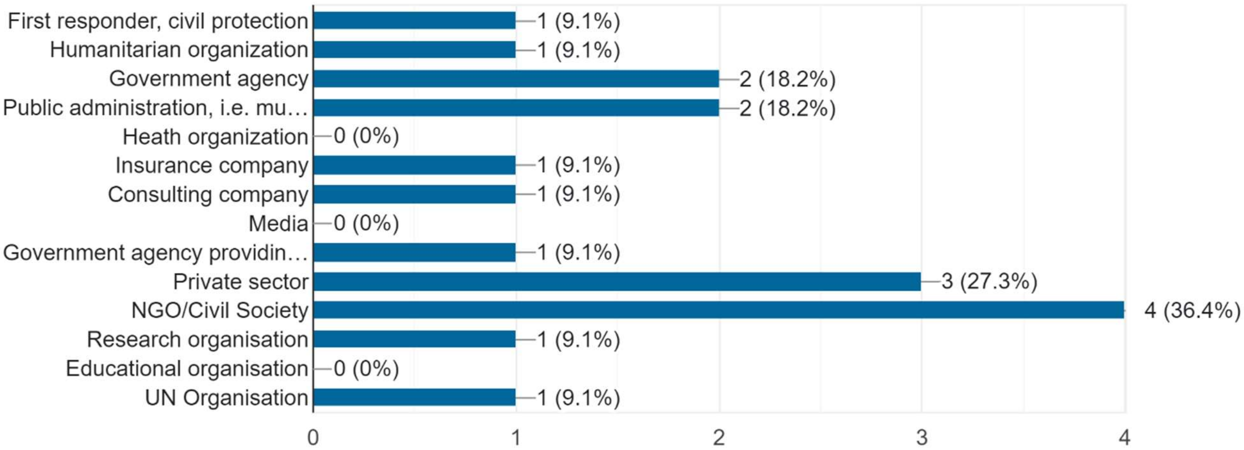


Figure 3.3.2: Answers to Question 1: In what type of organization do you work? (Multiple choice is possible)

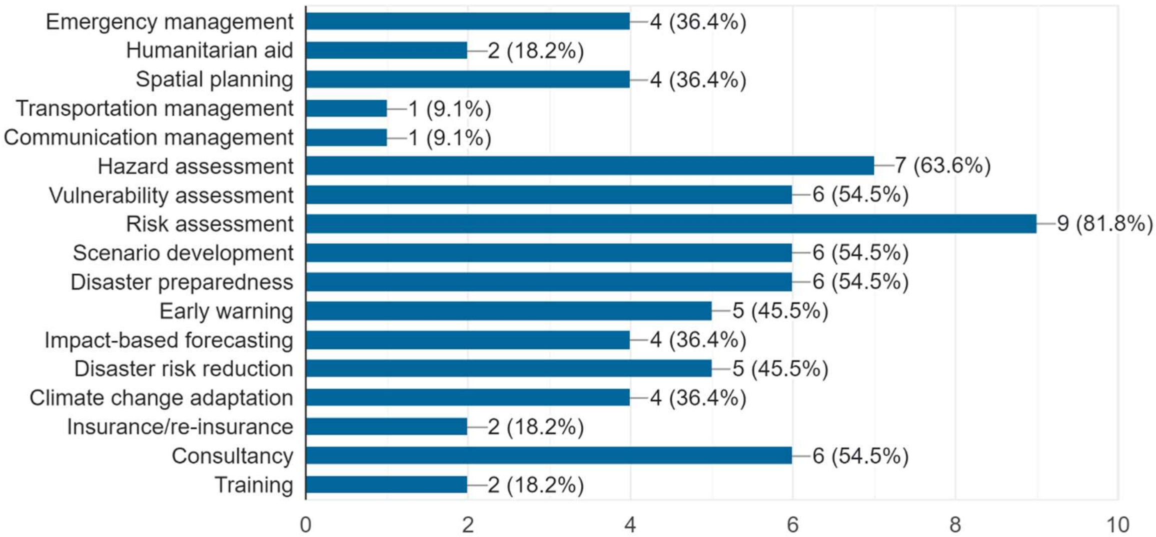


Figure 3.3.3: Answers to Question 2: Which tasks related to disaster risk management do you work on? (Multiple choice is possible)

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Table 3.3.1: Summary of the responses from the Questionnaire

Software	Description	Open?	Data
AfricaGIS	a specialised tool for index-based risk insurance, the remaining software tools are used for additional analyses	Yes	https://www.digitalearthafrica.org/ is using earth observation data
FloodArea	Torrential Flood Modelling software, for flood forecasting and for for Hazard and Risk Communication using the site: https://www.starkregengefahr.de/beteiligte-gebiete/	No	digital elevation data (pref. LIDAR), improved by additional filed mapping. Cloud based hydrodynamic modelling. The tool is used by municipalities as a communication tool, pricing depends on size of city (200-500 Euro/year)
ArcGIS	Generic and most common software for spatial analysis	No	Raster and vector data related to hazard, and risk
QGIS	Generic Open-Source software spatial analysis	Yes	Analysing the data of a region related to natural disasters.
BEAM	Assets Mapping for monetary risk evaluation,		This is an elements-at-risk database
Rockfall2	Rockfall modelling	No	DEM, land use, roughness, rock block size etc.
RAMMS	Debris flow modelling	No	DEM, volume of initiation, rheological parameters
SpaceWeather	Predominant dimension is time, and some important space weather parameters indicate processes that happen on a global scale, but I am, and I need to work on ways of showing those spatial aspects.		Allow for coupling of such time-based data and an interface for geospatial data. Adding now also data from ground stations and low orbiting satellites, for which the measurement location is very important for interpretation
XRisk	Aids with the analysis of undesirable events, calculates probability risks and represents risk mapping. It is available at www.xrisk.fr		It manages the implementation of various methods, facilitates the representation of tables and graphs
Community Risk Assessment (CRA)	for displaying risk data		Designed for anticipatory action and humanitarian aid
Python	For making trigger models	Yes	
IBF portal	For Impact based forecasting	Yes	Designed for anticipatory action and humanitarian aid
Postgres	Hosting databases	Yes	Software
Microsoft Azure	to host applications	Yes	Cloud computing platform for different applications

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3.4 Guidelines on user-centred design

Human-centred design (HCD) is a method to generate a better understanding of the user and the context of use through the user's perspective. It is an approach rooted in the belief that the people who face the problems are the starting point when developing a solution (de Jager, 2020[16]). HCD starts at desirability, but includes viability and feasibility (IDEO[17]). These three components of HCD will also be reflected in PARATUS user-centred design of the PARATUS platform.

- *''Desirability: What are the desires of the end-users/stakeholders?*
- *Viability: What is viable? What can be implemented? For how long is it viable? Who will maintain it?*
- *Feasibility: What is feasible with the available models and data, for example in terms of forecast skill?''*

To co-create the platform, concepts, and principles from design-thinking and HCD are instrumental. HCD sits at the intersection of empathy and creativity. It is a design and management framework that develops solutions to problems by involving the human perspective in all steps of the problem-solving process. Utilized in multiple fields, including social sciences and technology, HCD has been noted for its ability to consider human dignity, access, and ability roles when developing solutions.

Although there is no standardized or fixed methodology for HCD, many organizations follow the three steps in the "The Field Guide to Human-centred Design: Design Kit" (IDEO.org, 2015): inspiration, ideation, and implementation. In the inspiration phase, the goal is to identify the users and understand the user so we can create a concrete problem statement. In the ideation phase, the earlier observations are analysed, and ideas are generated. Additionally, prototyping and user-testing are done in this phase in order to validate the assumptions made and see if we solved the problem for the user before we build the solution fully. In the implementation phase, the practical embedding of the ideas is developed and executed in an iterative matter using Scrum methodology[18]. In each of these phases, the stakeholders and the end-users of the product are closely involved. This process is a staged approach, and between each phase, a go/no-go step is designed before continuing to the next phase. The Nielsen Norman Group[19] has a comparable design thinking framework. This design-thinking framework follows an overall flow of (i) understand (inspiration) (ii) explore (ideation) and (iii) materialize (implementation). *Figure 3.4.1* shows how these larger pillars cover six phases: *empathize*, *define*, *ideate*, *prototype*, *test*, and *implement*.

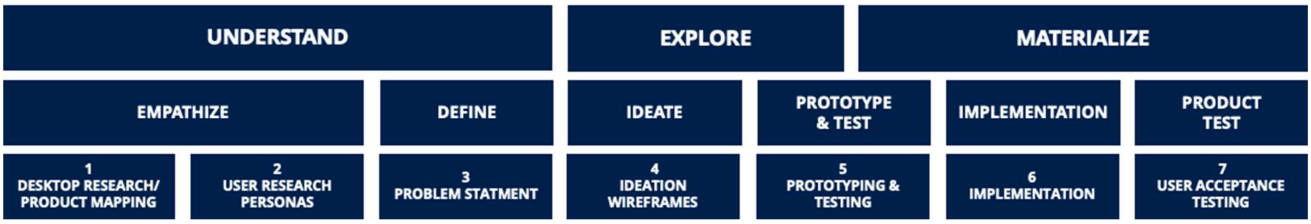

Figure 3.1.1 The design thinking framework mapped on the three human-centred design principles (NNgroup, 2022)

This section describes which frameworks are available that can be used "hands-on" in activities with the users and the stakeholders. *Figure 3.4.2* introduces the design activities, for example activities like personas, value proposition, and ideation wireframes which are particularly important to use early in the *empathize*, *define,* and *ideate* phase. *Table 3.4.1* gives definitions of the frameworks and related concepts. The benefit of investing in the understanding and exploration framework upfront is that if these frameworks are used properly, it will ensure that the co-creation process becomes user-driven **and not expert-driven.**

16 http://resolver.tudelft.nl/uuid:5d8d46ea-6353-476b-9260-72bd07d455eb
17 https://www.ideo.org/
18 https://www.scrum.org/resources/what-scrum-module
19 https://www.nngroup.com/

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A user-driven process can be characterized by a **listening mode**, where the designer does not only ask what solutions are needed and builds features based on requests but rather asks for the challenges and current way of working to build solutions based on local knowledge and needs. An expert-driven process is characterized by an **influencing mode**, where the experts influence the end users by show & tell and demonstrate available solutions in the portfolio of the expert. *Table 3.4.1* presents a non-exhaustive list of the activities and frameworks that can be used in the different phases as part of the human-cantered design approach.

Table 3.4.1: List of the activities and frameworks the human-centred design approach

The phase	Step	Actions
Empathize phase	DESKTOP RESEARCH/PRODUCT MAPPING	a. Desktop research on topic or country characteristics b. Understand the data, possibilities, and the limitations c. Gather requirements and input d. Map the goals, knowns, assumptions, and unknowns e. Stakeholder mapping
	USER RESEARCH/PERSONAS	a. Understand past research insights b. User Interviews, preferably on site c. Stakeholder interviews d. Insights clustering
Define phase	PROBLEM STATEMENT:	a. Develop personas b. Formulate problem statement c. Formulate value propositions per user segment
Ideate phase	IDEATION/WIREFRAMING:	a. Ideation sessions b. Benchmark research / comparative analysis / inspirations c. Design concept d. Rapid prototyping / Wireframes / Low-fi prototype e. Quick concept tests f. Agree on Minimal Viable Product (MVP)
Prototype & test phase	PROTOTYPING & TESTING	a. Iterating on the design concept b. Make High-fi prototype(s) c. User test(s), preferably on site d. Presentation and handover to developments
	IMPLEMENTATION	a. Refinement & prioritization b. Design adjustments based on feasibility
	USER ACCEPTANCE TESTING	c. MVP user acceptance testing d. Quality testing

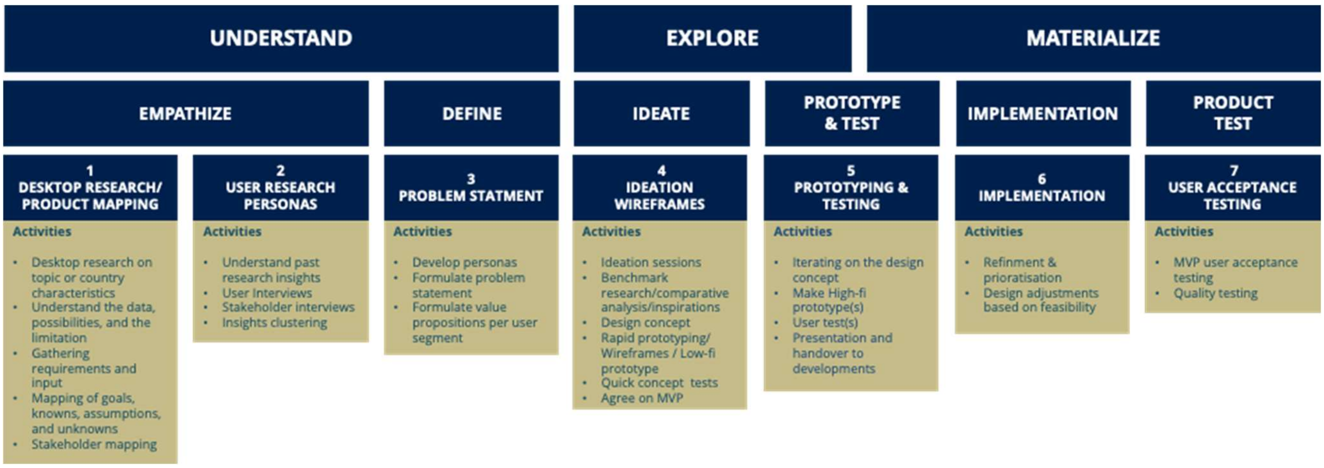

Figure 3.4.2 The co-creation framework from the PARATUS project maps onto the three design-thinking flows and their phases.

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Table 3.4.2 Overview of concepts and their definitions as used in strategic digital product development (check references for these definitions)

Concepts and tools	Definition
User	The user of the platform developed in the project (could include PARATUS members if they are intending to use the platform)
User story	A short, simple description of a need of the (end) user
User journey	A sequence of events or experiences a user might encounter while using a platform or a service (workflow)
Persona	Prototype to describe the user with basic characteristics, experiences, digital devices, challenges and opportunities, and goals
Value proposition	Specifies what makes the platform or service attractive or benefitable to the user
Ideation wireframe	A skeletal mock-up of the platform, typically used for designing the barebone structure of the user interface, content, and functionality
Service blueprint	A diagram that visualizes the relationships between different service components — people, props (physical or digital evidence), and processes — that are directly tied to touchpoints in a specific customer journey
Minimal Viable Product	Minimum Viable Product or MVP is a development technique in which a new product is introduced in the market with basic features, but enough to get the solve the users' main problems. The final product is released only after getting sufficient feedback from the product's initial users.

We intend to use the HCD methodology in an iterative way. Starting with the use case of the Caribbean, we will understand the specific users' needs within the context of the PARATUS project. We will align on the problem we are trying to solve by conducting a series of stakeholders and users' interviews. The users will (preferably) be identified in advance and if possible, the interviews should be done on site and in person to fully understand the context of the user's work and situation.

Then, we will propose a design concept based on what we learned from the users and assumptions we have gathered from the different stakeholders. We will use the concept to validate our assumptions and the problem statement. Presenting the design concept, we will need to prioritize and agree on the user requirements and functionalities that will be a part of the minimum viable product (MVP) we could build as a proof of concept (POC). Keeping the other case studies in mind we can start developing a POC for the Caribbean case study and test the solution on site again with the users before finalizing the development. Meanwhile, we can kick-off the same research process to understand the specific needs of the other case studies to identify how to develop the platform and incorporate their needs if applicable in the final solution.

3.5 The PARATUS Stakeholder Hub

The PARATUS platform will be hosted through the CMINE, the Crisis Management and Innovation Network, which is a professional network for anyone involved in Crisis Management. It currently has over 2000 members.

Building the Hub is a long-term activity which will be undertaken over the next four years, creating in a dynamic network of people interested in continuing the project's contribution to Societal Resilience long after it finishes

The Hub uses a pre-existing Online Community Platform - The Crisis Management Innovation Network Europe (CMINE)[20] to host a network of global partners. The whole PARATUS community will work to identify and 'sign-up' relevant members to partake in the activities (e.g., case studies). A fully inclusive approach will be taken to

[20] https://www.cmine.eu/

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all potential members of the Hub, regardless of individual or organisation. All opinions will be welcomed, and diversity/innovative thinking encouraged.

The Hub operates from a sound ethical foundation with clear rules and governance procedures with the aim of it becoming fully self-sustainable after the end of the project. Within the Hub, a specific End-User Board, specifically composed of end-user organizations (notably practitioners and decision and policymakers) external to the consortium has been established and will be expanded during the lifespan of the project (Figure 3.5.1).

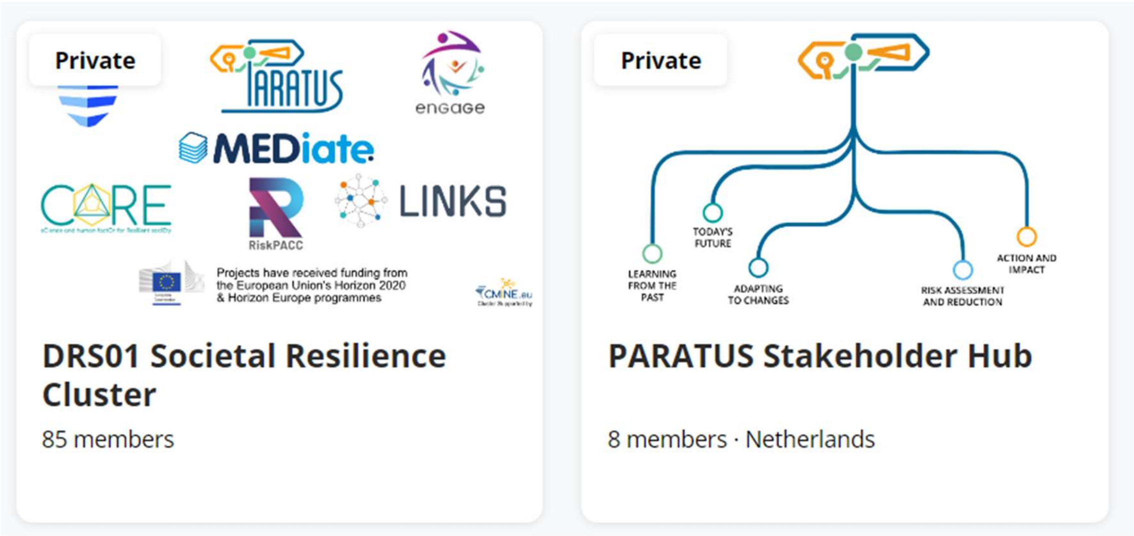

Figure 3.5.1: The PARATUS Stakeholder Hub on the CMINE platform.

Hub Activities

The Hub will provide two-way access to facilitate engagement between both the project and its Stakeholders *and* Stakeholders and the Project. It will:

- Feature updates on activities and initiatives
- Promote events
- Support a chat and discussion area
- Offer a repository for key documents relating to the project and its wider aims
- Provide the opportunity to interact with the much broader resilience and crisis management community

How stakeholders can get involved

- Register an account on CMINE and request membership of the Hub.
- As part of the process, you'll be asked to provide informed consent for limited use of your data (within the project only)
- Once confirmed, you'll be admitted to the Hub and encouraged to engage in a range of activities and to provide input and opinions on specific activities.

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4. General set-up of the platform

The Grant Agreement mentioned that the platform will have several sub-objectives: (i) design of multi-hazard impact chains and definition of the quantifiable components, (ii) model population with hazard, exposure and vulnerability data tailored to the specific user, (iii) co-development of future scenarios based on changes in causes (climate change, socio- economic changes), and (iv) co-development of planning alternatives and selection of optimal risk reduction options.

4.1 Components

The components that are currently envisaged in the PARATUS platform are illustrated in Figure 4.1.1. **The exact number of components, and the final structure of the platform will be determined iteratively through a number of stakeholder consultations, following a use-centred design, as described in the previous section**. It is important to state here that the design will be a compromise between the stakeholder needs of the stakeholders involved in the PARATUS project as project partners (DSU in Romania, ASFINAG in Austria, IMM in Istanbul and NRC in the Caribbean), and stakeholder requirements of stakeholders outside of the consortium. The platform should be both generic enough to be able to cater for stakeholders that work in different sectors, geographic setting, and interacting hazards, and specific enough to address (a number of) their needs for analysing the impact of compounding and multi-hazard events, with cascading impacts.

We foresee that the PARATUS Platform will have two major blocks: an **information service** that provides static information (or regularly updated information) and **simulation service**, which is a dynamic component where stakeholders can interactively work with the tools in the platform.

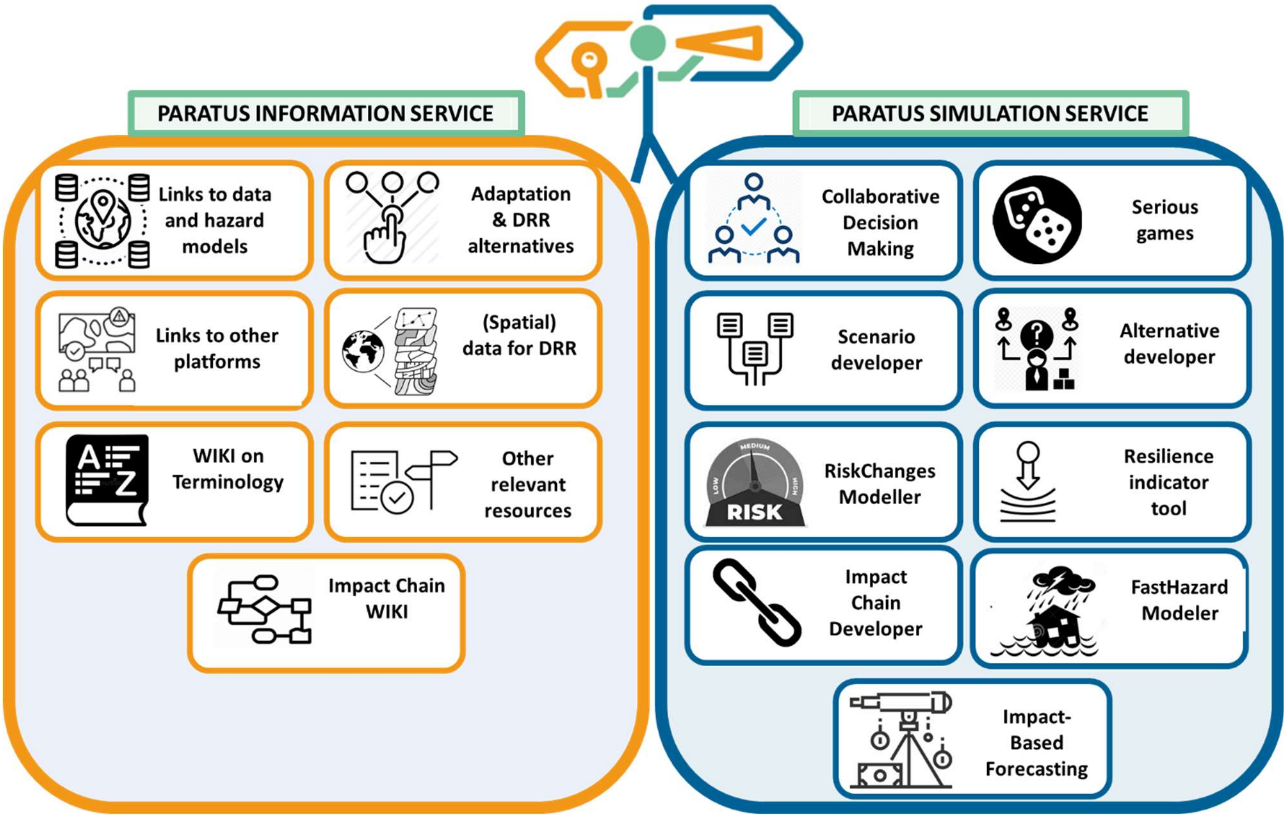

Figure 4.1.1: The PARATUS platform concept.

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4.2 The PARATUS information service

This will be the component of the platform where users can query and consult different types of information that are relevant for analysing complex multi-hazard impact chains.

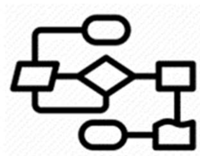
WIKI on Terminology & risk methods.

There are several other EU projects that have developed useful tools and repositories that PARATUS can link to, without reinventing the wheel. Under the MYRAID-EU project[21] a Wiki-style online crowdsourcing platform was developed with examples of qualitative and quantitative multi-hazard, multi-risk methods, models, and tools (approaches), including examples of their application. The wiki design, development, and deployment were undertaken by BGS. It was created using the freely available software, MediaWiki, which is designed for open content, and is hosted by the BGS. Functionality and the appearance of the wiki has been customised through the installation of extensions that are attached to the core software. The wiki, Disaster Risk Gateway[22] has a nested structure and pages are responsive allowing for page optimisation across all devices.

Links to other platforms.

We want to collaborate with other EU projects that have partly overlapping objectives. In particular, we would like to collaborate with the MEDIate project, which is also developing a similar platform as PARATUS as it addresses the same call.

Impact chain WIKI.



Based on the analysis of relational impact chain of vulnerability risk for the learning and application case studies, we will develop a WIKI with standardized impact chains. We analyse how the hazardous event impacted different sectors, such as society, human health, cultural heritage, environment and biodiversity, public finance, and key economic sectors. This includes reports, interviews with specific stakeholders, testimonies, videos, virtual workshops for learning cases and presence meetings for application cases organized in WP6. Consolidation of the collected information is done in a Wiki-type of the system which is based on existing software tools. Based on the experience with impact chains, we have decided to develop the impact chains in KUMU. EURAC has developed a guideline for this, and all the partners are asked to make several impact chains for historical events.

Links to hazard models and data.

Based on experience on other project the platform will contain a section with links to online and offline tools for hazard assessment. These are derived from the repository of hazard assessment algorithms that have been collected within the ANYWHERE[23] project and other projects. These will be further expanded with hazard models that consider certain hazard interactions. One of these is an integrated physically based modelling tool related to extreme rainfall events, earthquakes, and volcanic eruptions, called OPENLISEM[24] and FastFlood.org[25].

21 https://www.myriadproject.eu/
22 https://www.disasterriskgateway.net/index.php/Main_Page
23 http://anywhere-h2020.eu/the-challenge/hazards/
24 https://lisemmodel.com/
25 https://fastflood.org/

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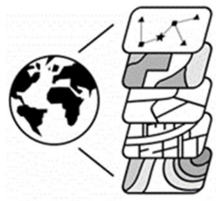
Adaptation and DRR alternatives.

PARATUS will co-develop context-specific decision-making tools suitable for stakeholders in different sectors and risk governance settings. They will consider the specific needs of stakeholders (including especially vulnerable groups), incorporate the uncertainty of the scenarios, and compare different alternatives for risk reduction. PARATUS will actively involve a range of stakeholders to develop and test methods and tools for selecting appropriate disaster risk mitigation measures that address Social Sciences and Humanities aspects (including gender aspects and disadvantaged groups, i.e., migrants). We will develop a WIKI type with suggestions for adaptation measures based on multi-hazards, scale of application and sector. This is based on extensive literature analysis considering examples such as the GreenBook[26], and Dynamic Adaptation Pathways[27]. This component will critically assess existing approaches and offer a special selection in the PARATUS toolbox, to be used in processes of the case study sites, but also offered to the learning sites. Co-production of adaptation and mitigation options will utilise The Learning Lab approach[28]. This approach is founded on principles of participation and trans-disciplinary action research. The Learning Labs are a series of interactive and deeply participatory workshops to facilitate the co-creation of adaptation and DRR options. This approach has been developed and tested by the Climate Centre and University of Cape Town in the FRACTAL[29] project - testing the City Learning Lab approach in 9 African cities. In PARATUS the Learning Lab approach will be used to facilitate deep stakeholder engagement with a range of stakeholders using an action research process.

(Spatial) Data links (hazard, exposure, scenarios etc).



This part of the platform will provide an overview of the spatial data links that are developed in the project or that are internationally available. These deal with data sources related to historical disaster events, hazard maps, elements-at-risk maps (build-up areas, land use, building footprints, transportation infrastructure, population etc.). The results of the remote sensing time series analysis that was used in combination with Artificial Intelligence and crowdsourcing techniques to improve data on historical events and for multi-temporal exposure datasets will be made available through this component. Climate scenarios for the different study areas will be provided from simulations by global climate models (CMIP6, Eyring et al. 2016), including high-resolution models (HighResMIP, Haarsma et al. 2016) and regional climate models (CORDEX, Gutowski et al. 2020). These climate model data are freely available using the Earth System Grid Federation (ESGF). Post-processing of that data for selected case studies will be done to provide metrics for hazards, such as frequency and intensity of heavy rainfall, temperature, droughts, or wind. If available, already post-processed data will be used. In addition, information from regional climate reports produced by national governments and other agencies, such as IPCC, WMO and the World Bank, will be applied. For the Caribbean region, climate scenarios are being developed by the KNMI with a focus on the islands Bonaire, St. Eustatius, and Saba. This will be done in collaboration with Caribbean Institute for Meteorology and Hydrology (CIMH). In addition, regional reports such as those by the Caribbean Development Bank (2020) and the Organisation of Eastern States (OECS) (2020) will be used.

4.3 The PARATUS simulation service

The other main group of tools on the PARATUS platform consists of tools that are dynamic and interactive, and which support the stakeholders to define, analyse and quantify the impact of multi-hazard events, now and under different future scenarios, and to evaluate which risk reduction options would be most suitable. The following tools are foreseen.

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[26] https://greenbook.co.za/
[27] https://doi.org/10.1016/j.envsci.2020.11.003
[28] http://www.thelearninglab.nl/
[29] https://www.fractal.org.za/wp-content/uploads/2020/03/IS1-FRACTAL-city-learning-lab-approach.pdf

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Impact Chain Development tool

PARATUS will develop an effective methodology to understand and analyse the dynamic and interactive conditions of risk to make better predictions for the future. PARATUS will develop a qualitative and quantitative conceptualization of systemic risk in complex disaster events with the help of impact chains through forensic analysis, remote sensing monitoring and disaster databases. The impact chain tool may be partly the same tool as the one used for the WIKI, but it now allows users to generate and modify impact chains. The impact chain development tool will be developed using Open-Source software, based on software tools such as the Living Textbook[30] and the CRIP tool from EURAC.

Hazard modelling tool

Although it is not possible to develop multi-hazard modelling tools for all hazards considered, we will use the FastFlood tool[31]. The current status of technological advancement does not allow to generate complete flood simulations in real-time for large geographic areas. This hinders warning-systems, interactive planning tools and detailed forecasts, and, consequently, the population cannot quickly or reliably be informed of where large masses of water will flow. Our novel method computes flood hazard maps much faster than current state-of-the-art methods. It applies physically based principles of steady-state flow to evade full dynamic aspects of flood simulations and directly estimates the relevant information for flood hazard, such as peak flow height, velocity, and flood arrival time. Performance indicators show similar or exceeding accuracy compared to traditional flow models depending on the type of event and quality of the used elevation data. In our tests, computational costs are reduced on average by a factor 1500. As a result, the developed method provides new perspective for the field of flood hazards, flood risk reduction through new types of early-warning systems, and user-interactive hazard assessment systems. As climate change is expected to aggravate flood hazard, the presented method can bring necessary efficiency to flood simulation, thereby saving lives and livelihoods.

RiskChanges Impact quantification tool

PARATUS will develop a tool to assess multi-hazard and multi-sector impacts, consisting of direct impact, and (where possible) indirect impacts. PARATUS will also co-develop a service to analyse dynamic exposure, vulnerability, and systemic risk, that can be applied in all phases of the disaster risk management cycle. RiskChanges is a Spatial Decision Support System for the analysis of current and future multi-hazard risk at local level, in order to select optimal risk reduction alternatives. The system has originally been designed in a European Research Project[32] by the University of Twente and other partners. Later the system was newly implemented using the most recent developments related to web-based open data analysis, by the University of Twente in collaboration with the Asian Institute of Technology, Geoinformatics Centre. The current version of the RiskChanges tool[33] is an Open-Source tool for multi-hazard risk assessment. The system is based on a series of Python scripts, which can be used directly by users that know how to work with Python. The code[34] is available in GitHub. This version of the RiskChanges Library is customized for local computation, and users can install the library[35] directly from GitHub or from PIP and start working with their own data, modifying the code. To further understand how the codes work, there are Jupyter notebooks in this project. More information can be found in the ReadTheDocs[36]. Users that are not experienced with Python can use the Graphical User Interface (GUI) which can be reached through RiskChanges.

[30] https://ltb.itc.utwente.nl/
[31] https://doi.org/10.31223/X5MM2Z
[32] http://www.changes-itn.eu/
[33] http://www.riskchanges.org/
[34] https://github.com/RiskChanges/RiskChangesDesktop
[35] https://pypi.org/project/RiskChangesDesktop/
[36] https://sdss-documentation.readthedocs.io/en/latest/

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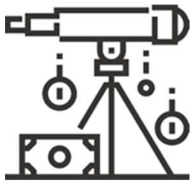
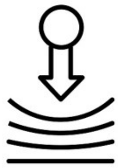
Impact-Based Forecasting tool



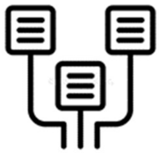
The Impact Based Forecasting (IBF) Portal takes the theory about risk, vulnerability and exposure and transforms it into actionable practice for local users such as disaster managers (see section 3.1). It is meant to be the one stop shop for disaster managers to find all the relevant information for them to respond adequately to an upcoming hazard.

Resilience to systemic risk evaluation tool



It will not be possible to quantify all the indirect impacts using the RiskChanges tool, either because the conditions that lead to an indirect impact are unknown or the data for that is missing. Therefore, the aim is to also develop an indicator-based approach, which is linked to the components of the impact chains, and the relation between the components.

Scenario development tool



PARATUS will develop a method to assess multi-hazard and multi-sector impact chains that will be applied to co-developed scenarios considering changes in climate conditions and dynamic exposure information and their interactions. Scenarios can be co-created with stakeholders using participatory planning tools. The scenarios refer to possible changes in hazard, exposure, and vulnerability. Hazard changes are related to changes in hazard types, frequency and intensity following climate change scenarios presented by the latest IPCC reports. These are translated into the components needed for risk assessment. Changes in exposure are evaluated based on the changes in drivers (demographic, economic, social, political, and climate change feedback), resulting in different land use, population, and infrastructure patterns. Changes in vulnerability will be represented in changes to physical vulnerability curves and holistic vulnerability indicators.

Adaptative Scenario development tool

PARATUS will co-develop context-specific decision-making tools suitable for stakeholders in different sectors and risk governance settings. They will consider the specific needs of stakeholders (including especially vulnerable groups), incorporate the uncertainty of the scenarios, and compare different alternatives for risk reduction.

Serious Game tools

With stakeholders, we will co-develop two serious games exploring creativity and experiential learning, using in-person/video processes and augmented reality. Serious Games are facilitating deeper learning in complex contexts, enabling participants to learn experientially and harness their creativity. The Climate Centre and CRS have been working with Serious Games for more than a decade[37]. They will collaborate with other groups[38] [39] that have a wide experience with Serious Gaming, an experiential process rooted in a more active, experiential methodology based on Kolb's Cycle[40]. This approach highlights the fact that knowledge acquisition is "created through the transformation of experience" and requires a more interactive environment that the players may explore.

Collaborative planning tool

The aim of collaborative decision support procedures is to involve stakeholders in decision making to solve conflicting issues. Consensus building methods include developing alternative planning scenarios, brainstorming jointly on evaluation criteria for certain plans, sketching different plan alternatives, or assigning individual priorities and criteria weights during an assessment. Structuring decision making processing following a sequence of converging and diverging steps helps to better integrate consensus building steps into the process.

[37] http://www.climatecentre.org/downloads/files/Games/CDKNGamesReport.pdf
[38] https://www.dkkv.org/de/serious-gaming
[39] https://www.fastcompany.com/90323110/these-board-games-play-out-how-climate-change-will-reshape-our-cities
[40] https://www.researchgate.net/publication/235701029_Experiential_Learning_Experience_As_The_Source_Of_Learning_And_Development

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5. The PARATUS Information Service

The PARATUS information service will consist of components that provide useful information to first and second responders and other stakeholders in Disaster Risk Management to evaluate the impact chains of multi-hazard events with particular emphasis on cross-border and cascading impacts. This PARATUS platform can be visualized as a website with several blocks. When users click on a block, they will be taken to a new page in which the specific component is worked out, and where the information is given. This can be also a page on another location (e.g., the WIKI on terminology is hosted on another website). *Figure 5.1* gives an impression of the PARATUS information service.

It is important to stress that the final set of components will be determined based on further interaction with stakeholders.

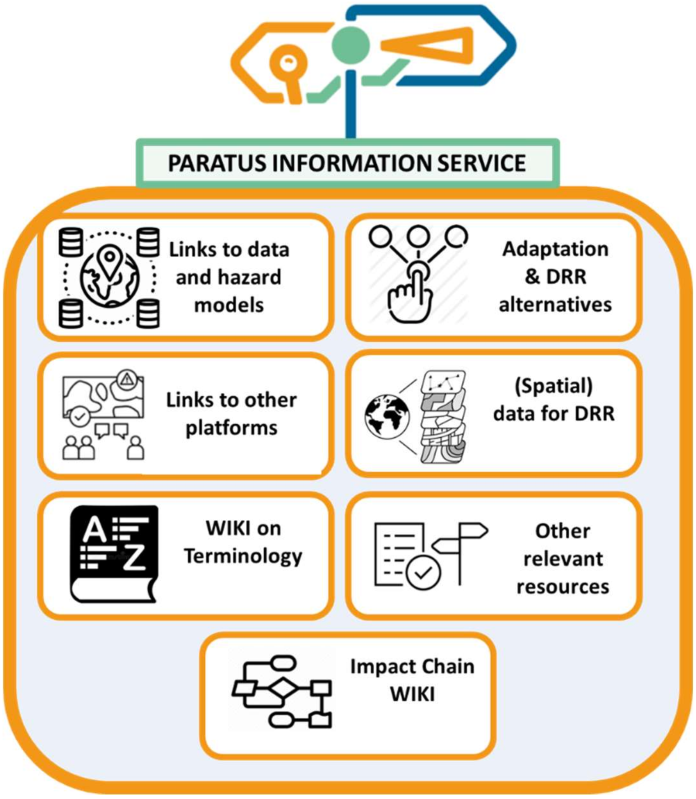

Figure 5.1: Impression of the PARATUS information service.

One of the key components of the PARATUS Information Service will be the Impact Chain WIKI. This is an entirely new concept, and this will be one of the central components. It will offer a new way of viewing the impact of historical disaster events, though an impact chain, which can be seen as a tree-like structure showing the interconnections between the triggering event(s), the hazard interactions, exposed elements-at-risk and their vulnerabilities and their direct and indirect impacts.

5.1 Terminology WIKI

The PARATUS project will contain a section that links to the terminology used in disaster risk management. This can be quite confusing, even though there are international agreed guidelines for terminology, such as:

- UNDRR Sendai Framework Terminology on disaster Risk Reduction[41]

[41] https://www.undrr.org/terminology

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- UNDRR Hazard definition & classification review (2020)[42]
- UNDRR Hazard Information Profiles (2021)[43]

The terminology used for compounding and multi-hazards and their impact is still rather confusing. Due to multiple hazards or drivers (such as heatwaves and droughts) occurring at once, earlier events or climate conditions making a system more vulnerable to subsequent events (for example intensive rainfall on saturated soils), or spatially coexisting events leading to local or global compounding effects (for instance globally harmonized heatwaves disturbing global production of food), when multiple drivers and/or hazards combine, their effects are frequently amplified[44]. The term *compound events* were introduced by IPCC Special Report on Climate Extremes (SREX) in 2012, and now, it is integrated within the risk framework of IPCC as "a combination of multiple drivers and/or hazards that contributes to societal or environmental risk"[45]. Studying compound events is a complex task, which often requires a multidisciplinary approach involving the understanding of the underlying physical processes beyond the impact, climate, weather elements, and advanced process-based and statistical modelling (Bevacqua et al., 2017). Better understanding their occurrence, quantifying key characteristics, analysing their drivers, and projecting how they will change in the future is of high societal importance (Sillmann et al., 2019). Traditional risk assessment approaches often consider only one driver at a time, which consequently causes the underestimation of risk. The Independent multi-hazard approach does not consider hazard interactions and directly deals with international policies of sustainability and risk reduction, for example: Agenda 21[46], the Johannesburg Plan[47], and the Hyogo Framework for Action[48]. The spatial approach was used for these policies, using the "all-hazards at place approach" by Hewitt and Burton (1971) and Gill and Malamud (2014) debated it as a "multilayer single hazard" approach, which involves approaches for single and multi-hazard risk assessment[49]. Currently, more attention is being called to multi-hazards and multi-risks[50,51]. The PARATUS platform will link to other resources that provide a review of approaches to multi-hazard risk assessment.

The 'Wiki-style online crowdsourcing platform of multi-risk methods, models, and tools' was produced as part of the MYRIAD-EU project. The aim of the task was to develop a Wiki-style online crowdsourcing platform of examples of qualitative and quantitative multi-hazard, multi-risk methods, models, and tools (approaches), including examples of their application. The wiki design, development, and deployment were undertaken by BGS. It was created using the freely available software, MediaWiki, which is designed for open content, and is hosted by the BGS. The current content is classified into two main categories: 'multi-hazard risk assessment' and 'multi-hazard risk management'. In addition to overviews of multi-hazard risk assessment and management approaches, the wiki, called the Disaster Risk Gateway[52], also contains definitions for key terms.

5.2 Links to Other Platforms

The PARATUS platform will contain a section that links to the platforms developed by a number of "sister projects", which are funded under EU HORIZON Europe programme. These projects were introduced in Table 2.3.1. Especially the projects MEDIATE, C2IMPRESS, MYRIAD-EU and the HuT Nexus.

The European research and innovation supporting programmes Horizon 2020 and Horizon Europe connect diverse actors, engaged to strengthen the impact of research and innovation in developing, supporting, and implementing EU policies, while tackling specific global challenges. Their active communication and

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[42] https://www.undrr.org/publication/hazard-definition-and-classification-review-technical-report
[43] https://www.undrr.org/publication/hazard-information-profiles-hips
[44] https://www.nature.com/articles/s41558-018-0156-3
[45] pp. 1513–1766, doi:10.1017/9781009157896.013.
[46] https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf
[47] https://digitallibrary.un.org/record/478154
[48] https://www.unisdr.org/2005/wcdr/intergover/officialdoc/docs/Hyogo-framework-for-action-english.pdf
[49] https://www.sciencedirect.com/science/article/pii/S2212420922000486?via%3Dihub
[50] https://meetingorganizer.copernicus.org/EGU2018/EGU2018-5439.pdf
[51] https://doi.org/10.5194/nhess-22-1487-2022
[52] https://www.disasterriskgateway.net

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collaboration through platforms such as the Community for European Research and Innovation for Security CERIS and clusters leads to deeper exploration of challenges and broader uptake of generated solutions, strengthened synergies and magnified benefits of research in strategic societal challenges. The Crisis Managers Innovation Network Europe CMINE is offering a dynamic, safe workspace to the established Clusters of projects, supporting their interaction-focused objectives throughout the project implementation cycles. PARATUS is collaboration with a number of other projects in the Societal Resilience Cluster.

With these projects we are having regular exchanges planned in the form of joint webinars, joint sessions during conferences, and attending each other's general assembly meetings. We are also actively investigating how we can reach a certain level of synergy, and potentially co-developing certain components. However, this needs to be in accordance with the Grant Agreements of the projects, which may make the joint development of tools more difficult.

In any case we are planning to make links to the tools developed in these projects on the PARATUS platform website.

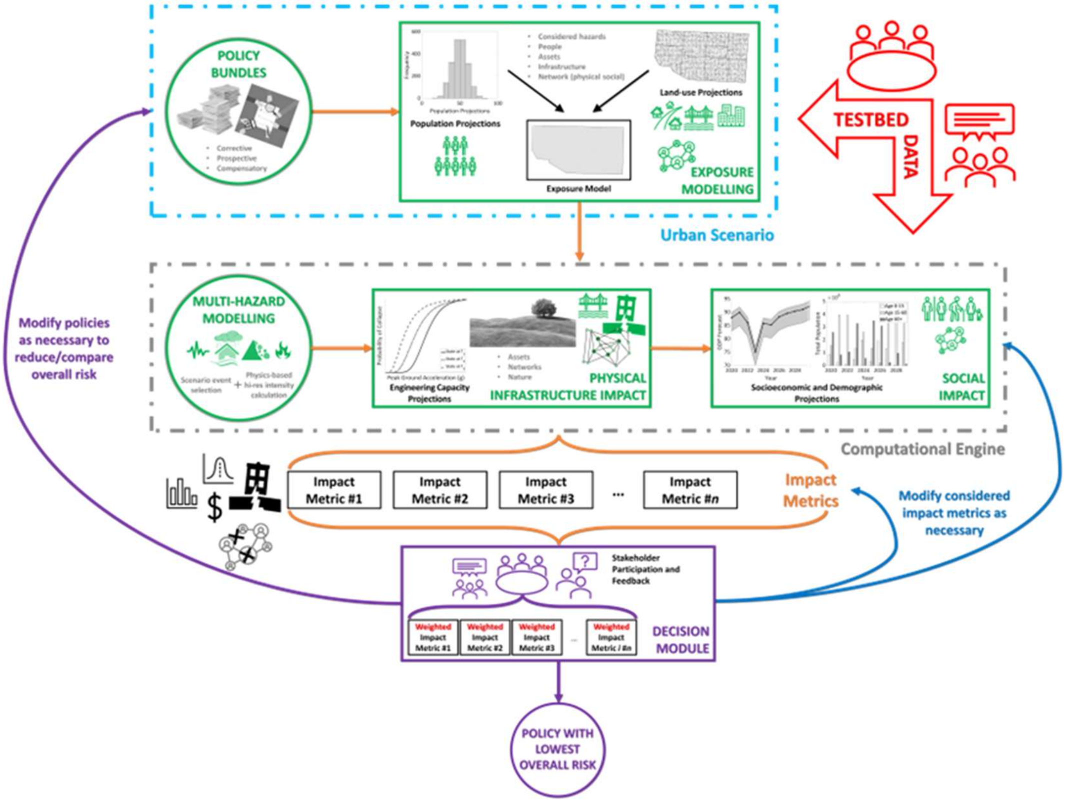

Figure 5.2.1: MEDIate concept[53]

[53] https://mediate-project.eu/

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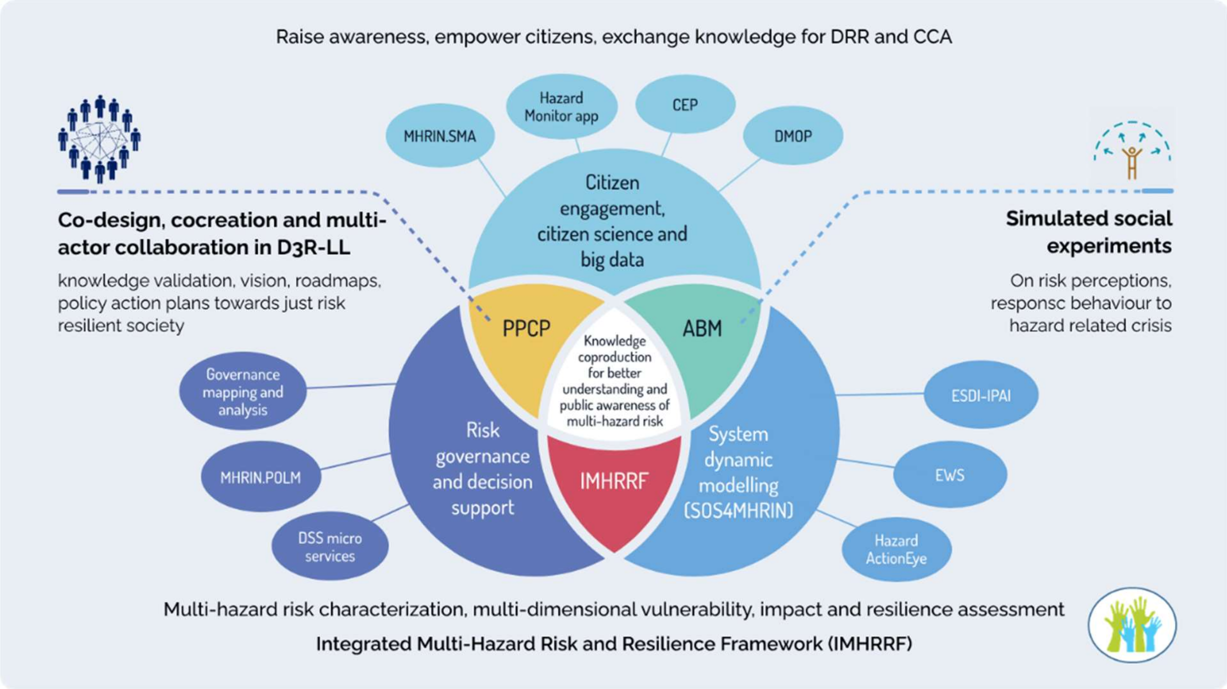

Figure 5.2.2: C2IMPRESS concept (See the list of Acronyms for the abbreviations)[54]

5.3 Links to data and hazard models

5.3.1 General links and information

The PARATUS platform will contain a section that will inform stakeholders on possible hazard models that can be accessed through internet, and hazard related data sources.

Different types of hazard models and spatial datasets have been developed by both previous projects and ongoing initiatives. One example is the ANYWHERE project[55] (See also *Table 2.3.1*) that created algorithms for multiple climate-related hazards, like floods, flash floods, debris flow and landslides, droughts, forest fires, heatwaves, snowfall, storms and sever winds. A catalogue of each hazard and the algorithms developed is categorised on their website[56]. However, because the ANYWHERE project had a strong commercial focus and the funding scheme was an Innovation Action, most of the algorithms are not publicly available. That's why only the open accessible models and results will be used in the PARATUS platform.

At European scale, the INSPIRE Geoportal[57] is the central access point to the data provided by EU Member States and several EFTA countries under the INSPIRE Directive, which was defined in May 2007. The Geoportal addresses 34 spatial data themes[58] including multiple administrative and environmental themes, which can be used for the systemic multi-hazard risk assessment. One example of these 34 themes is related to "Natural Risk Zones"[59] (which includes 1353 metadata records and 259 downloadable datasets.

In addition, there is the COPERNICUS Emergency Management Service (CEMS[60]), which uses remote sensing techniques (satellite imagery) to create mapping services in cases of natural disasters, human-made emergency situations and humanitarian crises in Europe and the world. The CEMS provides maps in two

[54] https://www.c2impress.com/
[55] http://anywhere-h2020.eu/
[56] http://aqua.upc.es/anywhere-catalogue-v2/
[57] https://inspire.ec.europa.eu/
[58] https://inspire-geoportal.ec.europa.eu/theme_selection.html?view=qsTheme
[59] https://inspire-geoportal.ec.europa.eu/overview.html?view=themeOverview&theme=nz
[60] https://emergency.copernicus.eu/mapping/ems/emergency-management-service-mapping

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temporal modes (rapid mapping and risk/recovery mapping). Another platform related to satellite imagery is the NASA Earth Observing System Data and Information System (EOSDIS)[61]. In that software tool at global scale, different hazards such as floods, forest fires, volcanoes, storms etc. can be visualized interactively and downloaded.

In the following, an overview of some specific links to hazards and models is given in the first part dividing them into major classes. In the second part, datasets and links related to exposure are listed.

5.3.2 Specific links regarding hazards

There are different platforms regarding **hydrometeorological hazards** like rainfall, snow, floods etc. First, there are different tools that provide information on rainfall and precipitation forecast. The European Flood Awareness System (EFAS)[62], gives accumulated rainfall forecasts that covers the entire area of Europe at a spatial resolution of 5km[63]. At global scale, the Daily Total Precipitation Probability can be observed at a spatial resolution of 18km at the ECMWF Integrated Forecasting System (IFS) [64]. Inside the EFAS platform, the Snow accumulation and snow water equivalent[65] can also be found at a spatial resolution of 5km and a daily update.

Focusing on **floods**, the EFAS platform provides a Probabilistic River Flood Hazard Forecasts that covers Europe, with a temporal resolution of 5-10 days and a spatial resolution of 5km. On the other side, flood hazard maps of different return periods were produced under the EU Floods Directive. Data availability varies by country and region and can be found for European scale[66] and for global scale[67] respectively.

Earthquakes, the web platform hazard. EFEHR[68] is operated by the European Facilities for Earthquake Hazard and Risk, EFEHR[69]. EFEHR is a non-profit network of organisations and community resources aimed at advancing earthquake hazard and risk assessment in the European-Mediterranean area. The hazard. EFEHR web platform provides access to interactive tools such as seismic hazard models, products, and information. Distributed data, models, products, and information are based on research projects carried out by academic and public organizations. Currently, the seismic hazard models and resources for Europe, the Middle East, the GSHAP global model and the Swiss Seismic Hazard Model are available. In addition, there is the Global Earthquake Model (GEM)[70], which includes open and collaborative seismic risk assessment on different scales. GEM aims to support disaster risk reduction planning and helps to develop multi hazard and systemic risk assessments to create integrated risk and resilience solutions.

For **droughts**, there is the European Drought Observatory[71], which includes a platform that indicates the Combined Drought Indicator (CDI) for Europe at 5km resolution with a temporal scale of 10 days[72].

Another process is **Landslides**. Information on these hazards can be found in the platform called "Global Landslide Hazard Assessment (LHASA)[73], which is globally available at 1km resolution. In addition, there is the European Landslide Susceptibility Map (ELSUS)[74], which covers Europe at 200m resolution.

5.3.3. Specific links regarding exposure

There are already existing databases representing elements-at-risk/exposure like population and buildings that are exposed to hazards in a certain area. Often these are collected by the municipalities, for instance cadastral or census data. Similar to the hazard models these types of datasets are not always publicly accessible and

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[61] https://worldview.earthdata.nasa.gov/
[62] https://www.efas.eu/en
[63]http://aqua.upc.es/anywhere-catalogue-v2/?product=accumulated-rainfall-forecasts#tab-additional_information
[64] https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model
[65] http://aqua.upc.es/anywhere-catalogue-v2/?product=simulated-snow-accumulation
[66] doi: 10.2905/1D128B6C-A4EE-4858-9E34-6210707F3C8 1
[67] https://data.jrc.ec.europa.eu/collection/id-0054
[68] http://risk.efehr.org/
[69] http://www.efehr.org/start/
[70] https://www.globalquakemodel.org/
[71] https://edo.jrc.ec.europa.eu
[72] https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1111
[73] https://gpm.nasa.gov/landslides/projects.html
[74] https://esdac.jrc.ec.europa.eu/content/european-landslide-susceptibility-map-elsus-v2

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freely available, that's why the focus of exposure data is also on already existing, open-access and globally available exposure datasets. In the following a selection of exposure datasets on population, land use and land cover as well as built-up area is given.

Regarding **Population** WorldPop[75] provides information on the distribution of the world's human population on a 100m x 100m pixel grid yearly from 2000 until 2020. A similar dataset is the Global Human Settlement (GHS) POP, which also shows the estimated distribution of residential population at a resolution of 100m to 1km in 5-year intervals between 1975 and 2020[76].

Land use and land cover (LULC) maps depict spatial data representing different types or classes of physical coverage found on the Earth's surface, such as forests, grasslands, croplands, lakes, and wetlands. There are various types of LULC datasets with different spatial, temporal, and thematic resolutions. CORINE Landcover shows LULC for Europe at 100m resolution for the years 1990, 2000, 2006, 2012 and 2018 with 44 different classes[77]. ESA WorldCover[78], Copernicus Global Land Cover[79] and MODIS Land Cover[80] provide LULC datasets on a global scale. ESA WorldCover maps the LULC at a spatial resolution of 10m for the years 2020 and 2021 including 11 classes, Copernicus Global Land Cover at a resolution of 100m per year between 2015 representing 23 discrete classes and 2019 and MODIS Land Cover at 500m pixels on a yearly basis between 2001 and 2021 with 17 classes.

Focusing on **Built-up Areas t**he World Settlement Footprint (WSF) Evolutions depicts the development of the built-up and non-built-up areas worldwide from 1985 until 2015 on an annual basis and at a resolution of 30m[81].

In addition to the POP data and several other products[82], the Global Human Settlement Layer (GHSL) also provides a Built-up Surface Grid (GHS-BUILT-S), which shows the distribution of built-up surfaces in square metres from 1975 to 2030 at 5-year intervals and 100m resolution[83]. The GHSL also gives a European Settlement Map (ESM) for the year 2015, that depicts human settlements with the three classes land, water, and built-up area at a high resolution of 2m and for 10m resolution with the classes land, non-residential built-up area, and residential built-up area[84].

Further building information is provided with crowdsourcing trough OpenStreetMap (OSM) data. OSM is a collaborative mapping platform where users contribute geographic/geospatial data, including information about infrastructure and exposure to hazards all around the world, for instance buildings, road networks or water surfaces[85]. Microsoft Building Footprints[86] and Open Buildings[87] derived from satellite imagery using artificial intelligence, include building polygons for specific regions of the world and globally.

75 https://www.worldpop.org/
76 http://data.europa.eu/89h/2ff68a52-5b5b-4a22-8f40-c41da8332cfe
77 https://land.copernicus.eu/global/products/lc
78 https://esa-worldcover.org
79 https://land.copernicus.eu/global/products/lc
80 https://modis.gsfc.nasa.gov/data/dataprod/mod12.php
81 https://download.geoservice.dlr.de/WSF_EVO/
82 https://ghsl.jrc.ec.europa.eu/download.php?ds=bu
83 http://data.europa.eu/89h/9f06f36f-4b11-47ec-abb0-4f8b7b1d72ea
84 http://data.europa.eu/89h/8bd2b792-cc33-4c11-afd1-b8dd60b44f3b
85 https://www.openstreetmap.org
86 https://planetarycomputer.microsoft.com/dataset/ms-buildings
87 https://sites.research.google/open-buildings/

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5.4 Risk Reduction and Adaptation Alternatives

This section of the PARATUS platform shares existing tools and case studies to show innovative examples of **Risk Reduction** and **Adaptation** around the world. The showcasing of a few selected tools and diverse examples will contribute to an improved understanding of possible DRR and Adaptation options.
This part of the platform is divided in an introduction and two main sections:

- Tools that allow to explore DRR and adaptation options by exploring a range of hazards and the ability to find matching DRR/ adaptation options through applying a filter.
- A range of case studies and examples from around the world that is searchable and includes many inspirational adaptation options that are curated and tested for robustness. This section also includes a multimedia library.

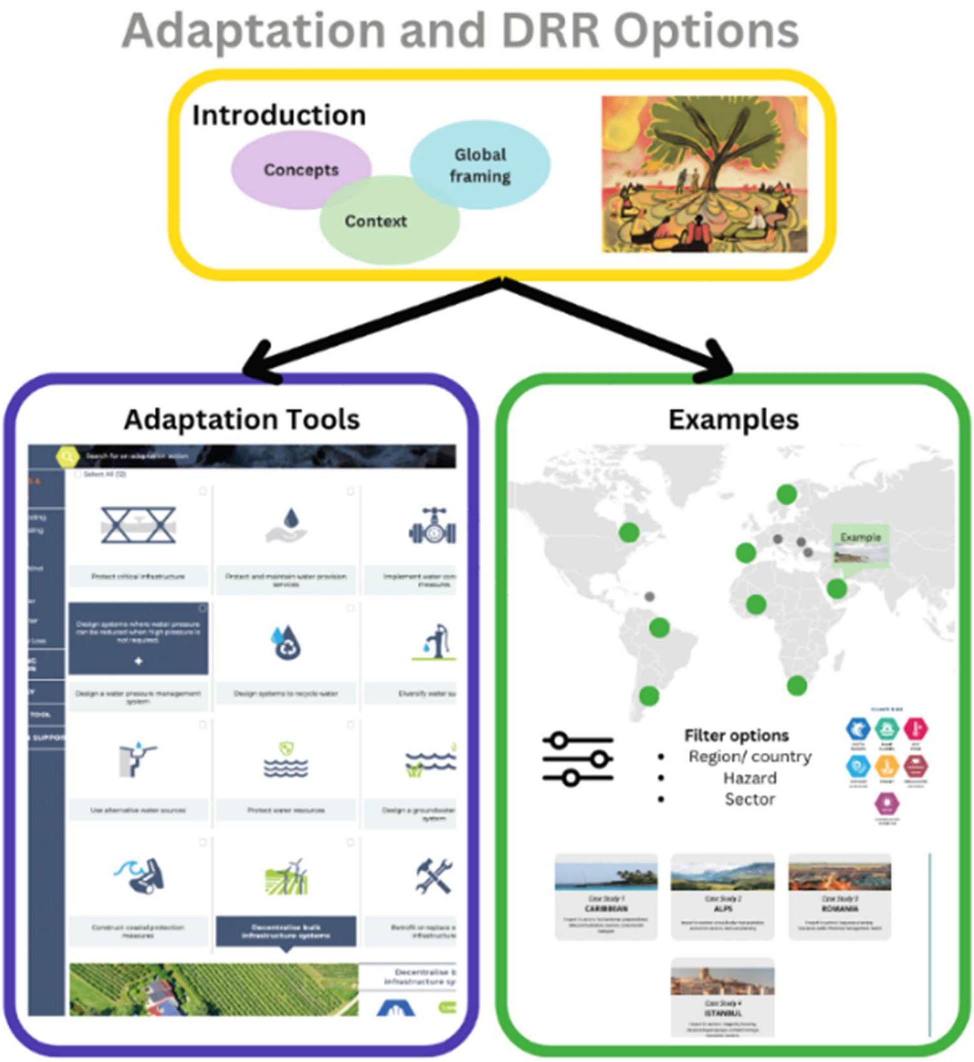

Figure 5.4.1: Impression of the toolbox Adaptation and DRR options

5.4.1 Exploring the concepts, context, and global framing

The introductory section focuses on exploring key concepts, the importance of considering context and the global framing as an introduction to the tools and examples in this section. It is crucial to convey to the platform reader the importance of understanding the application of DRR and adaptation measure in the context of a wider system perspective, considering context and possible unintended effects of adaptation measures.

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An intuitive introduction illustrates how some of the key concepts are key when exploring DRR and adaptation options. This hyperlinked infographic allows access to the following sections that contain a summary and hyperlinks to more in-depth information:

Framing of the climate emergency: exploring increasing risk and hazard, cascading and compound risk while linking to the IPCC Atlas, this section provides a basic introduction to key concepts, also linking to key areas in the platform.

Global responses and mechanisms: Summary introduction to global efforts to address climate change and mitigation and the relevant UN conventions: UNFCCC and UNCCD, including the importance of adaptation and mitigation. This section will place the adaptation options into the larger context and will also emphasize the importance of mitigation.

Exploring the DRR- Adaptation continuum: This section will explore the various processes on the DRR – Adaptation continuum, framing the examples given in this section and defining terminology while creating an overview of the importance of the DRR- Adaptation continuum. A special section will explore the importance of short-term resilience and long-term scenarios and responses. This section will also include hyperlinks to the examples below.

Tracking progress and learning: This section will unpack how a shifting baseline of climate and weather-related events can be considered when evaluating and learning about DRR and adaptation approaches. It will also explore the risk of maladaptation and how understanding larger systems and the impact chains can reduce the risk.

The importance of context

An introduction to understanding local context and the importance of considering systems thinking in developing DRR and adaptation responses. This section will showcase the importance of understanding the local context, working with existing processes and co-produce adaptation options that have local ownership.
This section will also explore systemic effects across sectors and will provide a range of approaches that have been used to develop adaptation options with local stakeholders.

Global framing

The section will highlight global framing and responses to DRR and adaptation. Starting with an introduction to the IPCC atlas, platform users are encouraged to explore possible climate change scenarios for their region. The platform will also summarize and link to some relevant global processes such as the UNFCCC, UNCCD and global policy processes to address the climate crisis.

5.4.2 Interactive exploration of DRR and adaptation tools

The platform will showcase a few tools that will offer a way to explore DRR and adaptation options. These platforms are publicly accessible on the internet and will be linked to the PARATUS platform, including a short guide on how to navigate the sites.
The introduction will illustrate the importance of understanding the system's perspective and considering feedback loops, compound and cascading risk when using these tools.
An overview page will present at least 3 interactive tools (TBD) and discuss their strengths and weaknesses for potential application. The tools are then linked to the platform and can be used independently. These platforms will be explored for inclusion: The Greenbook, a platform to support municipal decision making in the face of a variety of hazards and affecting a range of searchable sectors[88] , the UKZIP tools that is aiming at

[88] https://adaptationactions.greenbook.co.za

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guiding decision making processes for adaptation[89] or the Adaptat2Climate Tool that is specifically focusing on supporting adaptation planning in agriculture[90].

5.4.3 Collection of Adaptation Options

A collection of adaptation options will be presented in this part of the PARTUS platform. Examples will be from around the world and cover a variety of hazards and adaptation options. The examples are accessible on an interactive map and a filter will allow us to choose the type of hazard and priority sectors.

Example filter options are (these will be refined in the coming months):

- **By type of hazard:** Coastal Flooding, Inland Flooding, Heat stress, Wildfires, Increased wind speed, Drought, Groundwater depletion, Surface water depletion, Biodiversity Loss, Space weather
- **By response:** Early warning systems, Ecosystem restoration, Climate resilient infrastructure, Water supplies and security, long-term planning
- **Sector:** Infrastructure, Transport, Urban, Agriculture, Health, etc.
- **Type of user:** Decision maker, Planners, Civil society, Students

This section will also include a range of adaptation options from the PARATUS application case studies, showcasing how various sectors can be affected, explaining impact chains and possible adaptation options. This section will actively draw on examples from PARATUS and will also link to multimedia products from PARATUS project activities.
As depicted in the wireframe in the figure, the adaptation options will be searchable via navigation in the map, with summary information appearing in a popup window. More information per each adaptation option is then provided in a separate page, including a brief section on opportunities and limitations of this approach and where the approach is situated on the DRR-Adaptation continuum.
A special section will be exploring adaptation options from the experiences of the PARATUS case study areas, and this part of the platform will link to outputs of the PARATUS project, including multimedia assets.

Figure 5.4.2: Wireframe of the searchable platform depicting a choice of diverse DRR and adaptation options.

89 https://www.ukcip.org.uk/wizard/
90 https://tool.adapt2clima.eu/en/home/

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5.5 Impact chain WIKI

5.5.1 Introduction

The development of a Disaster Impact Chain Wiki is of utmost importance given the complex interactions between natural and man-made hazardous events, their spatial and temporal variations, and the evolution of risk across different environmental settings. Currently, existing disaster databases often focus on single hazards and direct impacts, leaving a significant gap in the understanding of how hazards interact and compound to create cascading effects, such as the combination of heatwaves and forest fires. To develop comprehensive and quantifiable multi-hazard impact chain models, it is crucial to base the analysis on historical data.

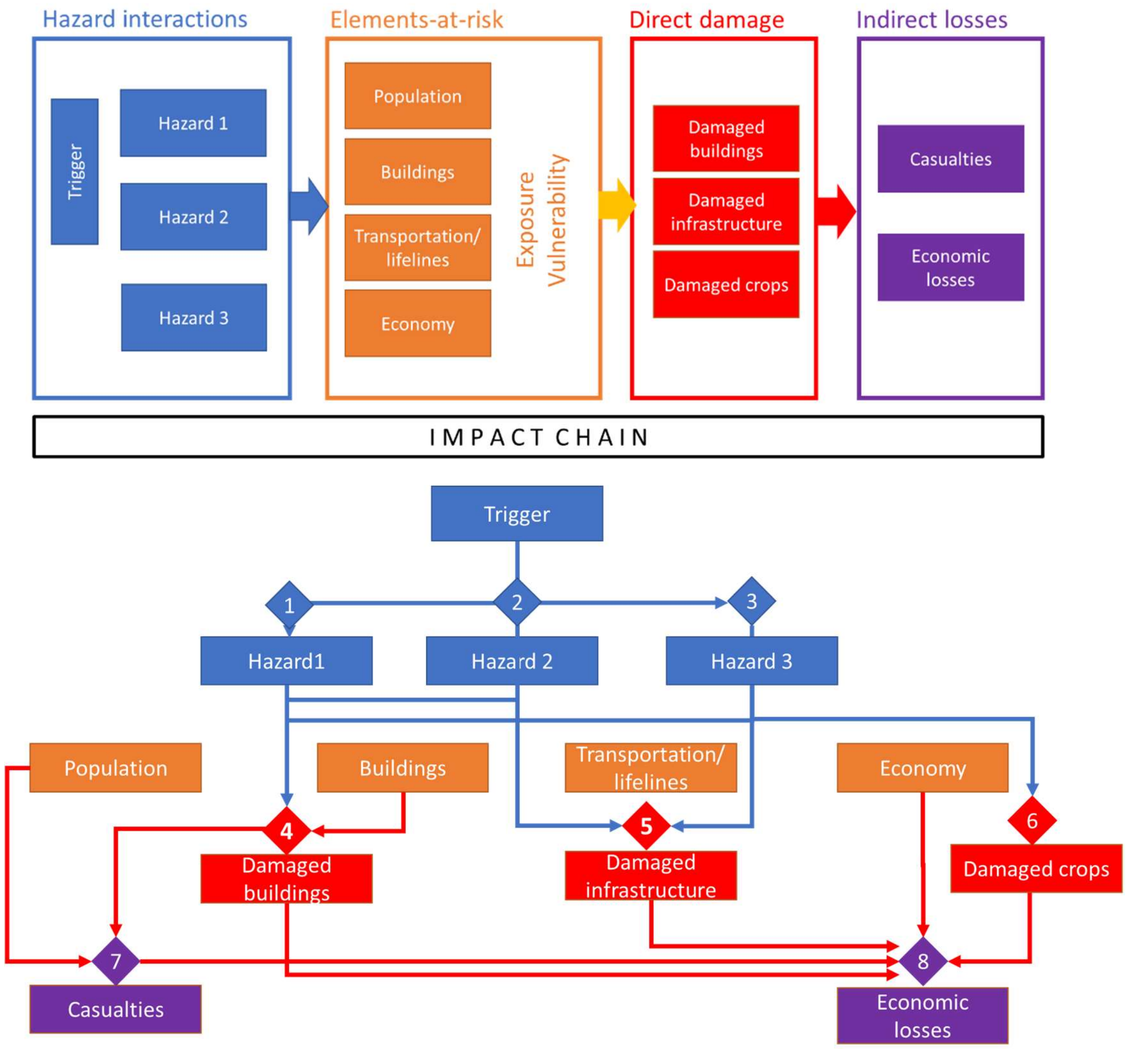

Figure 5.5.1: Schematic representation of an Impact Chain. Above: An impact chains represents a schematic relationship between a triggering event, hazard interactions, elements-at-risk, their exposure and vulnerability, leading to direct damage and indirect losses.

For an elaborate description of impact chains and examples for the four application case studies within the PARATUS project, the user is referred to Deliverable 1.1 Report on participatory workshops in the four application case study sites, including impact chains diagrams for each analysed event.

The Disaster Wiki can address this critical need by serving as a centralized repository of information that goes beyond the scope of traditional disaster databases. It can enable the attribution of impact caused by hazard interactions and provide a more in-depth description of risk pathways from root causes to resulting losses. By consolidating and synthesizing data from various sources, the Disaster Wiki can facilitate a holistic approach

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to disaster analysis, encompassing not only the direct impacts but also the underlying systemic, structural root causes, and risk drivers at global, national, and local levels.

The Post Disaster Needs Assessment (PDNA) approach has been instrumental in assessing physical damages, economic losses, and recovery costs after major disasters. However, estimating impacts and losses for future events is a challenging task. The Disaster Wiki can play a crucial role in addressing this challenge by providing a platform for collaborative research, data sharing, and analysis of historical disaster data. It can enable researchers and decision-makers to model and simulate different disaster scenarios, considering the dynamic nature of systemic risk and the rapidly changing economic, social, and environmental conditions.

Moreover, the Disaster Wiki aligns with the principles of the Sendai Framework, which stresses the need for an improved understanding of systemic risk and the development of new tools for risk-informed decision-making. By providing access to real-time and updated data, the wiki can support evidence-based decision-making in disaster management and preparedness efforts.

Overall, the Disaster Wiki's development is critical for advancing disaster risk reduction strategies and enhancing resilience in the face of increasingly complex and interconnected hazards. It can serve as an indispensable resource for disaster management professionals, researchers, policymakers, and communities worldwide, fostering collaboration and knowledge exchange to build a safer and more resilient future. By harnessing the power of collective expertise and data-driven insights, the Disaster Wiki can be a transformative tool in shaping effective disaster risk management policies and strategies, ultimately saving lives, and minimizing the impact of disasters on communities and societies.

5.5.2 Purpose of the Disaster WIKI

The purpose of the Disaster Wiki is to serve as a comprehensive and accessible online platform dedicated to disasters and disaster management. It will act as a repository of valuable information on a wide range of disaster-related topics, including emergency management, risk assessment, preparedness, response, recovery, and more. The wiki's primary aim is to provide a centralized hub where individuals, organizations, researchers, and policymakers can access and share knowledge, fostering collaboration and informed decision-making worldwide. By being freely available to the public, the wiki ensures inclusivity and eliminates barriers to accessing critical information. It encourages users to contribute their insights and experiences, creating a dynamic and evolving knowledge base. The real-time update capability of wiki pages ensures that the content remains current and relevant, reflecting the latest research findings and developments in the field of disaster management. Through its comprehensive resources and collaborative nature, the Disaster Wiki empowers individuals and communities to enhance their disaster preparedness, response, and resilience efforts. It fosters a global community committed to disaster risk reduction.

The Impact Chain WIKI has a number of requirements:

- Users should be able to make a selection of impact chains from the database, searching by disaster event, time period, geographical area ad hazard type;
- Once an impact chain is selected, users should be able to select only a section of an impact chain (e.g. by selection of a particular sector, as illustrated in figure 5.8.2.

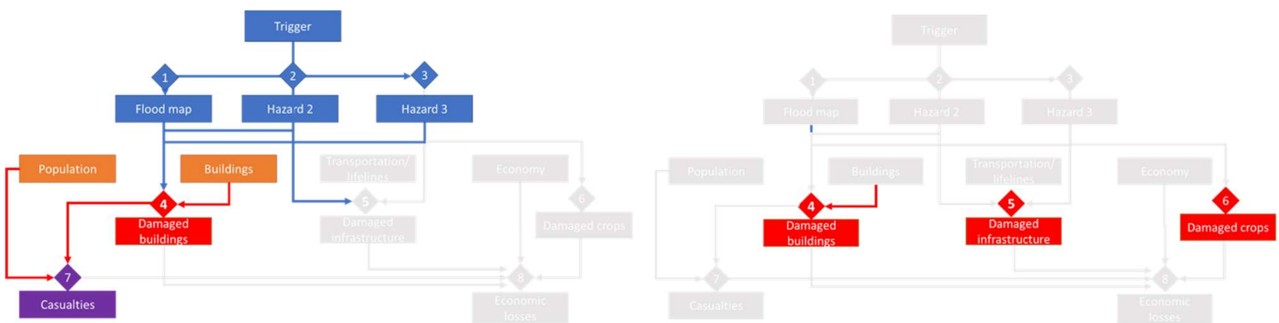

Figure 5.5.2: Selecting a part of an impact chain, e.g. by sector (left) or by risk component (right)

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- Impact chains should be coloured based on the risk components (triggers, primary hazards, secondary hazards, elements-at-risk, vulnerability, direct damage, indirect losses).
- It should be possible to zoom in and out of impact chains, while the font size is automatically adjusted.
- When clicking on a component, the relations to and from this component should be visualized.
- For each impact chain metadata should be stored on the components of the impact chain (the boxes in figure 5.8.3) and on the connections (the diamonds in figure 5.8.3). These should also be accessible in the form tables.
- The metadata should be in the form of descriptive text, but can also be in the form of maps (as illustrated in figure 5.8.4.
- It should also be possible to show for which part of the impact chain quantified values have been stored in the database, as illustrated in figure 5.8.3.

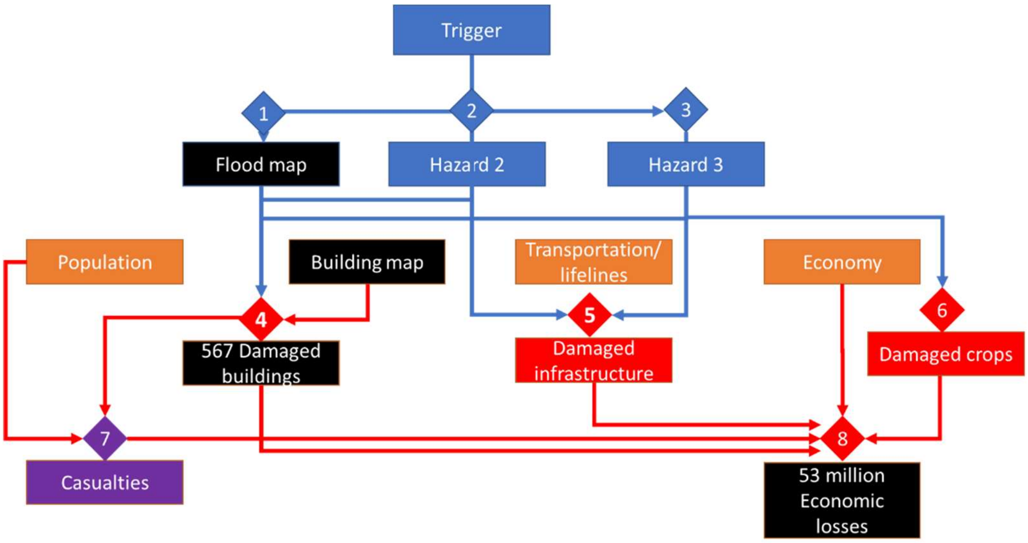

Figure 5.5.3: Show which parts of the impact chain can be quantified (here shown in black).

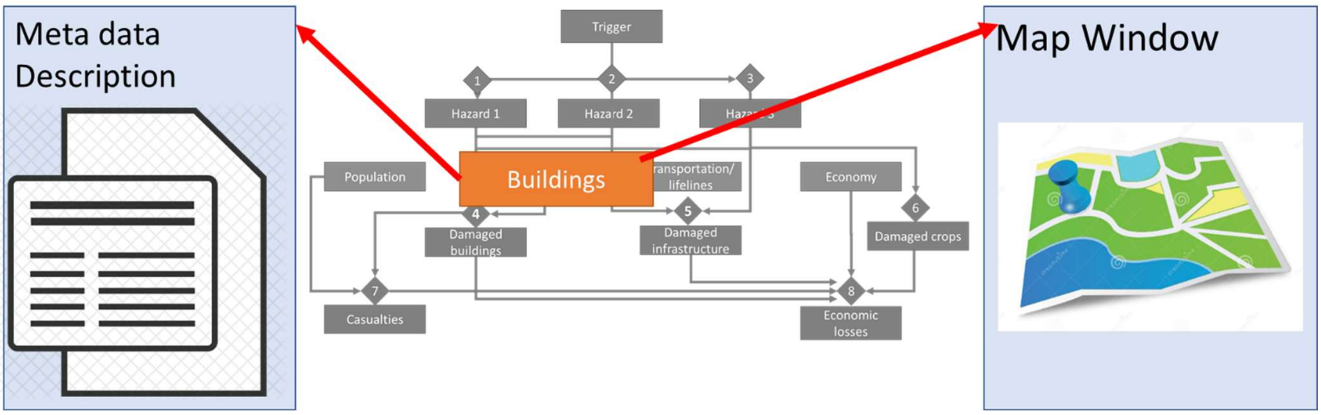

Figure 5.5.4: Illustration of metadata and map data related to a component of an impact chain

- The impact chain should be editable using the Impact Chain Development tool that will be described in Chapter 6.
- It should be possible to copy an impact chain and modify it for future scenarios or for risk reduction alternatives.

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5.5.3 General Overview and Design Guidelines/Approach

The Disaster Wiki would be a comprehensive online platform dedicated to disasters and disaster management, providing a centralized repository of information on a wide range of related topics. Its primary purpose is to facilitate knowledge-sharing, collaboration, and informed decision-making among individuals, organizations, researchers, and policymakers worldwide. The general overview and design guidelines for the Disaster Wiki are as follows:

- **User-Centric Approach**: The Disaster Wiki will follow a user-centric design, prioritizing ease of use, intuitive navigation, and a visually appealing interface. The goal is to ensure that users can access information quickly and efficiently, regardless of their level of expertise or background.
- **Comprehensive Content**: The wiki aims to cover a wide range of disaster-related topics, including but not limited to emergency management, risk assessment, preparedness, response, recovery, and adaptation. Comprehensive content ensures that users can find the information they need to address various aspects of disaster management.
- **Accessibility and Inclusivity**: The Disaster Wiki will be designed to be freely accessible to the public, promoting inclusivity and eliminating barriers to accessing valuable knowledge. The platform welcomes contributions from individuals worldwide, fostering a diverse and collaborative community.
- **Collaborative Platform**: The wiki will encourage collaboration and crowdsourcing of information. Users can contribute their expertise, experiences, and insights, enriching the content and creating a dynamic knowledge base.
- **Real-Time Updates**: Wiki pages would be updated in real-time, allowing the inclusion of the latest research findings, best practices, and developments in the field of disaster management. Real-time updates ensure that the information remains current and relevant.
- **User Contribution Management**: The Disaster Wiki would implement effective user contribution management to ensure the accuracy and reliability of content. Moderation and verification mechanisms may be employed to maintain high-quality information.
- **Robust Search and Filtering**: The wiki would incorporate robust search and filtering capabilities to enable users to find specific information and relevant articles easily. Advanced search functionalities help users pinpoint specific data or topics.
- **Interactive Visualization**: To enhance user understanding, the wiki would include interactive visualizations, such as charts, graphs, maps, and infographics. These visual elements facilitate data interpretation and engagement.
- **Multi-Language Support**: To cater to a diverse audience, the Disaster Wiki would support multiple languages, making information accessible to users globally.

5.5.4 Assumptions/Constraints/Risks

Assumptions:

- **User Engagement**: The assumption is that users will actively engage with the Disaster Wiki, contributing valuable information and collaborating to create a robust knowledge base. Encouraging and maintaining user engagement will be crucial to the success of the platform.
- **Data Accuracy**: The assumption is that the data and information contributed by users will be accurate and reliable. While moderation processes can help ensure data quality, there is a level of trust placed on the users to provide authentic information.
- **Sustainability**: The assumption is that the Disaster Wiki will receive ongoing support and resources for maintenance, updates, and improvements. Ensuring the sustainability of the platform is essential for its long-term usefulness.

Constraints:

- **Resource Limitations**: Development and maintenance of the Disaster Wiki may be constrained by limited resources, such as funding, technical expertise, and personnel.
- **Technical Compatibility**: The wiki's design may need to conform to technical constraints, ensuring compatibility across different devices, browsers, and internet speeds.
- **Data Privacy and Security**: As the Disaster Wiki collects user data and contributions, ensuring strong data privacy and security measures will be a constraint to protect user information.

Risks:

- **Content Quality**: There is a risk that some contributed content may be inaccurate, misleading, or biased. Implementing effective moderation and review processes will be crucial to maintaining high-quality content.
- **User Adoption**: There is a risk that user adoption may not meet expectations, resulting in limited engagement and a less dynamic knowledge base. Encouraging user participation and offering incentives may mitigate this risk.
- **Data Breaches**: Given the sensitive nature of disaster-related data, there is a risk of potential data breaches or cyberattacks. Robust security measures and encryption protocols must be in place to safeguard user data.
- **Legal and Copyright Issues**: There is a risk of potential legal and copyright challenges related to user-contributed content. Clear guidelines and terms of use will be necessary to address such issues.
- **Data Integrity**: There is a risk of data integrity being compromised due to misinformation, deliberate tampering, or technical errors. Regular data audits and verification processes can help maintain data integrity.
- **Technical Challenges**: The development and maintenance of the Disaster Wiki may face technical challenges such as system crashes, bugs, or server downtime. Having backup systems and technical support in place can help address these issues.

5.5.5 Design Considerations

To foster collaboration and knowledge-sharing, the platform would include user-friendly mechanisms for content contributions, edits, and reviews. Moderation processes will be essential to maintain data accuracy and quality. Enabling real-time updates empowers users to share the latest research findings, best practices, and developments in the field of disaster management, ensuring the content remains current and relevant. Incorporating interactive visualizations, such as charts, graphs, maps, and videos, will significantly enhance user understanding and engagement. These visual elements effectively communicate complex data and concepts, making the Disaster Wiki more engaging and informative. The Disaster Wiki would feature robust search and filtering capabilities to enable users to quickly find specific information and articles. Implementing advanced search functionalities assists users in pinpointing relevant data or topics efficiently. Data privacy and security will be paramount considerations in the design of the Disaster Wiki. Implementing strong encryption protocols and adhering to data storage best practices ensure the protection of user information and contributions. The platform's performance and scalability would be optimized to accommodate increased user traffic and content growth. Streamlining loading times, data handling, and server capacity is vital for a smooth user experience. To engage with users effectively, channels for feedback and support should be provided. Responding to user queries, suggestions, and technical issues promptly helps maintain user satisfaction and a positive user experience. Integration with external data sources, such as disaster databases, climate data repositories, and geospatial information systems, will enhance the richness and depth of information available on the Disaster Wiki.

5.5.6 Architectural Strategies

The design will adopt a modular architecture, enabling the system to be divided into separate components for ease of maintenance, testing, and future scalability. Implementing a microservices architecture will further enhance the platform's flexibility and fault isolation, allowing independent updates to specific services without disrupting the entire system. Additionally, a service-oriented architecture will be employed to create loosely coupled services that can be developed and updated independently, fostering flexibility and interoperability with third-party systems.

To handle the complex relationships between disaster data, graph databases or ontology-based systems will be utilized, improving data querying and analysis. Real-time updates will be enabled to facilitate contributions of the latest information and research findings on disaster-related topics.

5.5.7 User Interface of WIKI

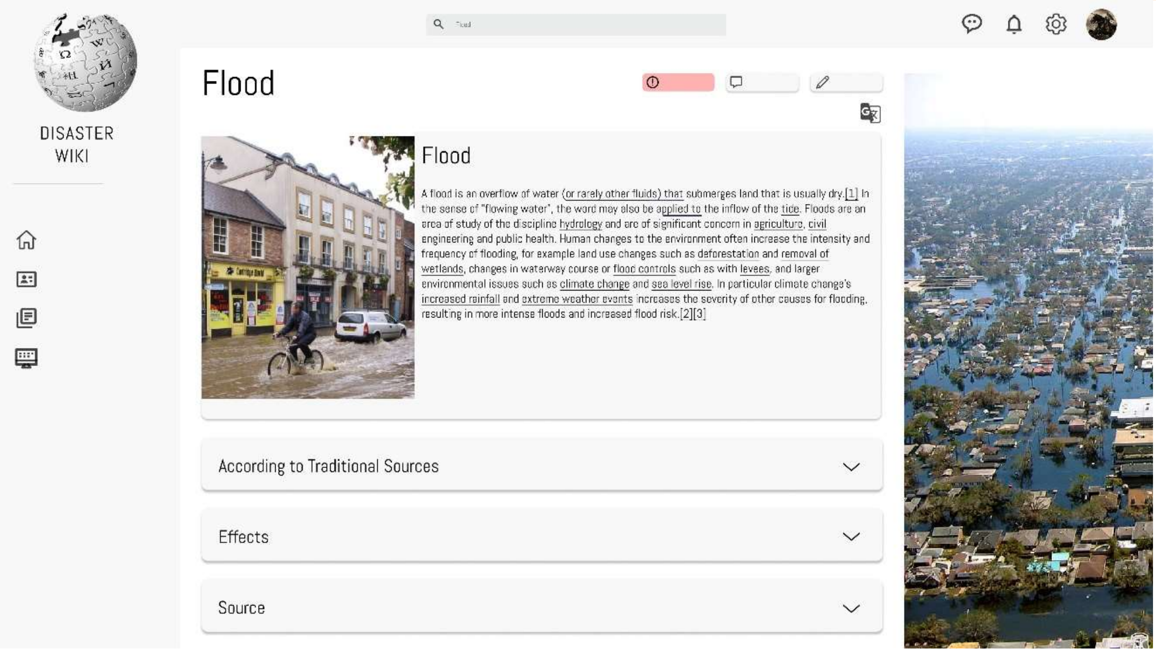

Figure 5.5.5: Disaster WIKI home screen

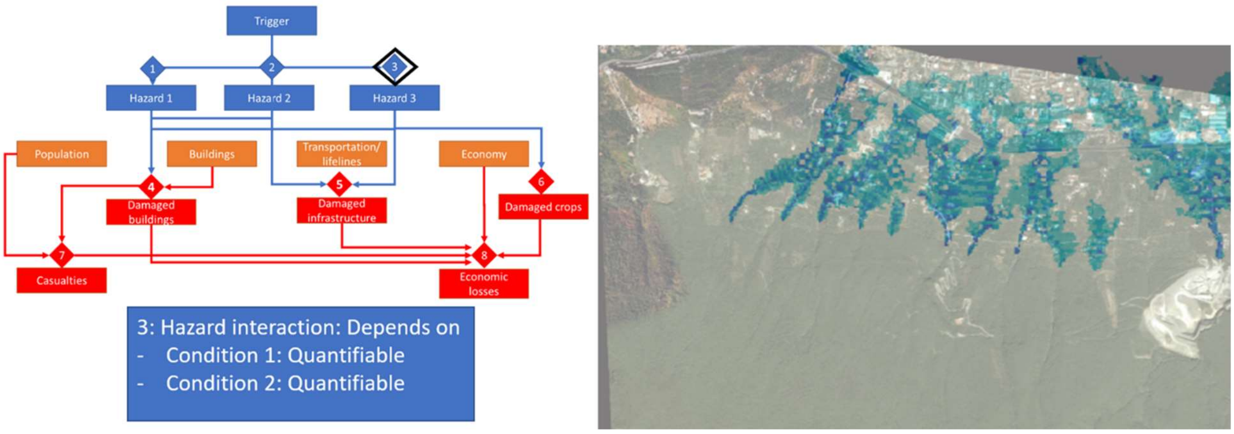

Figure 5.5.6: Visualizing a hazard component (e.g. flood hazard) from an impact chains and the associated map information.

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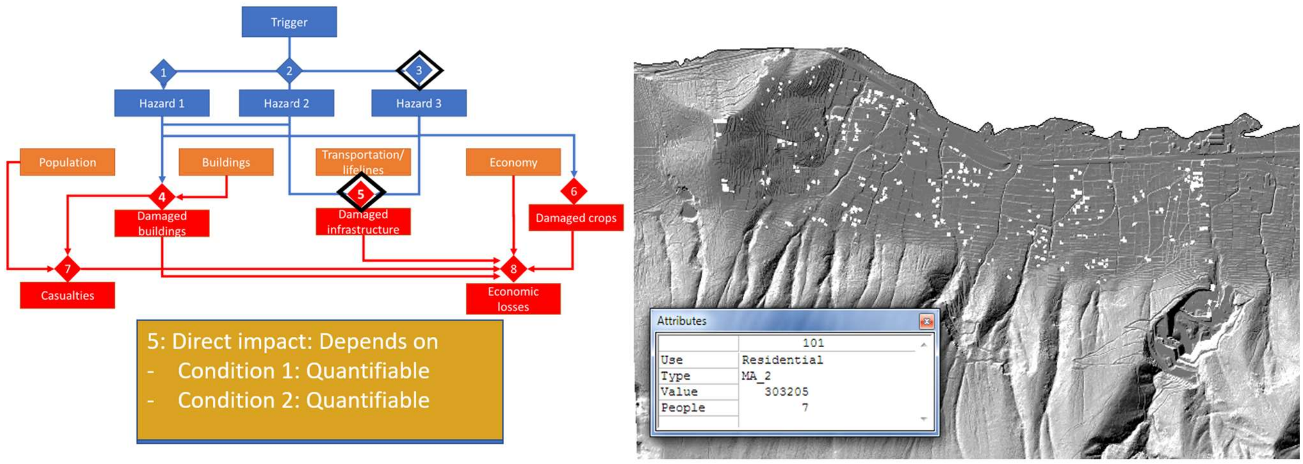

Figure 5.5.7: *Visualizing an element-at-risk component (e.g. damaged buildings) from an impact chains and the associated map information.*

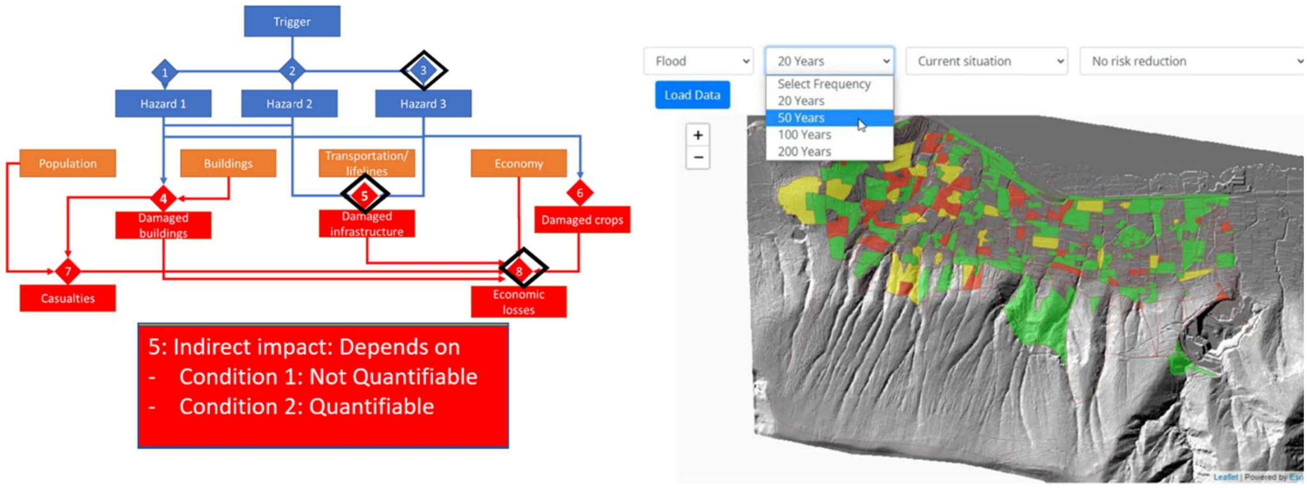

Figure 5.5.7: *Visualizing damage from a hazard event per land parcel from an impact chains and the associated map information*

5.5.8 Integration of Disaster WIKI with Impact Chain Development Tool

Disaster Wiki would serve as a comprehensive repository of valuable information related to various disasters worldwide. It will act as a knowledge hub, aggregating data, case studies, and best practices from past events. Impact chains are vital in understanding the complex cause-and-effect relationships that emerge during a disaster. They help us identify the ripple effects of a hazard, allowing for targeted interventions and more effective mitigation measures. By integrating Disaster Wiki with our Impact Chain Development Tool, we will harness the power of collective knowledge and leverage historical data to extract comprehensive impact chains. Disaster Wiki will serve as a foundational resource for our impact chain extraction process. Its vast collection of real-world scenarios and historical disaster data will act as a base to develop robust impact chains. Researchers and practitioners can draw upon information available on Disaster Wiki to analyse past incidents, map out impacts, and link causative factors to their outcomes. The integration of Disaster Wiki with our Impact Chain Development Tool brings forth several advantages. With access to a wide range of documented disasters, we can identify common patterns, trends, and factors that contribute to specific impacts. This knowledge will bolster the accuracy and relevance of our impact chain development.

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5.6 Data directory

Data will be shared through the UNISHARE platform[91]. Here we will focus on outputs, which will also be described with their full metadata. Outputs will receive a DOI, making them easily identifiable. Rich metadata will accompany the published datasets. The data will be described using the Dublin Core metadata scheme commonly adopted by most of the data repositories. The metadata items specified in DC will be extended with additional items for documenting temporal and spatial information: e.g., spatial resolution, spatial extent, and temporal resolution. Moreover, open keywords will be specified, but attention will be paid to using controlled vocabulary to optimize the possibility of a quick discovery of the datasets. Where possible scientific outputs will include DOIs of the used datasets. Otherwise, the metadata of the datasets will always include unique identifiers of the related scientific publications.

Internal datasets will also be shared through dedicated options, we have decided to use UNISHARE that is hosted by University of Twente, and it allows us collaborative and easy use and storage of large volume data.

All the codes will be hosted on GitHub under the PARATUS organization. The current version of the RiskChanges tool[92] is an Open-Source tool for multi-hazard risk assessment. The system is based on a series of Python scripts, which can be used directly by users that know how to work with Python. The code is available at GitHub[93]. This version of the RiskChanges Library is customized for local computation, and users can install the library directly from GitHub or from PIP[94] and start working with their own data, modifying the code. To further understand how the codes work, there are Jupyter notebooks in this project. More information can be found in the ReadTheDocs[95]. Users that are not experienced with Python can use the Graphical User Interface (GUI) can also be reached through RiskChanges.

Every release of the software versions will be tagged with a unique DOI. All the Python notebooks will be versioned on GitHub, publicly accessible. These documents will be archived on Zenodo[96], and the DOIs will be provided in related publications.

During the PARATUS project outputs will be deposited in the MICROSOFT TEAMS site, UNISHARE (concerning data) and the Open Deliverables also in the ZENODO repository during the active phase of the project. This includes deliverables and underlying data, milestone documents, intermediary results and intermediary data, code, reports and working documents. Outputs are preferably deposited under the CC-BY 4.0 (Attribution 4.0 International) licence and using recommended file formats.

Detailed and complete metadata should be provided with data and information. When using the ZENODO upload interface all required fields must be completed including 'Upload type' (for e.g., Publication/Project deliverable or Dataset), full list of 'Authors', 'Description', 'Version' (if applicable). For the field 'Authors' please note that the optional field 'Contributors' is also available allowing you to identify contributions such as Project Member or Work Package Leader where more appropriate. The following recommended/optional fields must also be completed: 'Funding' (select European Commission with value 101073954), 'Related/alternate identifiers' (if appropriate provide links to related outputs PIDs), 'Contributors' (see note above at 'Authors'), 'Publisher' (use PARATUS).

File naming in the project, related to deliverables, should include the number and name of the relevant deliverable or milestone, the name of the Deliverable and appropriate indicators like "V01", "Vdate" (for e.g., PARATUS D6.10 Data Management Plan Initial Version V20230331). The deliverables are stored in a specific section of the PARATUS internal communication platform. There is a difference between the deliverables that are still under construction and the submitted deliverables. See for example: Submitted Deliverables

[91] https://www.utwente.nl/en/service-portal/hardware-software-network/data-storage/unishare
[92] http://www.riskchanges.org/
[93] https://github.com/RiskChanges/RiskChangesDesktop
[94] https://pypi.org/project/RiskChangesDesktop/
[95] https://sdss-documentation.readthedocs.io/en/latest/
[96] https://zenodo.org/communities/paratus/

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The source files relative to reports, publications, presentations, and posters will be versioned in repositories, publicly accessible. Details regarding the implementation (naming convention, keywords, version, etc) will be detailed in the deliverables during the scope of the project and made public via the PARATUS website.

In the same way as publishing the data in a repository, at the end of the research, the collected data containing personal information will be archived in the data archive, Areda, for at least ten years at the University of Twente in compliance with the GDPR regulations. Rich metadata of the archived data will be provided in the research information Pure system to ensure the findability of the data and the project website.

This addresses the following issues:

- How will the data be licensed to permit the widest re-use possible?
- When will the data be made available for re-use? If an embargo is sought to give time to publish or seek patents, specify why and how long this will apply, bearing in mind that research data should be made available as soon as possible.
- Are the data produced and/or used in the project useable by third parties, after the end of the project? If the re-use of some data is restricted, explain why.
- How long is it intended that the data remains re-usable?
- Are data quality assurance processes described?

To be able to confidently reuse certain data, we will make sure that there is sufficient metadata, such as variable description, measurement units, coding scheme, data collection methods and processing procedures, data provenance (what, why, how, by whom the data was collected or generated) etc., to understand the data. We will assign a clear usage license to the (open) data, specifying what kind of reuse is permitted. Certain data cannot be made open due to the sensitive nature of the data such as personal data and commercial data as previously indicated. If the data is under restricted access due to privacy or contractual provisions, we will provide accurate information under which conditions the data can be reused.

To facilitate re-use of data two-way documentation will be provided, linking data with the reports that explain the applied methodology, analysis, and results. In the reports links will be provided to the underlying data. And in the data repository read-me files will be added to link to the reports. In addition, the data should as "self-explainable" as possible by clear and consistent file-naming, appropriate headings (if applicable) including measurement units, dates, locations).

As described in the previous section, all data will – in principle - be made freely available in the public domain to permit the widest re-use possible, licensed using standard reuse licenses, in line with the obligations set out in the Grant Agreement.

For more information on the management of data, please see Deliverable D6.10: PARATUS Data Management Plan.

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6. Simulation service

6.1 Impact chain development tool

6.1.1 Introduction

Impact chains are a crucial tool in disaster management, providing a systematic framework to trace the sequence of events and actions that lead to specific impacts. They help in identifying and understanding causal relationships between different components of a disaster, risk assessment and analysis, resource allocation and decision-making, preparedness planning, policy development and decision-making, and policy development and decision-making. Impact chains provide essential insights for risk assessment, resource allocation, preparedness planning, policy development, and decision-making, ultimately contributing to more effective and efficient disaster management practices.

Disaster wiki platforms and quantitative impact chains are valuable tools for disaster management and response, providing a collaborative and dynamic platform for collecting, sharing, and updating information related to disasters. They foster collaboration, innovation, and community engagement in disaster management. That is why PARATUS has proposed to develop an open-source platform for dynamic risk assessment that allows to analyse and evaluate multi-hazard impact chains, risk reduction measures, and disaster response scenarios in the light of systemic vulnerabilities and uncertainties.

The ICDevelopment Tool would be powerful analytical tool that will help in identify and understand the cause-and-effect relationships between hazards, vulnerabilities, exposure, and the resulting consequences during a disaster event. It will facilitate the analysis of complex interactions among different factors, enabling decision-makers and emergency responders to make more informed decisions and implement effective strategies to mitigate the impact of disasters. In the following ways the ICDevelopment Tool will be valuable in disaster management:

- **Identifying Root Causes**: The impact chain tool will help in pinpoint the root causes of a disaster by tracing the chain of events leading to the disaster's occurrence. It will allow decision-makers to identify the primary hazard, underlying vulnerabilities, and contributing factors that led to the disaster.
- **Understanding Cascading Effects**: Disasters often involve cascading effects, where one hazard triggers other hazards or amplifies vulnerabilities. The ICDevelopment Tool l will reveal these interconnected relationships, providing insights into the potential escalation of impacts during complex disaster scenarios.
- **Vulnerability Assessment**: By analysing the impact chains, the tool will help in assessing the vulnerabilities of critical infrastructures, communities, and ecosystems. Understanding vulnerabilities is crucial for developing targeted risk reduction measures.
- **Risk Assessment and Prioritization**: The impact chain tool will also assist in quantifying the potential consequences of a disaster, helping prioritize risk reduction measures based on the severity and likelihood of impact.
- **Scenario Simulation**: Decision-makers can also use the impact chain tool to simulate various disaster scenarios. This will enable them to assess the effectiveness of different response strategies and preparedness measures before a real disaster occurs.
- **Resource Allocation**: Knowing the potential consequences of different disaster scenarios allows for optimized resource allocation. Emergency responders can allocate resources where they are most needed to minimize the impact and save lives.
- **Policy Formulation**: Understanding the impact chains helps policymakers develop targeted policies and regulations to address specific vulnerabilities and reduce disaster risk in a proactive manner.
- **Learning from Past Events**: By analysing the impact chains of past disasters, lessons learned will be identified and incorporated into future disaster management strategies.

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- **Continuous Improvement**: As the understanding of hazards and vulnerabilities evolves, the impact chain tool will be updated and refined to reflect the latest knowledge and data.

The ICDevelopment Tool in disaster management would be an asset for analysing the complex relationships and interactions between hazards, vulnerabilities, exposure, and consequences during a disaster event. It will provide decision-makers and responders with critical insights to develop effective strategies, optimize resource allocation, and enhance disaster resilience in communities and infrastructures.

6.1.2 Purpose of the Impact Chain Development Tool

While impact chain tools play a crucial role in disaster management by identifying cause-and-effect relationships, it is true that some existing tools have limitations that hinder their full potential. Two significant limitations are their qualitative nature and lack of proper visualization of impact chains. However, advancements in technology and data analysis offer promising solutions to overcome these challenges and enhance the effectiveness of impact chain tools. In the development of the Impact Chain Development (ICDevelopment) tool, we recognize the existing gaps in traditional impact chain tools and aim to build a comprehensive and robust platform that goes beyond being just a conceptual framework. By addressing these limitations, our goal is to create a powerful analytical tool that significantly enhances the effectiveness of impact chains in disaster management.

6.1.3 General Overview and Design Guidelines/Approach

The development of a sophisticated open-source platform for dynamic risk assessment is a significant advancement in the field of disaster management and risk reduction. This platform enables users to analyse and evaluate multi-hazard impact chains, assess the effectiveness of risk reduction measures, and simulate disaster response scenarios, considering systemic vulnerabilities and uncertainties. The platform's capabilities contribute to more informed decision-making and improved disaster resilience strategies. Let's explore the key features and benefits of this innovative tool.

The application of quantitative impact chains offers a systematic approach for understanding the complex causal relationships and consequences of disasters. By quantifying the relationships between various events and their impacts, quantitative impact chains enable a more comprehensive and data-driven analysis of disasters. These chains help identify critical points and leverage points for intervention, as well as evaluate the effectiveness of different mitigation strategies. The use of quantitative methods in impact chain analysis enhances decision-making processes by providing quantitative evidence and supporting scenario-based simulations. This approach aids in resource allocation, policy formulation, and the prioritization of actions for disaster risk reduction.

6.1.4 Assumptions/Constraints/Risks

Assumptions

- **Availability of Data**: The tool assumes that relevant data on hazards, vulnerabilities, exposure, and historical disaster events will be accessible and of sufficient quality to conduct impact chain analysis effectively.
- **User Expertise**: It assumes that users have a basic understanding of disaster management concepts and are capable of interpreting and using the tool's outputs appropriately.
- **Data Validity**: The tool assumes that the data provided by users or integrated from external sources is accurate and reliable.
- **Model Validity**: The tool assumes that the impact chain models and algorithms implemented are valid representations of real-world disaster dynamics.
- **User Feedback and Engagement**: It assumes that users will provide feedback and actively engage with the development team to improve the tool's functionalities.

Constraints

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- **Resource Limitations**: The development of the tool may be constrained by budget, time, and personnel resources.
- **Data Privacy and Security**: The tool must adhere to data privacy regulations and ensure that user data and sensitive information are securely handled.
- **Compatibility**: The tool may be constrained by the compatibility of its features with various web browsers, devices, and operating systems.
- **Scope:** The tool's scope must be well-defined to ensure that it remains focused on the specific requirements of impact chain definition and does not become overly complex.

Risks

- **Data Quality Issues:** Poor data quality may lead to inaccurate impact assessments and compromise the effectiveness of the tool.
- **Modeling Limitations**: If the impact chain models fail to capture the complexities of real-world disasters, the tool's outputs may not reflect actual impacts accurately.
- **User Adoption**: There is a risk that users may not fully embrace the tool or may misinterpret the results, leading to suboptimal decision-making.
- **Technical Challenges**: Developing and integrating advanced features, such as dynamic modelling and real-time data updates, may present technical challenges.
- **Lack of User Feedback**: A lack of user feedback and engagement may hinder the tool's continuous improvement and refinement.
- **Scope Creep**: Expanding the tool's scope beyond its defined objectives may result in delays and increased development complexity.

To mitigate these risks, the development team would conduct thorough research, validate models and algorithms, prioritize user engagement, and regularly assess the tool's performance against predefined objectives. Clear communication and collaboration with stakeholders are also crucial in managing assumptions, constraints, and risks effectively throughout the development process.

6.1.5 Design Considerations

Goals and Guidelines

Developing the ICDevelopment Tool requires clear goals and guidelines to ensure its effectiveness and usability. The primary goals are to enable comprehensive impact chain analysis, provide quantitative and data-driven assessments, implement dynamic modelling and scenario simulations, and offer a user-friendly interface with advanced visualization and geospatial analysis capabilities. If applicable, the tool should integrate real-time data updates during ongoing disaster events. Open-source development encourages collaboration and contributions, while data security and privacy measures safeguard user information. Thorough model validation and calibration using historical disaster data ensure accurate outputs. User engagement and feedback are crucial throughout the development process. Involving domain experts, prioritizing data quality, and following user-centric design principles contribute to a robust and valuable Impact Chain Definition Tool.

Quantitative Approach: To make impact chain tools more robust, there is a need to integrate quantitative data and models. By incorporating quantitative data on hazard magnitudes, vulnerability indices, and exposure levels, the impact chain tool can provide more precise and data-driven insights. This integration allows decision-makers to quantify potential impacts, probabilities of occurrence, and potential losses, thereby enabling evidence-based risk assessment and prioritization of response strategies.

Data Integration and Analysis: Improving the quality and availability of data is crucial for enhancing the quantification capabilities of impact chain tools. Utilizing data from various sources, such as remote sensing, geographic information systems (GIS), meteorological agencies, and socio-economic data, can provide a comprehensive and accurate picture of the disaster landscape. Advanced data analysis techniques, like

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machine learning and predictive modelling, can help extrapolate missing data and improve the overall reliability of the tool's outputs.

Dynamic Modeling: Introducing dynamic modelling to impact chain tools allows for real-time simulation and analysis during disaster events. This capability enables emergency responders to assess the evolving impacts and adjust response strategies accordingly. Dynamic modelling can account for factors like changing weather conditions, evolving vulnerabilities, and adaptive responses from affected communities.

Visualization and Geospatial Analysis: Addressing the visualization gap is critical to making impact chain tools more user-friendly and accessible. By integrating advanced geospatial visualization techniques, such as interactive maps, heatmaps, and time-series animations, the tool can present impact chains in a visually engaging and easily understandable manner. These visualizations can help decision-makers grasp the complexities of disaster scenarios and identify critical intervention points.

Open Data Standards and Interoperability: Promoting the use of open data standards and interoperability among various disaster management tools and platforms can enhance the exchange of data and information. This facilitates data sharing and collaboration between different stakeholders, ultimately improving the accuracy and comprehensiveness of the impact chain tool.

Community Engagement and User Feedback: Involving disaster management practitioners, researchers, and affected communities in the development and improvement of impact chain tools is essential. Gathering user feedback and experiences will lead to iterative improvements and ensure that the tool meets the practical needs of its intended users.

Validation and Calibration: To build trust in the quantification capabilities of the tool, it should undergo rigorous validation and calibration processes. Comparing the tool's outputs with historical data and real disaster events can help assess its accuracy and reliability.

6.1.6 Architectural Strategies

A modular architecture would be employed, dividing the tool into separate components or modules based on functionality, allowing for easier maintenance, testing, and scalability. The service-oriented architecture (SOA) approach would create loosely coupled services, independently developed, deployed, and updated, promoting flexibility and interoperability with other systems. A microservices architecture would be considered, building individual components as small, independent services communicating via APIs, enabling better scalability and fault isolation. Caching mechanisms would be implemented to store frequently accessed data, reducing redundant computations, and improving the tool's performance. Load balancing techniques would distribute incoming requests evenly among multiple servers, optimizing resource utilization and responsiveness. Clear and well-documented APIs would facilitate integration with other systems, enabling developers to extend the tool's functionalities seamlessly. Prioritizing user experience (UX) design through user testing and iterative refinement ensures an intuitive and user-friendly interface for improved navigation and usability. By adopting a graph database with ontology-driven design and applying these architectural strategies, the Impact Chain Tool would offer optimal performance, seamless scalability, and an exceptional user experience, empowering effective disaster management and risk assessment.

6.1.7 System Architecture and Architecture Design

The creation of a sophisticated open-source platform for dynamic risk assessment will marks a major stride in disaster management and risk reduction. This innovative platform will empower users to analyse and assess multi-hazard impact chains, evaluate the efficiency of risk reduction measures, and simulate disaster response scenarios, all while accounting for systemic vulnerabilities and uncertainties. By harnessing the platform's capabilities, decision-makers gain valuable insights that lead to more informed choices and enhanced disaster resilience strategies. Following are the key features of this innovative tool.

- **Multi-Hazard Impact Analysis**: The platform will allow users to model and analyse the potential impacts of various hazards, such as earthquakes, floods, wildfires, pandemics, and more. It will consider the interconnectedness of hazards, enabling a comprehensive understanding of cascading effects and compound events.

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- **Systemic Vulnerability Assessment**: The platform would consider systemic vulnerabilities within critical infrastructures, supply chains, and communities. By assessing vulnerabilities at a systemic level, decision-makers can identify weak points and prioritize risk reduction measures.
- **Uncertainty Modelling**: Disaster events often involve uncertainties related to hazard intensity, timing, and human response. The platform would incorporate probabilistic models to account for uncertainties, enabling users to explore different scenarios and their potential outcomes.
- **Real-Time Data Integration**: The platform is proposed to support real-time data integration from various sources, such as meteorological agencies, seismic networks, and public health databases. This will ensure that risk assessments are based on the latest information, improving the accuracy and relevance of results.
- **Impact Chain Analysis**: Users would be able to simulate impact chains, tracing the cause-and-effect relationships between hazards, vulnerabilities, and consequences. This analysis will provide valuable insights into the interconnected nature of risks and inform mitigation strategies.
- **Scenario Simulation and Planning**: The platform will enable the creation of various disaster response scenarios, allowing decision-makers to evaluate the effectiveness of different strategies and preparedness measures before an actual event occurs.

System Architecture Diagram

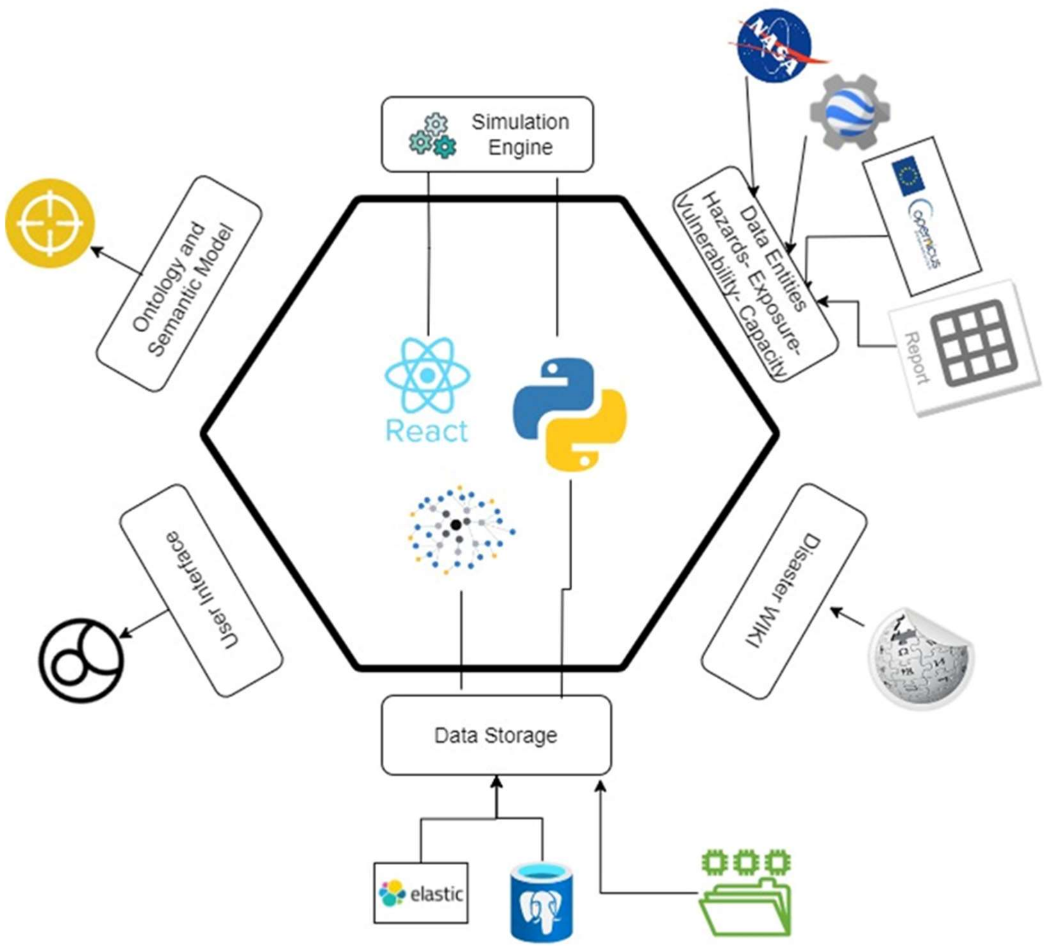

Figure 6.1.1 :System Architecture Diagram

Software Architecture

The software component of the Impact Chain Tool involves the user interface, data processing, modelling, and visualization functionalities. The ICDevelopment Tool will be developed using Python and Django for the

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backend and React Native as the front-end framework. For the front-end, modern technologies like HTML, CSS, and JavaScript will be employed, along with a popular frontend framework like React to create an intuitive and interactive user interface. To process data and perform impact chain analysis, dynamic modelling, and probabilistic assessments, algorithms and data processing modules will be implemented. Geospatial libraries such as GeoDjango or Leaflet will be incorporated to visualize impact chains on interactive maps, providing users with a comprehensive view of disaster scenarios. The tool will also feature a simulation engine capable of performing scenario-based simulations, considering both real-time and historical data to assess disaster impacts dynamically.

Data visualization will play a significant role in presenting the impact chain results in visually appealing and informative charts, graphs, and heatmaps, utilizing popular libraries like D3.js or Plotly. If necessary, real-time updates will be enabled on the user interface using technologies like WebSockets or server-sent events, keeping users informed during ongoing disaster events. Authentication and authorization mechanisms will control access to specific features and data within the tool, ensuring data security and privacy. Rigorous testing and quality assurance procedures will be implemented to guarantee the accuracy and reliability of the tool's functionalities. Finally, the tool will be deployed on a suitable platform to make it accessible to users over the internet, and version control systems like Git will facilitate collaboration among developers throughout the development process.

Information Architecture

The Information Architecture of the Impact Definition Tool encompasses the organization and structure of information within the tool, aiming to create a user-friendly and efficient user experience. It involves designing a clear and logical navigation structure that enables users to access different functionalities and sections easily. The tool's data would be categorized and classified into various data categories, such as hazard data, vulnerability data, exposure data, and consequence data, with a well-defined taxonomy to make data input and management straightforward for users. Users would be able to customize simulation settings, including time limits, simulation parameters, and response scenarios, through an intuitive interface.

The tool would also incorporate error handling, contextual help, and documentation to guide users through the data input and simulation processes. Search and filtering functionalities facilitate quick access to specific data, simulations, or results. Integration with external data sources ensures seamless data integration, and the architecture would design with accessibility considerations in mind to accommodate all users.

Data

The Disaster ICDevelopment Tool requires a diverse range of data to facilitate comprehensive analysis and evaluation of disaster impacts. Key categories of data include hazard data, providing information on different types of hazards, their magnitudes, intensity, frequency, and spatial distribution. Vulnerability data is essential, representing the susceptibility and resilience of elements at risk, such as buildings, infrastructure, and communities. Exposure data is needed to identify the geographic distribution and characteristics of elements at risk, including their locations, sizes, and population densities.

Historical disaster data provides records of past events, aiding model validation and calibration. In scenarios involving ongoing disasters, real-time data, such as weather updates and infrastructure status, can be crucial for dynamic modelling and simulations. Probabilistic data, if applicable, includes recurrence intervals, probabilities of occurrence, and intensity distributions for probabilistic impact assessments. The tool also requires data on risk reduction measures, population demographics, geospatial information, and may integrate data from external sources such as meteorological agencies and research institutions. Ensuring the accuracy and completeness of these data sets is vital for reliable and effective impact chain analysis within the tool.

Internal Communications Architecture

The Internal Communications Architecture for the ICDevelopment Tool is crucial in ensuring efficient data exchange and coordination among its internal components and modules. It would facilitate seamless communication between the backend server (Python and Django) and the frontend user interface (React Native), allowing smooth interaction between user inputs and backend data processing and analysis. The data

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processing and analysis modules internally will communicate to handle data inputs, conduct impact chain analysis, dynamic modelling, probabilistic assessments, and simulation engine functionalities. By establishing a well-defined Internal Communications Architecture, the tool will ensure the smooth operations, effective integration of functionalities, and improved user experience for impactful disaster management insights.

6.1.8 Database Design

The database plays a pivotal role as the backend storage for all data and information related to the Impact Chain Tool. To efficiently handle complex relationships and interconnected data required for impact chain analysis and simulations, a graph database would be proposed as the backbone. This type of database, unlike traditional RDBMS, excels in representing and traversing intricate relationships between entities, such as hazards, vulnerabilities, exposure data, consequences, and simulation parameters. In addition, the database would design with a well-defined ontology, providing a semantic framework that organizes and defines the domain-specific concepts and their relationships. This ontology would aid in structuring the data and capturing domain knowledge, enhancing the tool's understanding of the data semantics. The database's graph-based architecture and ontology-driven structure will allow for seamless integration of various data sources, including meteorological data, socio-economic data, GIS data, and historical disaster records. This comprehensive integration would foster a holistic approach to impact chain analysis and enables the tool to gain deeper insights into the complex dynamics of disaster events. Moreover, the graph database can efficiently support real-time data updates during ongoing disaster events, ensuring that the tool stays up to date with the latest information.

6.1.9 User Interface Design

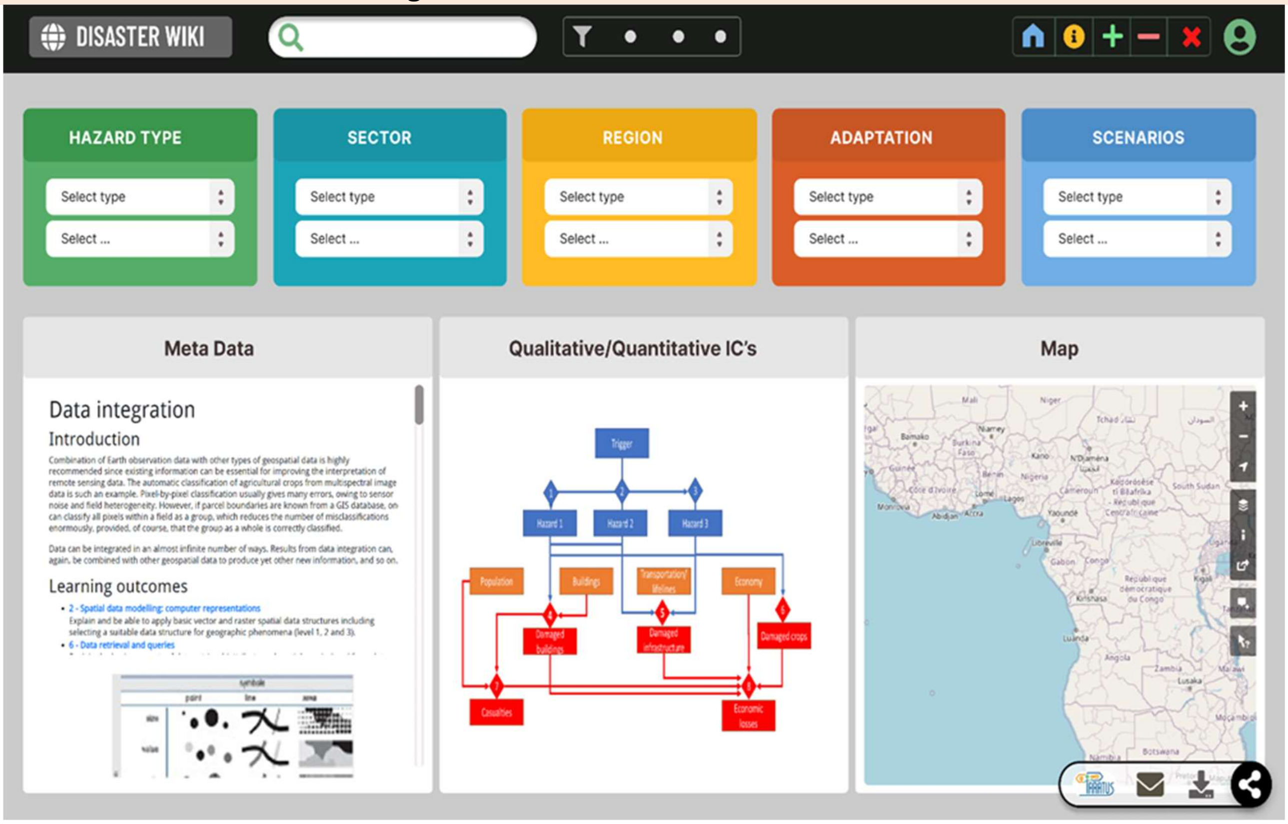

Figure 5.6.1: User Interface Design

The user interface of the Impact Chain Development Tool is thoughtfully designed, providing users with a comprehensive set of components and functionalities to analyse, generate, and customize impact chains. The interface consists of three main components.

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The first component is the Meta Data section, which displays essential information about the impact chains and the underlying data. Users can quickly access details such as the data source, date of last update, and any other relevant metadata related to the impact chains. The second component is dedicated to displaying the Extracted Impact Chains. Here, users can observe the actual impact chains that have been extracted and identified based on the data and query inputs provided. These impact chains vividly illustrate the complex relationships and interactions between various elements such as hazards, vulnerabilities, exposure data, consequences, and other factors relevant to disaster scenarios. The third component presents the Link to Spatial Information. Through this interactive feature, users can access a spatial information system or a map interface, allowing them to visualize the geographical distribution of impact chains. This valuable feature helps users understand the spatial extent of different disaster scenarios and gain insights into their implications across regions.

Additionally, the user interface incorporates Query Models, enabling users to customize their impact chain analysis. By specifying parameters such as hazard types, sectors, regions, adaptation measures, and scenarios, users can focus on specific disaster scenarios or study the impact of different variables. The interface provides users with ample Customization Options, empowering them to generate customized impact chains tailored to their specific criteria. This flexibility allows users to explore and analyse various scenarios, providing a dynamic and adaptive tool for comprehensive disaster management insights. Furthermore, the user interface offers convenient options for Sharing and Downloading impact chains. Users can easily share their generated impact chains with others, encouraging collaboration and knowledge exchange within the disaster management community. Additionally, the option to download the impact chains in various formats enables users to perform further analysis or incorporate the findings into their research and reports. To facilitate effective communication of the impact chain analysis, the tool includes a Reporting functionality. Users can generate detailed reports summarizing the key findings, complete with charts, graphs, and other visualization aids. These reports empower users to understand and communicate the outcomes efficiently, supporting evidence-based decision-making and disaster response strategies.

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6.2 FastHazard tool

The PARATUS project aims to develop and information and simulation service for multi-hazard risk analysis. The PARATUS SIMULATION SERVICE aims to let users generate and interact with spatial hazard and risk information. Through various hazard simulation platforms, users can simulate the behaviour of natural hazards, explore alternative scenario's, mitigation, and interact with global datasets on landscape parameters, climate, and hydrology. A separate but linked tool will enable the users to take any hazard information, either from the afore-mentioned hazard simulation platforms, or from other models or observations, and estimate direct and indirect risk and losses. In addition, by providing additional scenario's, cost-benefit analysis can be carried out. This tool links with global repositories of vulnerability data and elements-at-risk.

6.2.1 General overview

The PARATUS simulation service will encompass dynamic and interactive tools for the simulation (Assessment), alteration and analysis of multiple hazardous processes in geo-spatial context.

1. Web based simulation tool for natural hazards
2. Fast speed for interactivity and scenario sketching
3. Interactions with other hazard simulation tools
4. Interactions with risk analysis tools
5. Low operational costs, with free usage for aspects of the model that do not require hosting costs
6. Linking with global datasets for easy usability around the globe

An example of this design guidelines is the FastFlood[97] website, which is one of the tools we aimed to develop, that is already in a far stage of technological readiness.

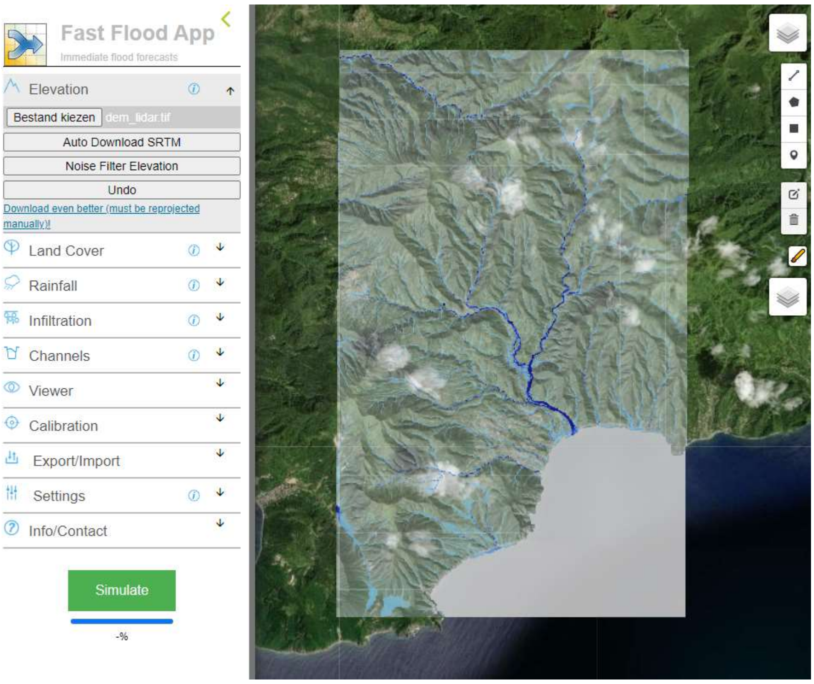

Figure 6.2.1.1 The FastFlood simulation platform for flood processes, running real-time in your browser on any device.

Our aim is to extent this platform by developing separate and linked tools for multiple natural hazards. We envision web-tools for hazard simulation focused at

- floods

[97] https://www.fastflood.org

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- mass movements such as landslides and debris flows

For these two hazards, we already have working technological concepts and are confident their development is feasibly. Eventually, we aim to further develop the underlying science to include processes for which it is not yet clear the rapid physically based modelling framework will work with sufficient accuracy.

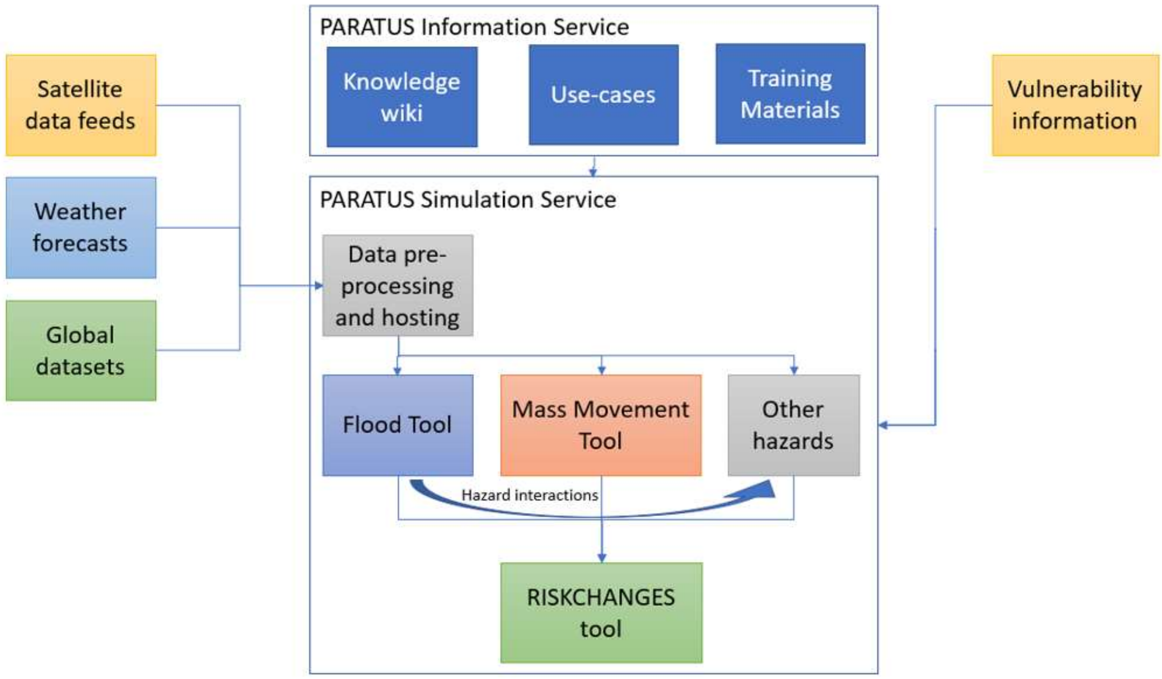

Figure 6.2.2 Overview of the link of the simulation platforms with the PARATUS simulation service, and the input data.

6.2.2 Assumptions/constraints/risks

As is currently the case with the FastFlood website, the simulation service requires minimal resources to keep operational. As all the modelling code runs on the local users' machine, no dedicated servers for compute purposes are required. The tool itself consist of static JavaScript/html for the interface, and WebAssembly code for the model. These files can be hosted on static hosting platforms such as GitHub pages, Cloudflare pages, which use global content delivery networks (CDN's) to speed up connection to users and serve the website.

The SIMULATION service primarily depends on foundational software components that are operationally proven and robust. Examples of these include the technologies underlying the web (JavaScript, html), or geo-spatial information technologies (The GEOTIFF file format, the GEOJSON file format). For the risk analysis platform, python and the Django framework are used.

There is a variety of constraints that limit the design and scope of the modelling tools.

Hardware or software environment.

The platform should be available for a wide variety of machines, both in terms of hardware and software. The operating systems Windows, Linux and MacOS, android and iOS should at least be supported. Both x86, x64 and ARM hardware should be supported as well. Development of separate tools for each of the possible platforms is prohibitively expensive, so software stacks that support all of these out of the box might be considered. In addition, the model should work rapidly on a wide variety of hardware levels. From phones, tables to computational severs, the model should still be functioning and allow for some interactivity.

Availability or volatility of resources.

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For external data input such as weather forecasts, the tool will not be dependent on these. However, if the pre-processed datasets are provided to the models, this component of the simulation service will be dependent on the continued operation. Examples are:

- ECMWF and GFS global weather forecasts
- SOILGRIDS global soil database
- SRTM Amazon tiled S3 Bucket
- NASA SMAP global soil moisture product
- OpenStreetMaps global dataset on roads and buildings.

Standards compliance.

The model underlying technology for physically based modelling of the hazardous processes should be in line with industry and scientific standards as much as possible. The primary innovation, the rapid modelling framework as demonstrated on FastFlood, is a required innovation that must be used to provide the interactivity and speed in a web-based tool. Besides this, standard methods should be chosen were possible to maximize support and precedence.

Interoperability requirements.

The simulations tools should work with (both import and export) data in standardized and well-established data formats in the field of geo-spatial analysis and modelling. Currently, the choices for this are GeoTIFF for spatial rasters and GEOJSON for vector data files.

Licensing requirements.

Some of the global datasets come with limitations to their usage and distribution. All the required datasets mentioned in this document are available freely for commercial and education or non-profit usage. User-uploaded datasets for the RiskChanges platform are only available through a secured environment where users have logged in using their credentials.

Data repository and distribution requirements.

The hosted data does need to be publicly available or distributed to a general audience. Data is hosted either to serve users pre-processed global datasets, or to store user-provided information on landscape properties and spatial information on hazard and vulnerability.

Security requirements (or other such regulations).

The platforms will work with data that might be under strict regulations (high-detail elevation models and other confidential governmental datasets). Security is fully guaranteed, as the data never leaves the device of the user. All computations are carried out on the user's machine, and no server is involved except for hosting the website files. As no data is send to a server, there is no risk on the side of the simulation tool for having or leaking this data.

Performance requirements.

To enable the interactivity and ease-of-use, we aim for simulation times that are typically lower that 2.5 seconds. This speed is possible due to the fast simulation framework that is demonstrated on FastFlood[98].

Network communications.

As a web-based tool, network communication is required for running the simulation tools. Because we aim to reach people with limited internet connectivity, we aim to minimize the size and network load of the website. For automated downloads of datasets, the user will have to deal with their network speed. However, we will compress the data, as is supported by the GeoTIFF file format in which the data will be hosted. There might be

[98] https://www.fastflood.org/

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an option to develop stand-alone desktop tools and phone apps using the same technologies, using Electron framework for example.

Verification and validation requirements (testing).

We will employ periods of internal testing where a limited group of people, including students, interns, scientific staff, will test the software and be able to submit bug reports. After testing periods of several weeks to months, a final version of the update is published. As a backup, previous versions of the web-based platform will be hosted as well, so users who depend on version-specific behaviour can always use the version they are used to.

6.2.3 Design considerations

Goals and guidelines

The primary considerations in the development of the platforms can be thought of along two axes. First, the level of specialization for the tool is a major choice and impacts the type of end-users.

Hazard simulation tools often feature a variety of technical settings and options to help users improve the quality of their modelling results when compared with observations about disastrous events. For flood modelling for example, the type of flood process can determine if a user needs to implement a more detailed hydrological description to get the model to work well. While flash floods might be modelled with a simpler infiltration-runoff model, large catchment with riverine flooding caused by longer events require some estimation of evapotranspiration, baseflow, and groundwater dynamics. For this reason, even rapid assessment tools like FastFlood, often allow for customization. This benefits the applicability and customization. A downside to this is the required knowledge on the physical processes to correctly use the model. By providing the options for the user, experts will be able to refine their modelling results to a much higher level. However, non-expert users might need additional training materials to correctly use the tool.

Our vision is that end-users trained in the related field would be instantly able to use the model, without any additional training. For end-users with another background, consuming open training materials for a day/some days should bring them the knowledge to assess the model working and its accuracy.

The second consideration is the weighing of ease of use and cost of hosting the simulation service (particularly in terms of data-processing and availability). We aim for the simulation service to allow for the user to load their own data for analysis and modelling. However, often global datasets are used, such as elevation data (SRTM or COPERNICUS 30), or national-scale governmental datasets which are hosted either freely or commercially. Users will have to pre-process this data before using it in the tools. This can be a heavily involved task, that required significant expertise from the user. For data that is useful for the modelling tools, such as higher-quality elevation data, weather forecasts, climate data, and landscape properties, pre-processed data can be made available to the simulation service. This would allow users to simply select the desired area and automatically download the required datasets. This can significantly open the space of potential end-users and make the tools much more viable for scenario-exploration and rapid assessment. However, hosting these datasets in pre-processed form, and in a format that can be used in the web-tools, is costly. The global datasets are multiple terabytes, and depending on the usage by users, hosting providers will charge the host of the platform.

Our vision is that the end-users can at least use the full modelling technology, and computations are provided in a free format. This requires that, where possible, computations run on the user's machine. FastFlood currently employs such a structure and can therefore offer its modelling technology for free. For platforms such as RISKCHANGES, client-side calculation is not viable due to the emphasis on collaborative work projects and saving sessions on the site.

Spinoff

The simulation tools (e.g., FastFlood) will be developed as a spinoff company with a semi-commercial goal. This will allow us to build, in addition to the free hazard model, professional features such as improved data, automatic processing, and forecasting. These features require compute power and hosting that is costly and

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cannot be provided as a free service. These options could be offered commercially and build upon the freely developed tools.

The freely available platform will include

- All simulation functionality
- Basic free datasets

The commercial extension will include

- Improved global datasets for elevation, automatic downloading
- Global datasets for weather, automatic downloading, and flood forecasting
- Global datasets for extreme discharge and weather events, automatic downloading, and in-tool usage.

The commercial functionality required costly pre-processing and hosting in formats that can be used directly in the web-based flood simulation tool. Because of the involved cost, these features could not be offered in the free tool.

The methods and the simulation platform will be openly published and made available freely.

The underlying code, as well as the commercial features, will be property of the spinoff. During the PARATUS project, their alignment with the other tools developed as part of the PARATUS simulation and information platform will be ensured.

Development Methods & Contingencies

The simulation tools will be developed using a mix of structured and object-oriented methodologies where needed. Most of the interface code will be written in JavaScript, in a structured way. The majority of the model code will be written in C++ and compiled using Emscripten to a WebAssembly module. This code will utilize some object-oriented code for geo-spatial data.

One potential risk for the planned development methods pertains to the use of WebAssembly as a technology for providing rapid simulation in a web-based environment. In recent years, WebAssembly has seen several changes due to the risk of its use in hacking and security circumvention. While these have been addressed by all major browsers, and the technology is supported more and more, there is a risk a new security weakness might be exposed and the resulting changes to browsers to adapt to these risks might limit the capabilities of the technologies.

Our simulations tools will not use many (exotic) features. The primary feature at risk might be multi-threading within a single WebAssembly module. This is supported through the Emscripten compiler set, using Web Workers as a background scheduler.

Hazard simulation platform - Serverless Design

For the hazard simulation tools (e.g., flood, mass movements), we aim to utilize a serverless design architecture. This architecture works by hosting the separate parts of the backend technological stack distributed among large datacentres.

Database -> Hosted in google firebase cloud service (Google Firebase)

Backend Code -> Hosted as serverless functions through Cloudflare edge network (Cloudflare Functions)

Frontend Code -> JavaScript/HTML hosted in content delivery network (Cloudflare Pages)

Cost and Speed

Usage of a serverless design bring benefits as it limits the cost of hosting the simulation tools. The JavaScript/HTML front-end code can be freely hosted globally, with automatic scaling. The back-end code, hosted as edge functions, are cheap at approximately 5 euros per million activations. Rendering is also faster, as the data and code are distributed on a global network of servers, reducing latency.

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However, without the usage of dedicated servers, simulations must run on the user's machine. This has benefits and drawbacks. While somewhat slower, as dedicated servers can be equipped with high-end hardware, such compute servers are prohibitively expensive. For the user experience, this requires rapid simulation techniques. The FastFlood method has been developed with this in mind, but this is not possible for all other natural hazards. Currently, research is ongoing to include debris flows and landslide processes as well. The simulation platform for mass movements will rely heavily on the existing components developed for FastFlood, and follow a very similar interface, design structure, and link with global datasets.

Scaling

One of the primary benefits of a serverless architecture is the automatic scaling. When websites start to attract higher numbers of users, they must scale their capacity to deal with incoming traffic. With the usage of dedicated servers, this means traffic must be distributed among multiple servers instead, and users' traffic must be automatically directed to distribute the load. This is a complicated task, in particular, when databases are involved, and servers must communicate about a shared state of data in the database. The serverless framework scales automatically, as the edge functions can be started in a fraction of a second, and more of these are started in datacentres around the world, responding to the number of active users in real-time.

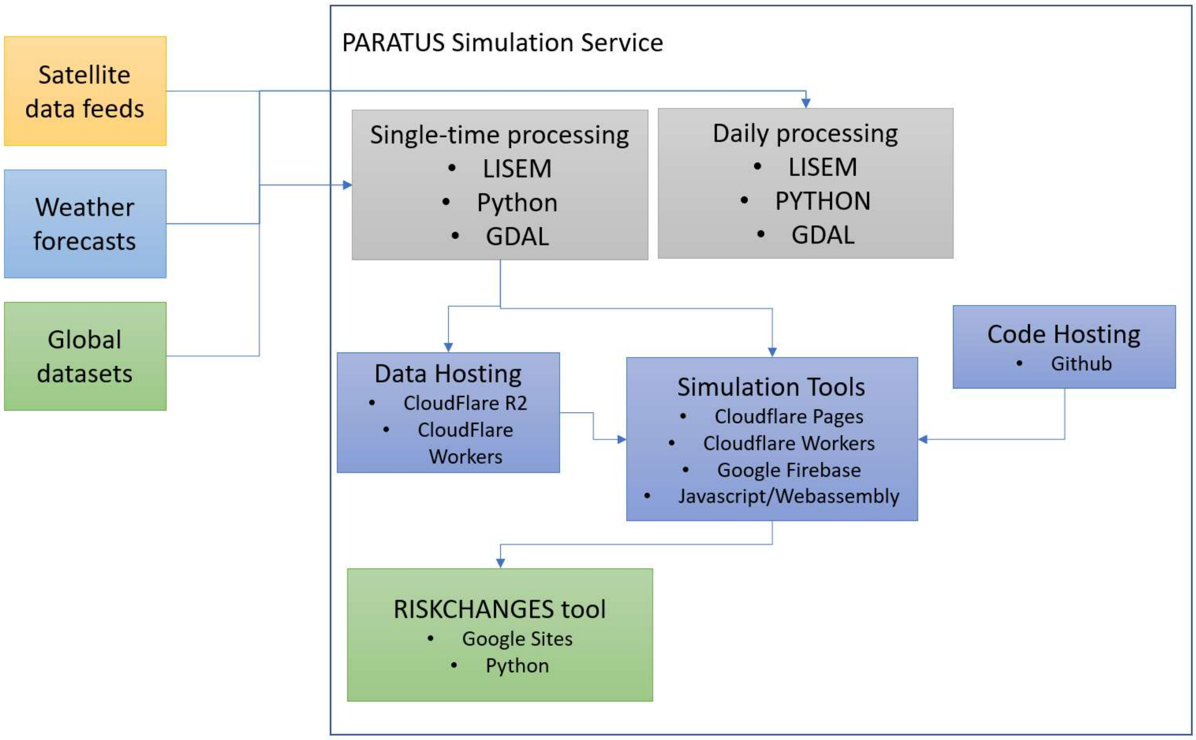

Figure 6.2.3 Overview of the logical structure of the platform, where data is processes, hosted, and how the tools interact.

Software architecture

There will be two primary components to the system. First, the Web-based Simulation Tools

- Flood Model (FastFlood.org)
- Slope/Mass movement model

These tools will use a variety of software to carry out the automatic processing of global datasets.

- LISEM (data processing, projection, and tiling)
  - Used core libraries: GDAL, QT
- Python (data downloads, task scheduling and running)

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  - Used libraries: ecmwf-opendata, cdsapi
- RClone (uploads to storage servers)
- Cloudflare pages/Functions/R2 (hosting the code/interface)
- Google Firebase (Hosted the database)
- GitHub (code hosting and tracking)

Security

The platform will only require security for the commercial features of the platforms, as the free component will not host, process, or transfer any data on the back end of the platform. Instead, all data remains with the user exclusively. For the commercial features, our security is based on industry standard verification mechanisms such as JWT tokens with standard hash algorithms (sha-256) for password storage (hashed, salted, peppered) and authentication.

6.2.4 Information architecture

Input data

A variety of datasets will be used to provide the simulation tools with a default global option that users can select to parameterize the model. These include

- Global elevation datasets
  - SRTM elevation
  - Copernicus 30 Elevation
- National scale datasets
  - AHN
- Weather Forecasts
  - Global Forecast System
  - ECMWF Forecast
- Soil Information
  - SoilGRIDS database
  - SMAP Soil moisture estimates

User input data

The user can provide their own data to improve the parameterization of the model.

- Landscape parameters
- Climate data
- Observational data
- Elements-at-risk
- Vulnerability data

For the simulation tools, all data is stored in local memory, and no servers are used to store the data thanks to the serverless design.

The simulation tools have one user-role, hazard simulation. The input/output flow for this type of user is shown below.

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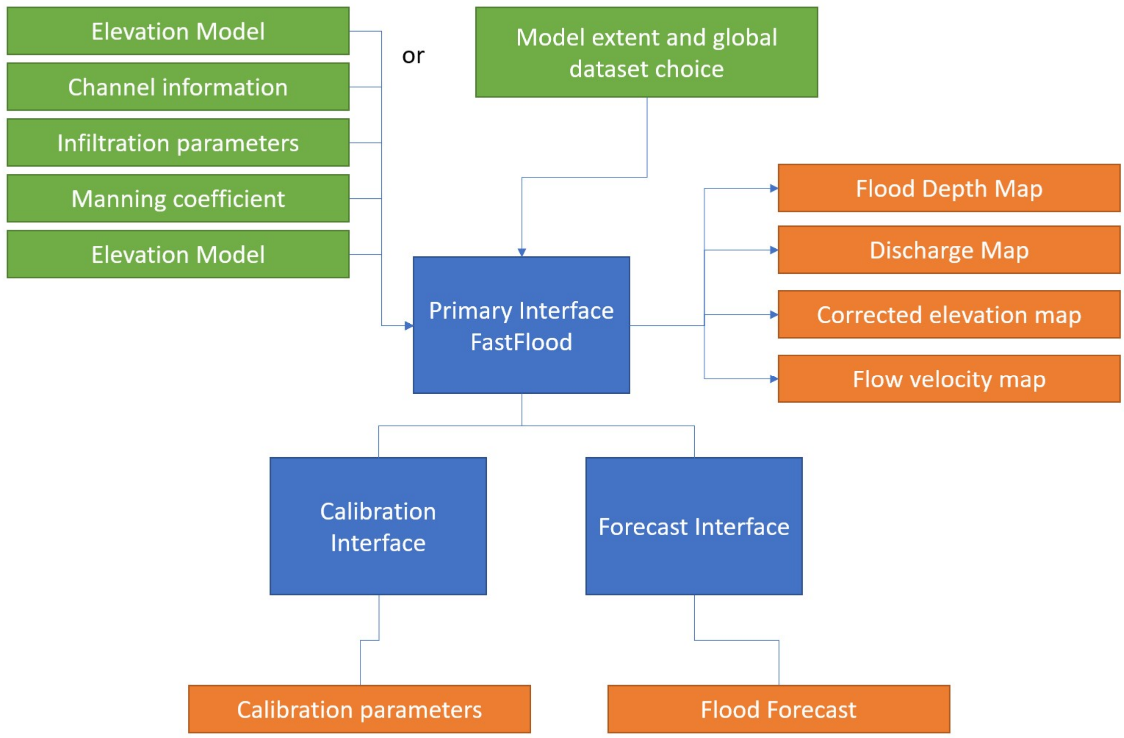

Figure 6.2.4 The input and output data flow for the FastFlood platform. The debris flow and mass movement platform will have a similar structure.

Simulation Tools

For the flood and mass movement simulation tools, a variety of datasets will be made available on the platforms as pre-processed, pre-projected global datasets that are divided into a tile-server layout for rapid downloading and processing in the front-end of the model. The structure of this database will be as follows:

- Cloudflare Bucket
  - Copernicus 30m Elevation
    - Tile server levels 7 to 12 (600 to 20m resolution), pseudo-Mercator projection
  - SRTM 30m Elevation
    - Tile server levels 7 to 12 (600 to 20m resolution), pseudo-Mercator projection
  - AHN 5m Dutch National Elevation
    - Tile server levels 14 (5m resolution), pseudo-Mercator projection
  - Forecasts
    - ECMWF
      - Tiled weather forecast, global coverage in 20x20 tiles, WGS84 coordinates
    - NASA SMAP
      - Tiled soil moisture estimates, global coverage in 20x20 tiles, WGS84 coordinates

A backup of these is stored locally at Twente University to maintain the option for rapid restoration after some failure has occurred.

6.2.5 User Interface design

As a design reference for the simulation tools (e.g., FastFlood), we use the current prototype, shaped through usage by ourselves and close collaborators in consulting, education, and research.

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The main interface consists of a single webpage, and acts as an app. The page is covered by a full-page map, with several thematic maps as background options. On the left side is a menu containing all the input and output options for the model. On the right side, additional input tools for geo-spatial inputs are available. Once a simulation is carried out, the primary output is provided on the map, where flood depth simulation results are shown as an overlay on the background map.

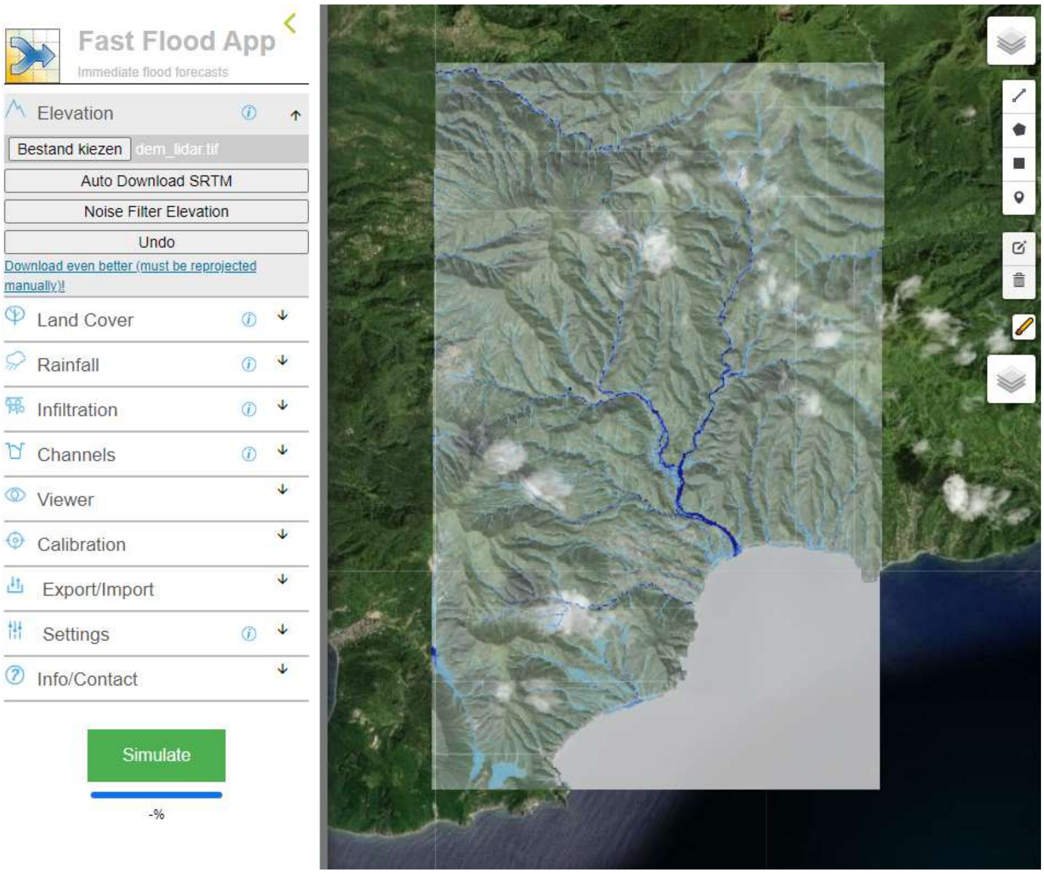

Figure 6.2.5 The FastFlood user interface, with the main menu on the left, and the map-based user tools on the right.

Several tools and options have some small additional interface contained in a popup. An example of this is the forecasting tool. Here, users can run the model automatically based on downloaded weather forecasts. Here, users can download real-time weather forecast. The data from the ECMW global forecasts is pre-processed and hosted in a tiled format for fast downloading and usage in the FastFlood platform. The user can visually see the rainfall forecast over time (10-day coverage, with 3-6 hours intervals), and by selecting a forecast time, see the spatial distribution of the precipitation.

In addition, the user can select the interval of the simulations and automatically run the model at this interval. Finally, by selecting a simulation and choosing the 'edit' option, the soil moisture and precipitation data is taken back to the main editor so a user can use the same simulation and use all the other tools available in the FastFlood platform.

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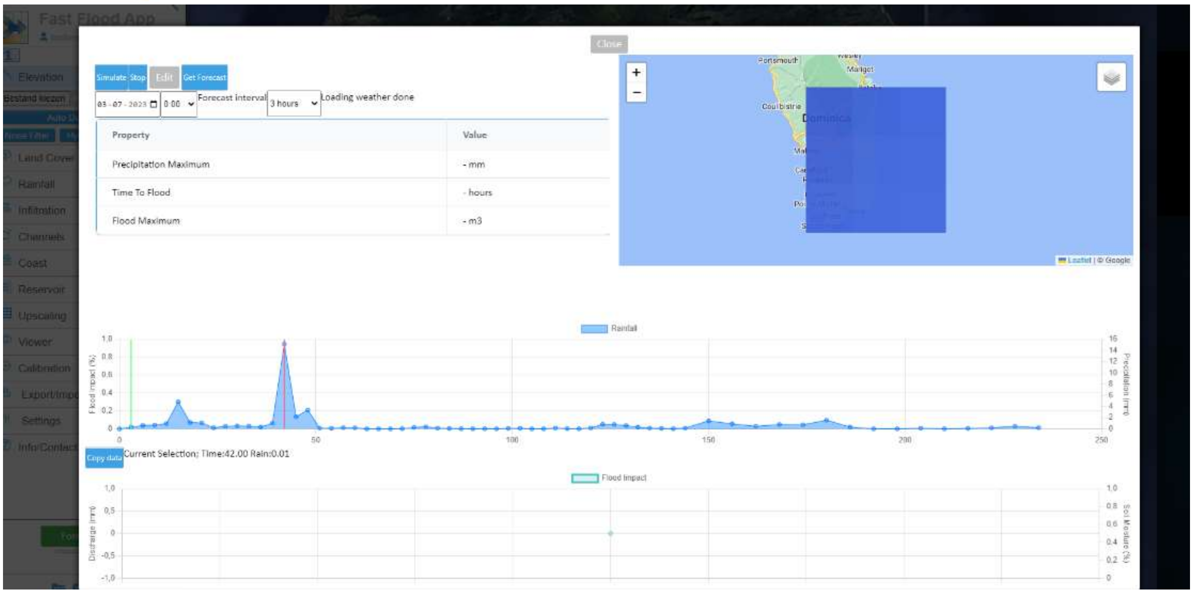

Figure 6.2.62 The forecast interface, where users can visualize and download weather forecast and forecast flood events.

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6.3 RiskChanges tool

PARATUS will develop an open and online, tool for exposure, vulnerability, loss, and risk assessment. RiskChanges is a Spatial Decision Support System for the analysis of current and future multi-hazard risk at local level, to select optimal risk reduction alternatives. The system has originally been designed in a European Research Project[99] by the University of Twente, and other partners. Later the system was newly implemented using the most recent developments related to web-based open data analysis, by the University of Twente in collaboration with the Asian Institute of Technology, Geoinformatics Centre). For the development of RiskChanges tool agile approach has been opted as it is an iterative and collaborative approach to system design and development. It emphasizes flexibility, adaptability, and customer collaboration throughout the design process. RiskChanges is an open-source web-based system designed for data processing using cloud. The system is generic and can be applied to various hazards and elements-at-risk at different scales. Users can generate their own projects within the system. It is based on a multi-hazard concept, allowing for the assessment of risks associated with multiple hazards. The system enables loss estimation, including both physical and population-related losses. It also supports risk assessment by spatial or administrative units, providing a comprehensive understanding of the risks at a localized level. Users can analyse the current risk levels, explore various risk reduction alternatives, and analyse future trends in risk.

Figure 6.3.1: Impression of the current version of RiskChanges

6.3.1 Current functionality

The system is designed to be user-friendly, catering to users with limited expertise in modelling. It offers flexibility in terms of data requirements, allowing users to work with the available data sources. In cases where data is insufficient, the system can integrate expert opinions or estimations. This open-source web-based system provides a versatile platform for assessing and analysing risks associated with different hazards and elements-at-risk. It empowers users to generate their own projects, estimate losses, conduct risk assessments, explore risk reduction options, and analyse future risk trends. It is user-friendly, flexible in terms of data requirements, and can accommodate expert opinions when data availability is limited.

[99] http://www.changes-itn.eu/

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RiskChanges aim to analyses multi-hazard risk in risk prone area. The tool includes several major features: multi-hazard, multiple assets, vulnerability database, multi-user, compare risk and spatial analysis. The multi-hazard feature performs the risk assessment for multiple natural and manmade hazards. Multiple assets feature allows to analyse the risk of multiple asset type with different spatial characteristic. The vulnerability database feature, give an access to the user to use and share physical vulnerability curve. The multiuser feature has the capacity to perform the risk assessment by multiple users, who can access the tool at the same time and the input data can be provided by different users for the same project. Compare risk feature conducts a comparison between current risk and future risk also different planning alternatives can be compared using this feature. And by using the spatial analysis feature the user can analyse the risk spatially through the web-based map interface. In general, the tool has three main components to conduct the multi-hazard risk assessment: data management, analysis, and visualization component.

The tool includes several major features:

- The system is based on a series of Python scripts, which can be used directly by users that know how to work with Python. More information can be found in the Python part of this ReadTheDocs.
- Users that are not experienced with Python can use the Graphical User Interface (GUI) which can be reached through http://www.riskchanges.or
- Users can upload their own datasets (in the form of hazard maps, elements-at-risk maps, administrative unit maps, and vulnerability curves). More information on the data types can be found here.
- Users can also link with data stored on Open Geospatial Consortium (OGC) compatible servers for geospatial data or through database connections.
- Several users can work on projects where different users can upload the various data types. The administrator can generate projects and assign users to them.
- Elements-at-risk data can be of different types, such as points (individual objects), lines (e.g., transportation networks), building footprints or land parcels. They are uploaded as shapefiles. You can analyse different types of elements-at-risk in the same area and combine the risk. The elements-at-risk information requires attribute information on the types, the value, and the number of people.
- Hazard maps are raster maps (Tiff files) and can be of two different types. The most simple option is the use of susceptibility maps, which have several classes. The ideal type of hazard information is in the form of intensity maps for different return periods.
- The system allows the use of multiple hazard types, which can be natural and man-made. When calculating the risk, the user must define the type of hazard interaction.
- The system uses an open vulnerability database, where vulnerability curves can be consulted, and selected based on the hazard and element-at-risk combination. Users can also upload their own curves. Uncertainty in physical vulnerability can be incorporated in the curve database. Curves are made for specific combinations of hazard type, hazard intensity and classes of elements-at-risk, and can represent physical, population or functional vulnerability.
- The users can determine which combinations of elements-at-risk and hazard maps will be used for the generation of exposure maps. Exposure can be calculated for the individual elements-at-risk or aggregated to administrative units.
- Exposure and vulnerability are combined in a loss calculation for each combination of element-at-risk and hazard.
- Loss maps are integrated in a risk map, where the user indicates the interaction between the hazard types.
- Risk can be calculated in different ways, as the number of elements-at-risk, in monetary values, or as population risk.
- Risk can be calculated for the current situation, and for possible future scenarios, and future years.

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- Users can define these scenarios and provide the metadata to the hazard and elements-at-risk maps.
- Risk can also be calculated for risk reduction alternatives, and the difference in risk levels can be used in cost-benefit analysis to evaluate the optimal risk reduction alternative.

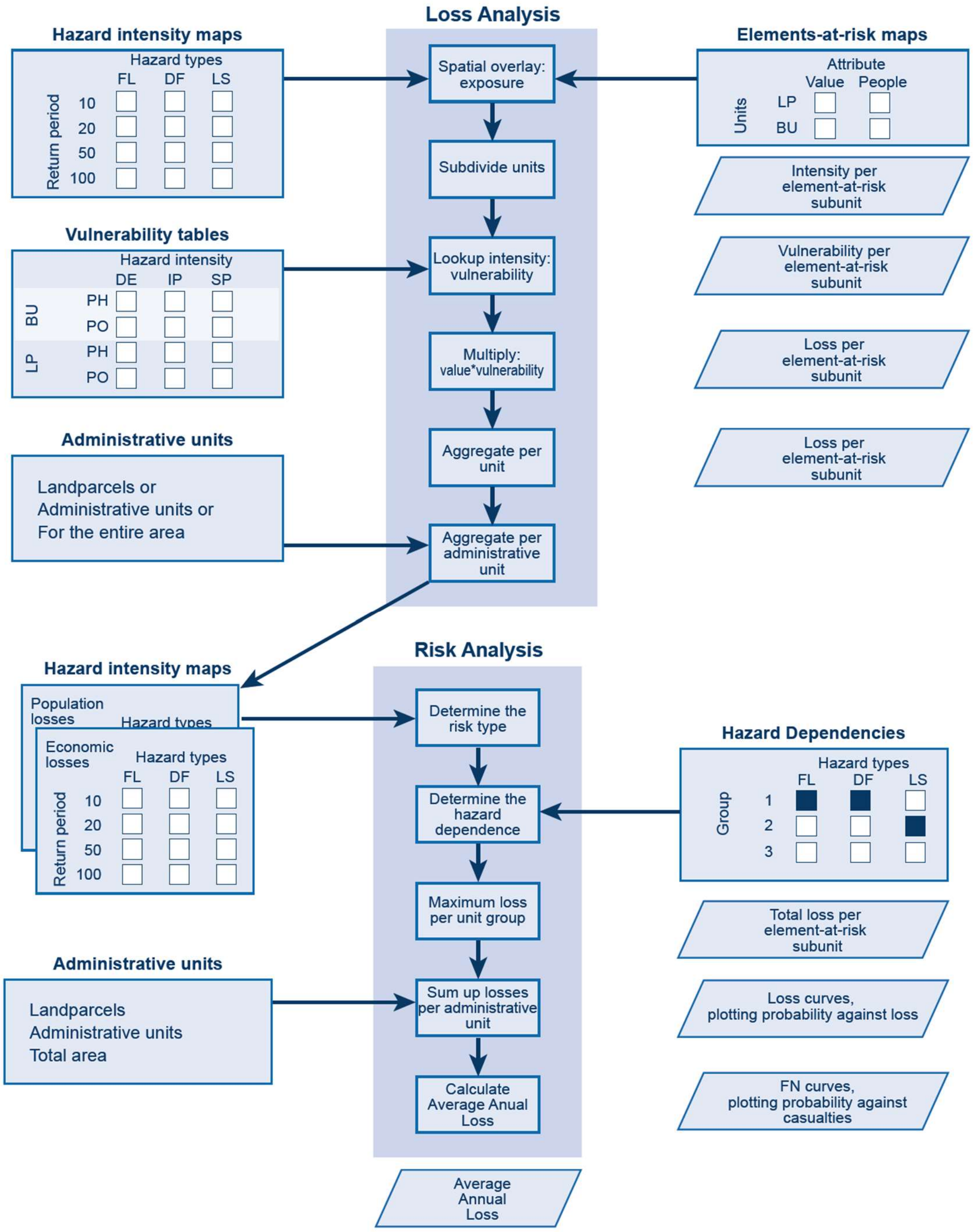

Figure 6.3.2: Method used for Loss and Risk Analysis in RiskChanges.

The users can determine which combinations of exposure and hazard maps will be used for the generation of specific hazard exposure maps. Exposure can be calculated for the individual elements-at-risk or aggregated to administrative units. Exposure and vulnerability are combined in a loss calculation for each combination of elements-at-risk and hazard interactions. Loss maps are integrated in a risk map, based on the interaction between the hazard types. Risk can be assessed in different ways, as the number, length or area of elements-at-risk exposed or damaged, in monetary values, or as population risk.

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6.3.2 Proposed functionality

To use the RiskChanges tool within the PARATUS platform a number of additional functionalities are planned.

- **Elements-at-Risk layers should be accessible as gridded datasets**. For example, for built-up areas, population, or land use.
- **Direct links with sources of building data** (such as OpenStreetMap). Building footprints, however, do not have attributes, or are only incomplete. Using road networks directly from OpenStreetMap would also be helpful.
- **Link with Google Earth Engine & Microsoft Planetary Computer:** Now only public OGC services can be used to test connections and upload the data. If there is no permission to use the WFS service, then the layers need to be downloaded and processed at first in a GIS software and then manually upload the file. The OGC option needs to connect the web servers (e.g., Geoserver, Mapserver, Mapnik etc). Develop procedures that make it possible to obtain input maps from Google Earth Engine (GGE). GGE could then be used to prepare certain datasets. For example, it would be possible to generate maps of flooded areas, wildfire areas etc in Google Earth Engine, which could then be used in RiskChanges to calculate exposure (and risk). There is an open-source version (Open EO from COPERNICUS). We could do this for floods (Sentinel1 or Sentinel2) images, and we can do this for landslides using an existing algorithm. For earthquakes we could make a link to the USGS.
- **Links to Admin Unit datasets**: If we want to make the tool suitable for use in the system. This could also be done, e.g., through GADM maps and data[100] and in GGE[101].
- **Link to FastFlood Hazard Modelling tool**: The current version of RiskChanges doesn't generate hazard maps, as there are many models for each hazard type, each with its data requirement. Modelling request very specific skills that many of the intended users will not have. And many modelling approaches require high computation capacity. However, it would be very helpful if the hazard effects of possible risk reduction alternatives and future scenarios could be directly calculated. There are good developments with the FastFlood tool that has reduced calculation time considerably, and perhaps also for other hazards such rapid models could be implemented. Also, empirical approaches are available for runout hazards (debris flows, rockfall, landslides, snow avalanches). Incorporating simple approaches for hazard assessment in RiskChanges or making links with these tools would make it much more versatile. There can be a faster link between FastFlood and RiskChanges. So, without every time uploading it in RiskChanges.
- **Error detection and recovery**: Error detection and recovery strategies are essential throughout the entire application development lifecycle from design and development to deployment and maintenance. to ensure the stability and reliability of software systems. Here are some common approaches to detect and recover the error encountered:
  - Error Logging: A robust logging mechanism is being implemented to record detailed information about errors and exceptions that occur during runtime which helps in identifying the cause of errors and provides valuable insights for debugging and troubleshooting.
  - Exception Handling: The exception handling mechanisms provided by the corresponding programming language or framework are being used to properly handle exceptions by catching and gracefully recovering from them. This involves using try-catch blocks to catch and handle exceptions, allowing the application to continue execution or perform appropriate error handling actions.

[100] https://gadm.org/
[101] https://developers.google.com/earth-engine/datasets/catalog/FAO_GAUL_2015_level1

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  - Error Reporting and Analysis: When any computation failed during modelling (exposure, loss, and risk), the user can report the errors they encounter. Thus, these errors will be collected and analysed to identify common issues and prioritize bug fixes or system improvements.
  - Defensive Programming: The defensive programming techniques have been implemented wherever it is possible to validate inputs, check for potential errors, and handle exceptional cases proactively to ensure that the application functions correctly and does not encounter unexpected errors.
- **Cost-Benefit analysis:** This component will allow us to analyse Net Present Value and Internal Rate of Return of a range of risk reduction alternatives, that will have an influence on the annual risk, and will require initial investments and annual maintenance. The annual risk reduction may vary depending on the future scenarios that are selected. This tool will allow decision makers to obtain information on the best performing alternative from a monetary point of view.
- **Make a link with the Impact-chain tool**: Within PARATUS an impact chains definition tool will be developed (based on a combination of KUMU, Living Labs and CRISP). Within that tool we would like to make the possibility to link it to calculations within RiskChanges. The impacts in the Impact Chain tool will be defined in terms of their controlling factors. For direct damage this would be the hazard maps, elements-at-risk maps, and admin units. A direct link could then be made to the RiskChanges tools to calculate the results. Also, the display of maps in the impact chain tool could be done through RiskChanges.
- **Include indirect losses in the analysis**: The current version of RiskChanges only considers direct losses. It doesn't consider the impact chains that may be resulting from these direct losses. This is an important additional component, which needs to be developed, and which is based on the mapping of the possible impact chains, and the quantification (as much as possible) of the impact in the individual components of the chain. The system should be able to offer the tools to quantify those components that can be quantified and offer estimates for the other ones, that can be used in the decision supper modules
- **Include network analysis module**: based on the results of the direct loss estimation for specific disaster events on networks, an analysis should be done which parts of the network are no longer reachable. For this we can make use of the open-source module Openrouteservice.org.

6.3.3 Assumptions/Constraints/Risks

Assumptions

- Availability of Community Support: It is assumed that there is an active and supportive community of developers and users contributing to the open-source platform. This community can provide assistance, resolve issues, and offer guidance when needed.
- Compatibility and Interoperability: The platform assumes compatibility with various operating systems, databases, and software frameworks. It assumes the ability to integrate with other tools and systems seamlessly, ensuring interoperability with existing infrastructure.

Constraints

- Technical Expertise: Effective utilization of an open-source platform may require a certain level of technical expertise from users. They need to be familiar with the platform's configuration, installation, customization, and maintenance processes.
- Limited Vendor Support: As an open-source platform, it may have limited, or no formal vendor support available. Users may rely on the community or forums for troubleshooting and addressing technical issues.

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- Some other important constraints might be: Hardware or software environment; End-user environment; Availability or volatility of resources; Standards compliance; Interoperability requirements; Interface/protocol requirements; Licensing requirements; Data repository and distribution requirements; Security requirements (or other such regulations); Memory or other capacity limitations; Performance requirements; Network communications; Verification and validation requirements (testing); Other means of addressing quality goals; Other requirements described in the Requirements Document

Risks

- Security Vulnerabilities: Open-source platforms may have security risks, such as vulnerabilities in the code or dependencies. Users should regularly update and patch the platform to mitigate potential security threats.
- Lack of Documentation: The availability and quality of documentation for the open-source platform can vary. Insufficient or outdated documentation may pose challenges when configuring or troubleshooting the platform.
- Long-term Sustainability: The long-term sustainability of the open-source platform relies on continued community support, active development, and user adoption. If the community support diminishes or development stagnates, it could impact the future viability and maintenance of the platform.
- Intellectual Property Issues: When using an open-source platform, users need to be mindful of any licensing obligations or intellectual property restrictions that may apply. It is important to comply with the terms of the open-source licenses and ensure the legal use of the platform.
- Dependency on Third-party Components: Open-source platforms often rely on various third-party libraries, frameworks, or modules. Changes or issues in these dependencies can affect the functionality and stability of the platform.

It is essential for users to assess and mitigate these assumptions, constraints, and risks associated with the open-source platform. This may involve investing in training, establishing backup support mechanisms, regularly updating, and securing the platform, and monitoring the sustainability and development activity of the open-source community.

6.3.4 Design considerations

Goals and guidelines

Before attempting to devise a complete design solution for an open-source RiskChanges application, several issues needed to be addressed or resolved to ensure a successful and effective development process. Here are some key considerations:

- **Requirements gathering**: Thoroughly understanding the requirements and objectives of the RiskChanges application. Engagement with stakeholders, end-users, and domain experts were made sure to identify and document the specific functionalities, features, and constraints of the application. Also, to clarify any ambiguities and ensure a shared understanding of the project's scope.
- **Domain knowledge**: By gaining insights into the specific needs and challenges faced by risk professionals, we designed a solution that effectively addressed those requirements. This understanding allowed us to create a robust and user-centred application that met the unique demands of risk management.
- **User research**: A user research and feedback mechanism would be devised from potential users or target audience. To identify their pain points, expectations, and preferences when it comes to risk changes and management. This research will provide valuable insights into designing a user-c3ntered application that meets their needs and enhances their workflow.

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- **Data management**: Determine the data requirements of the application. Identify the types of data that need to be stored, such as risk information, exposure, and vulnerability. Data models, relationships, and database schemas has been defined to ensure efficient data management and retrieval.
- **Security and privacy**: Security measures, such as access controls, encryption, and secure communication protocols, to protect data confidentiality and integrity has been incorporated. By implementing these security measures, the application ensured the safeguarding of sensitive information throughout its usage.
- **Integration**: Integration requirements with other Projects' components and tools would be assessed for a seamless workflow between these components.
- **Scalability and performance**: Potential scalability and performance requirements of the application has been anticipated. Consider the volume of risk data, concurrent user load, and any anticipated growth. Architected the system to handle increased data storage, user traffic, and computational demands without compromising performance or user experience.
- **User Interface and experience**: Designed an intuitive and user-friendly interface that allows users to easily navigate, view, and modify risk-related information. Conduct the usability testing and gather feedback to refine the user experience.
- As RiskChanges application would be an opensource tool for its development, there are several goals, guidelines, principles, and priorities that are being followed to ensure a successful and collaborative development process. Here are some key points:
- **Openness**: Emphasize has been given to the importance of openness and transparency throughout the development process. The source code would be accessible to everyone, and the project encourage contributions and feedback from the community.
- **Collaboration**: Collaboration among developers, users, and contributors would be encouraged. Foster an inclusive and welcoming environment where people can freely exchange ideas, provide feedback, and contribute to the project's development.
- **Community-driven**: Place the community at the heart of the project. Listen to user feedback, understand their needs, and prioritize features and improvements based on community demand. Actively engage with the community through forums, mailing lists, social media, and other channels.
- **Quality and Reliability**: Strive for high-quality code and ensure the RiskChanges application is reliable, robust, and well-tested. Thorough documentation, automated testing, and code reviews would make sure to maintain code integrity and minimize bugs and issues.
- **Modularity and Flexibility**: The application has been designed with modularity in mind, allowing for flexibility and extensibility. Follow best practices for modular architecture, clean code, and reusability, making it easier for contributors to understand and enhance the project.
- **Usability and accessibility**: Prioritized user experience by developing an intuitive and user-friendly interface. Consider accessibility guidelines to ensure the application can be used by individuals with disabilities or diverse needs
- **Security and privacy**: Placed a strong emphasis on security and privacy. Regularly address vulnerabilities, conduct security audits, and follow best practices for data protection, encryption, and secure communication protocols.
- **Documentation**: Comprehensive and up-to-date documentation would be provided that helps users understand and utilize the application effectively. Document not only the code but also instructions, configuration options, and troubleshooting guides.
- **Continuous improvement**: It is planned to improve the application by regularly releasing updates, addressing issues, and incorporating new features based on user feedback and changing requirements. Maintain a roadmap to guide the project's development and communicate its future plans.

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- **Development Methods & Contingencies**
- The object-oriented approach has been employed to construct the logical view of the RiskChanges application, bringing numerous benefits to its design and development process. By leveraging object-oriented principles and concepts, the application can effectively model and manage the complexities of risk analysis and management. Here's how the object-oriented approach has been utilized:
- **Encapsulation**: The application employs encapsulation to group related data and functions into objects. Each object represents a specific entity or concept within the risk analysis domain, such as risks, vulnerability analysis, or exposure calculation. Encapsulation ensures that data and behaviour are encapsulated within the relevant objects, providing data integrity, and promoting modular design.
- **Abstraction**: Abstraction is used to define simplified, high-level representations of complex risk management concepts. It allows the application to focus on essential characteristics and behaviours while hiding implementation details. For example, the application might provide an abstract Risk class that defines common properties and methods, which can then be extended or specialized by concrete subclasses representing specific types of risks.
- **Inheritance**: Inheritance facilitates code reuse and promotes a hierarchical organization of objects. It enables the application to define a base class or superclass with common attributes and behaviours, which can be inherited by subclasses. In the RiskChanges application, inheritance could be used to create specialized classes for different types of risks, inheriting properties and methods from a generic Risk class.
- **Polymorphism**: Polymorphism allows objects of different classes to be treated uniformly, providing flexibility and extensibility. The application can utilize polymorphism to define common interfaces or abstract classes for handling various risk-related operations. This enables the application to work with different risk objects interchangeably, regardless of their specific types.
- **Modularity and reusability**: By using object-oriented principles, the logical view of the application promotes modularity and code reusability. Each risk-related concept or functionality is encapsulated within a separate object, making it easier to understand, test, and modify. This modular design enables developers to reuse objects and components across different parts of the application or even in future projects.

Programming languages:

- **Python**: Python is a widely used programming language known for its simplicity, readability, and versatility. One of Python's strengths lies in its extensive standard library, which provides a wide range of modules and functions for various tasks, reducing the need for external dependencies.
- **JavaScript**: JavaScript is a versatile and powerful client-side scripting language that brings interactivity and dynamic behaviour to web applications. Its significance in the system architecture lies in its ability to handle user interactions, manipulate the DOM, facilitate real-time updates, and provide an engaging user experience.

Framework:

- **Django**: Django is used for backend development in this project which is a high-level Python framework that follows the Model-View-Controller (MVC) architecture pattern. This framework provides a set of tools and libraries that help developers to build complex and scalable web applications quickly. One of the significant advantages of using Django is its efficient way of handling database queries and user authentication, which makes it a popular choice for building web applications.
- **ReactJS**: ReactJS, a JavaScript library, is used for frontend development in this project. It provides a modular approach to build components, which makes it easier to maintain and update the application. It also provides excellent performance due to its virtual DOM and efficient rendering.

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Database:

- **PostgreSQL**: PostgreSQL is the open-source relational database management system that manages the storage, retrieval, and manipulation of data in a structured format. It provides the core functionality of a database, including managing tables, executing queries, enforcing data integrity, and handling transactions. PostGIS is a powerful geospatial database extension that enables the storage, indexing, and querying of spatial data.

Database Management Tool:

- **PgAdmin**: PGAdmin, is a client application that provides a graphical interface for interacting with PostgreSQL. It allows users to connect to PostgreSQL databases, perform administrative tasks, write, and execute queries, and manage database objects, among other things. PgAdmin acts as a front-end tool that facilitates the management and administration of the PostgreSQL DBMS.

Mapserver:

- **Geo-server**: Geo-server is an open-source server for publishing and sharing geospatial data that supports industry-standard protocols such as Web Map Service (WMS), Web Feature Service (WFS), and Web Coverage Service (WCS). It also provides a web interface for publishing and managing spatial data and services.

Mapping Library:

- **Leaflet.js**: Leaflet.js is a lightweight JavaScript library for interactive maps which provides a simple and flexible way for displaying and interacting with maps on web pages.

Version Control System

- **Git**: Git is used for a codebase version control system that allows developers to track changes to the codebase, collaborate on projects, revert to previous versions if necessary, and troubleshoot issues easily through a complete history of changes.

Webserver:

- **Nginx**: Nginx is used as a web server in this project which is widely adopted open-source web server and reverse proxy server. It offers high performance, scalability, and efficient handling of concurrent connections. Additionally, it serves static content rapidly and can act as a reverse proxy, load balancer, and caching solution.

Containerization:

- **Docker**: Docker is an open-source platform that enables developers to automate the deployment, scaling, and management of applications using containerization. It allows applications to run in isolated containers, which package all the necessary dependencies and configurations, ensuring consistency and portability across different environments. It offers a range of benefits, including consistent development environments, efficient resource utilization, simplified deployment, scalability, and rapid development. Its ecosystem and community support further enhance its value for project development.

6.3.5 System architecture

The system architecture of the RiskChanges application is comprised of mainly four components: Backend Development, Frontend Development, Quality Assurance and Deployment which are described below.

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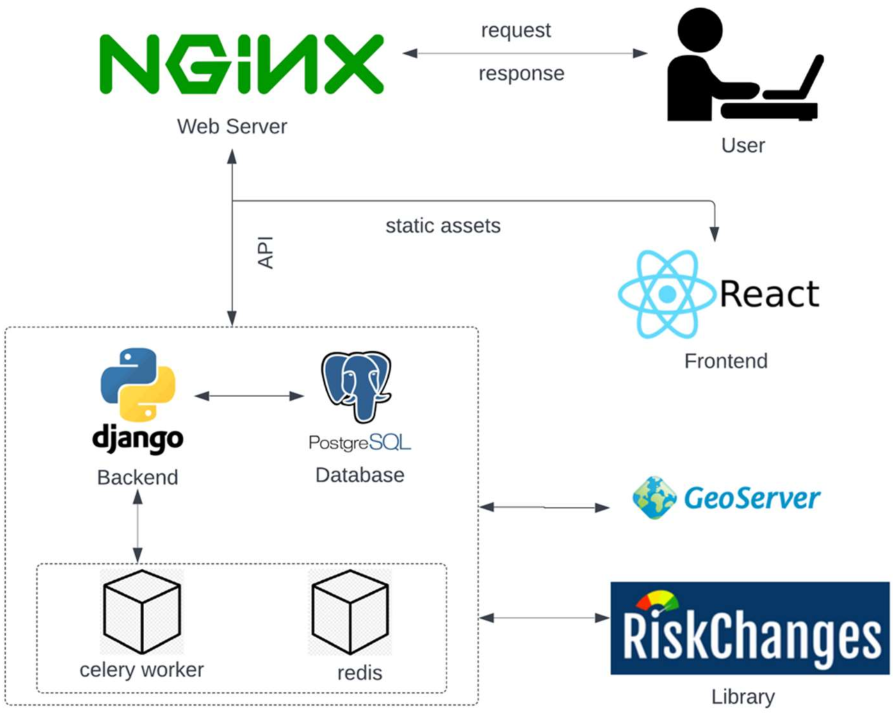

Figure 6.3.3: RiskChanges System Architecture

Backend Development

The backend development is the most critical part of web application development that involves building the server-side components that power the application's functionality. In this project, **Django** is used for backend development which is a high-level Python framework that follows the Model-View-Controller (MVC) architecture pattern. **PostgreSQL** with PostGIS extension is used as the database in this application. PostGIS is a powerful geospatial database extension that enables the storage, indexing, and querying of spatial data. All the non-spatial and spatial vector datasets are uploaded and stored in the database, making it easier to manage and query the data. Moreover, all the raster format datasets are stored and published in Geoserver. **Geoserver** is an open-source server for publishing geospatial data that supports industry-standard protocols such as Web Map Service (WMS), Web Feature Service (WFS), and Web Coverage Service (WCS). In this application, WMS will be served so that the map can be visualized in the front end. Data backup (database and other important files) is created daily by setting the crontab job schedule so that they can be restored whenever needed or in case of system failure.

Front-end Development

Frontend development is part of web application development that involves building the user interface and handling user interactions within the application. In this application, **ReactJS**, a JavaScript library, is used for frontend development. Whereas **Leaflet.js,** mapping library is used for the spatial data visualizations using the WMS streamed from the Geoserver. Frontend interacts with the backend APIs through axios (JavaScript library) to send and receive the data by allowing the user to send GET, POST, PUT, DELETE, and other types of requests to a server.

Deployment: During the development phase, the application is deployed, tested, and evaluated on a local server. Once the development phase is completed, the application is deployed on a google cloud server, which will make it accessible to a wider audience and allow for more scalability.

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Quality assurance

The aim of the quality assurance is to ensure that the application meets the specified requirements, agreed upon the development standards and procedures, and thus finally delivered without any bugs and provides a satisfactory user experience on all relevant devices and browsers.

The several types of testing methods that will be undertaken throughout the system development are described below:

- **Design testing:** Design testing will be conducted in the early stages of development of new feature to ensure that the application's design meets the specified requirements and is aligned with the user's needs. This testing will mainly focus on evaluating the application's user interface (UI), user experience (UX), and overall design elements such as layout, navigation, and visual appeal. Thus, in this phase, design flaws or inconsistencies that may hinder usability of the application will be identified to achieve their goals effectively.
- **Functional testing:** Functional testing will be performed to verify that the application functions correctly and meets the functional requirements specified during the development phase. It will involves testing individual functions or features of the application to ensure that they behave as intended produces the expected output.
- **System testing:** System testing is a comprehensive testing approach, and this method will be carried out to evaluate the application. It involves testing the integrated system to ensure that all components and modules work together seamlessly and meet the specified requirements. System testing focuses on assessing the system's behaviour in different scenarios, including edge cases and boundary conditions, to identify any issues that may arise from the interaction between different components.
- **Performance testing:** Performance testing is conducted to assess the application's performance under different workloads and usage conditions. It involves evaluating factors such as response time, scalability, stability, and resource usage. Performance testing helps identify potential bottlenecks, optimize the application's performance, and ensure that it can handle the expected user load without any performance degradation or system failures.
- **Integration testing:** Integration testing will be performed to verify how the system will interact and respond between different modules, components, or systems within the application. It will be ensured that data flows correctly between various parts of the system and that the integrated components function harmoniously. Thus, in this approach, any issues or inconsistencies that may arise when combining different elements of the application will be identified to ensure seamless communication and data exchange between them.

The system is deployed using Nginx, a popular open-source web server and reverse proxy server software that allows for high-performance delivery of web content by handling incoming requests from clients and serving static content directly from disk.

The application is containerized using docker to ensure consistency and portability across different environments providing greater flexibility and scalability.

Git is used for a codebase version control system that allows developers to track changes to the codebase, collaborate on projects, revert to previous versions if necessary, and troubleshoot issues easily through a complete history of changes.

Security software architecture

Certain pages such as the home, datasets, and vulnerability pages are accessible to all users without any restrictions. However, to access components like data management, modelling, and visualization, users are required to register and login to the system.

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The signup view for RiskChanges is shown below. User can sign up to the system simply by providing the details such as first name, last name, email, and password. These details will be used for user registration and later for authentication to access the system.

After the user clicks the signup button, the system will prompt a confirmation message instructing the user to check their email and verify their account if all the provided details are valid. The signup process will only be completed, once the user clicks the verification link sent to their email.

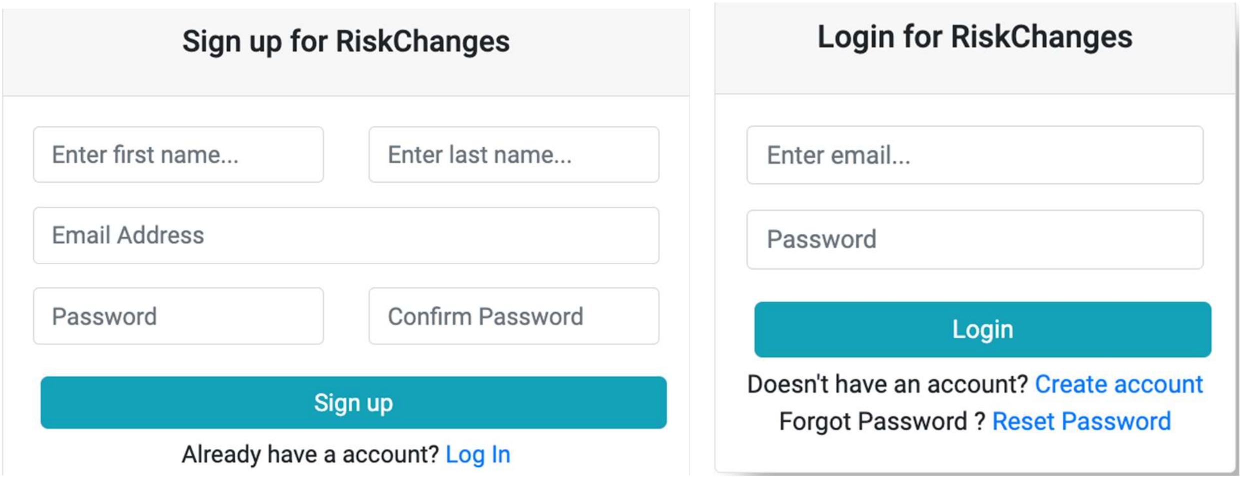

Figure 6.3.4: Sign up and Login screens

In this application, a third-party package called "Django-rest-knox" is implemented as an authentication module that provides token-based authentication for Django REST Framework. It works by generating and managing tokens that are used for user authentication. When a user signs up or registers in the system, their information such as username and password is stored in the database. After successful registration, Django Rest Knox generates a unique authentication token for the user. This token serves as a proof of identity and is associated with the user's account. The generated token is securely stored in the database. It is linked to the user's account and can be used for authentication in subsequent requests. When the user makes a request to access protected resources, they include their token in the request headers or as a parameter. Django Rest Knox verifies the token's authenticity and matches it with the corresponding user account. Once the token is validated, the user is considered authenticated, and their request is processed. Django Rest Knox provides a straightforward way to verify the token and retrieve the associated user details. In this system, the token TTL (Time-To-Live) is set to four weeks, thus the authentication tokens generated by Django Rest Knox will be valid for a period of four weeks. After that period, the tokens will expire, and users will need to re-authenticate to obtain a new token.

6.3.6 Information architecture

Input data

- **Element at Risk (EaR)**: These are the vector (point, line, and polygon) datasets which are added in the system by compressing shapefile in compressed (.zip) format.
- **Administrative Unit**: These are the polygon datasets which are added in the system by compressing shapefile in compressed (.zip) format.
- **Hazard Maps**: These are the raster datasets which are uploaded the application in Geo tiff format. They can be intensity maps or susceptibility maps.
- **Vulnerability**: These are the datasets which are uploaded in CSV formats. The CSV must follow the template which is provided in the form.

The information related to user, organization, projects, vulnerability, alternative, scenario, hazard metadata, EaR metadata, admin metadata etc. are stored in public schema of database.

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When organization is created within the application, separate schema, and workspace in created in PostgreSQL database and Geo-server respectively. The Element at Risk and administrative unit datasets tables are created in corresponding organizational schema in the database, then feature store is created and finally layer is published in Geo-server. Whereas for hazard datasets, the coverage store is created, and layer is published in corresponding organizational workspace in Geo-server. After the calculation of exposure, loss and risk, outputs are stored in exposure result, loss result and risk result table respectively in corresponding organizational schema.

6.3.7 Internal communication design

The RiskChanges tool is hosted on the Google Cloud Platform (GCP) where the communications network is typically built using standard networking technologies and protocols. It utilizes a modern networking infrastructure that leverages Internet Protocol (IP) networking, virtual networks, and various networking services provided by Google. GCP provides the Virtual Private Cloud (VPC), an isolated virtual networking environment for the project which allows to define IP ranges and firewall rules to control network traffic.

Firewalls: firewall rules are setup in the project to control inbound and outbound network traffic to the resources. These rules apply to both IPv4 and IPv6.

Network Monitoring and Logging: GCP offers tools for monitoring and logging network traffic and performance, which is used to analyse and troubleshoot network-related issues.

6.3.8 Database design

The diagram of the database can be seen below[102]. The details of the database design is also available[103].

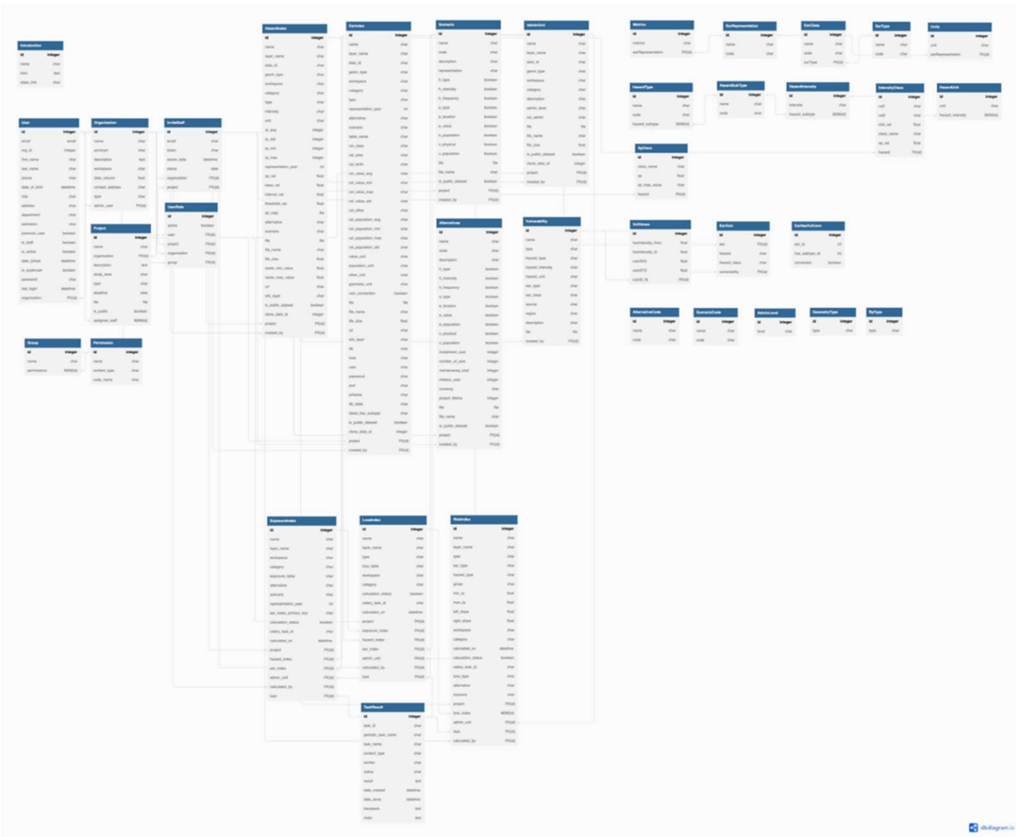

Figure 6.3.5: Database Design[104].

[102] https://dbdiagram.io/d/6305c980f1a9b01b0fd0bc3e
[103] https://gist.github.com/rabinatwayana/53a73b920bff7b77e80ab0effad1edf2
[104] https://dbdiagram.io/d/6305c980f1a9b01b0fd0bc3e

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Data conversion: All vector and raster datasets that are uploaded in the system are transformed into a common reference system known as WGS84 (EPSG 4326). It facilitates easier data integration, spatial analysis, and visualizations that combine various data sources as they all share the same reference frame.

6.3.9 Use-Machine-readable interface

We have three types of user roles and each role comprised of different set of permissions in application. Here's a description of each user type and their potential roles and responsibilities:

System administrator: The system administrator is a high level of role in the application and has all the permissions to make changes within the application and can access the Django administration interface.

Organization administrator: Organization admin can create one organization in the system and manage the organization account. They can create multiple projects within the organization or just import the public projects that are available in the public datasets. They can also send an invitation to the users who they want to involve in specific projects. In addition to this, the organization admin can also remove the project staff from the project.

Project staff: The users with the project staff role have limited access and permissions in the system but can contribute fully into the projects they are invited to.

General User: These are the users who just want to visit and explore the application without signup and login. The table below explains the actions that each role can perform in the RiskChanges system

Table 6.3.1: User Management

Category	action	System Administrator	Organization Admin	Project User	General User
Project	create/edit/delete	yes	yes	no	no
	view project	yes	yes	yes	no
	import public project	yes	yes	no	no
Staff	Invite project staff	yes	yes	no	no
	View project staff	yes	yes	yes	no
	Remove project staff	yes	yes	no	no

Table 6.3.2: Data Management

Component	Action	System Administrator	Organization Admin	Project User	General User
EaR, Hazard, and Admin unit	Upload data	yes	yes	yes	no
	View/edit/delete data	yes	yes	yes	no
	Visualize map	yes	yes	yes	no
Alternative and Scenario	Upload data	yes	yes	yes	no
	View/edit/delete data	yes	yes	yes	no
Vulnerability	Upload data	yes	yes	yes	no
	edit/delete data	yes	yes	yes	no
	View data	yes	yes	yes	yes

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Table 6.3.3: Data Modelling:

Component	Action	System Administrator	Organization Admin	Project User	General User
Exposure/ Loss/ Risk	Compute	yes	yes	yes	no
	View	yes	yes	yes	no
	Visualize map	yes	yes	yes	no
	Download data	yes	yes	yes	no
	Delete data	yes	yes	yes	no

Table 6.3.4: Data visualisation

Action	System Administrator	Organization Admin	Project User	General User
View Layers	yes	yes	yes	yes
Filter Layers	yes	yes	yes	yes
View Legend	yes	yes	yes	yes
Query Exposure	yes	yes	yes	yes
Filter Data	yes	yes	yes	yes
View Feature Information	yes	yes	yes	yes

Table 6.3.5: Datasets

Component	Action	System Administrator	Organization Admin	Project User	General User
Project	Create/edit/delete	yes	no	no	no
Ear, Hazard, and Admin Unit	View	yes	yes	yes	yes
	Create/edit/delete	yes	no	no	no
	Visualize map	yes	yes	yes	yes
Alternative and Scenario	View	yes	yes	yes	yes
	Create/edit/delete	yes	no	no	no

6.3.10 User Interface design

Uploading Hazard data

In this section, user can define one or multiple hazards for risk calculation. The data can be added with two different methods either by uploading the file directly or via the OGC service.

Step 1: Upload Data

Option 1: File Upload

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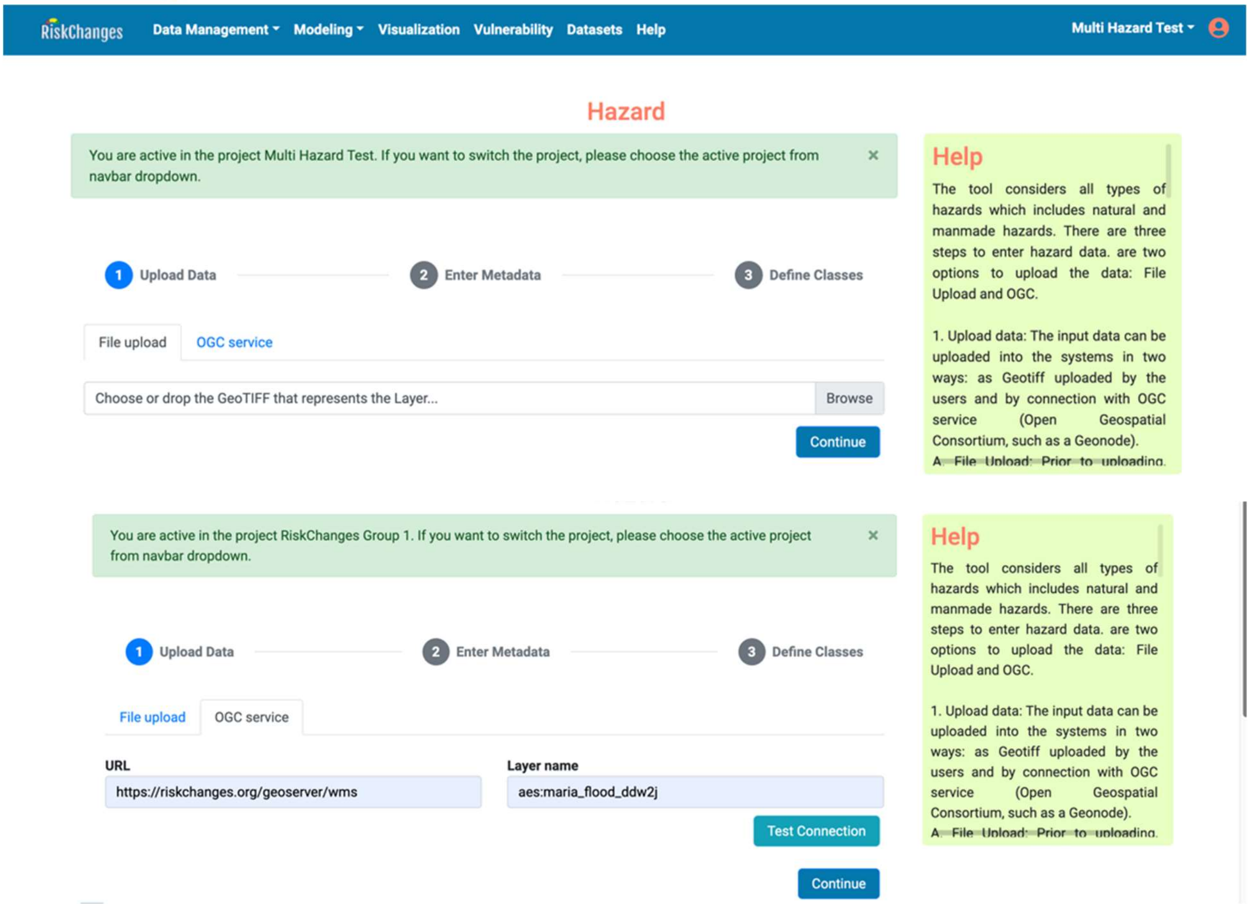

Figure 6.3.6: Hazard upload data. Above: Manual, and below using OGC services.

In this approach, the user can upload the data by simply by selecting a raster file (GeoTIFF format) that represents the chosen element at risk. Then, the user can continue to the metadata section.

In this approach, user can add hazard layer through OGC services for web map. For this user first need to make a connection with Geoserver by adding Geoserver URL and exact name of the raster layer. User can check the connection by clicking on "Test Connection" button and will see a prompt message informing that "Layer is available" if the connection is successful. Then, user can continue to the metadata section.

Step 2: Enter Metadata

In this section, user will add the details of the hazard layer in which layer name, hazard type, hazard intensity type, hazard intensity unit and return periods are mandatory fields. By default, risk reduction alternative and future scenario are set to A0 and S0 respectively however user can select the other alternative and scenario from the dropdown options if it is defined within the specific project.

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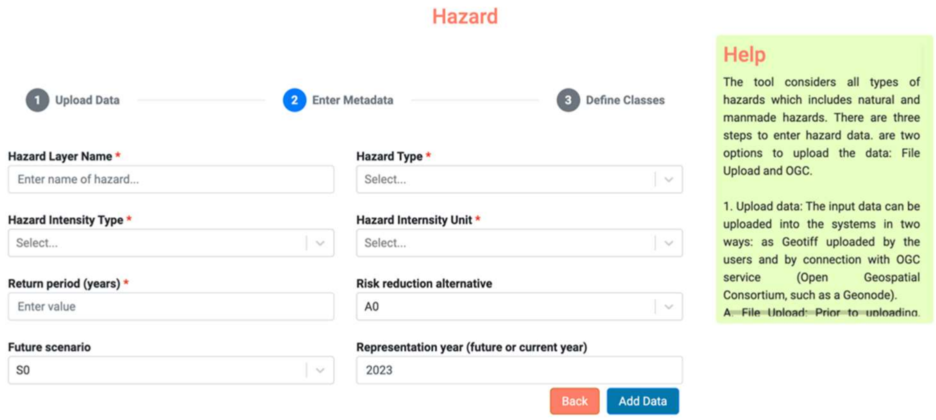

Figure 6.3.7: 5Enter metadata for hazard maps.

Step 3: Define Classes

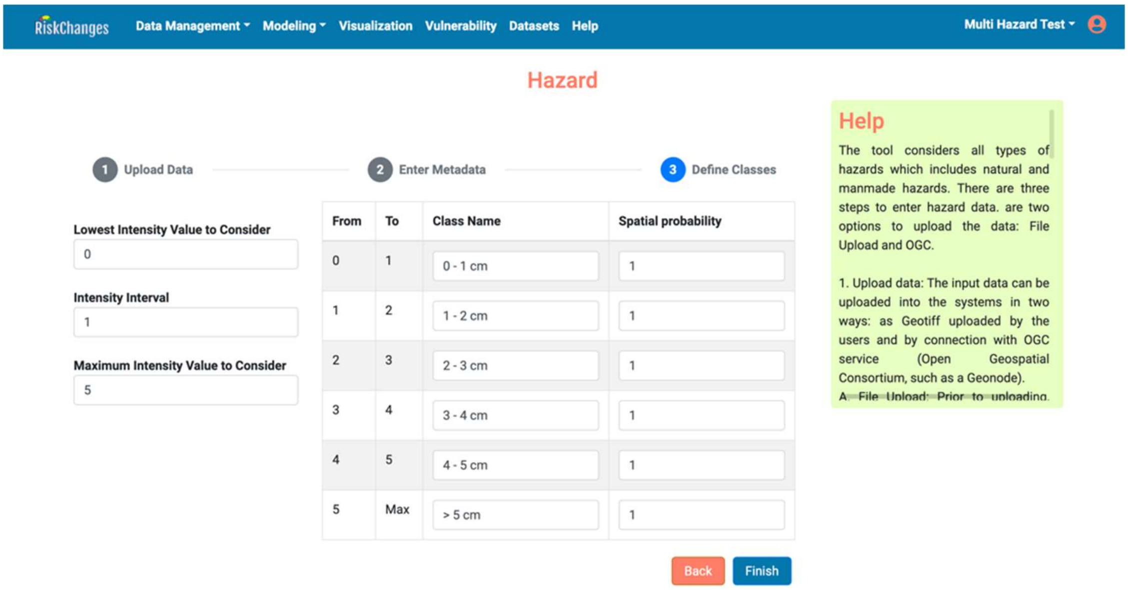

Figure 6.3.8: Define Hazard classes

Once uploaded, the layer will be shown in the list below.

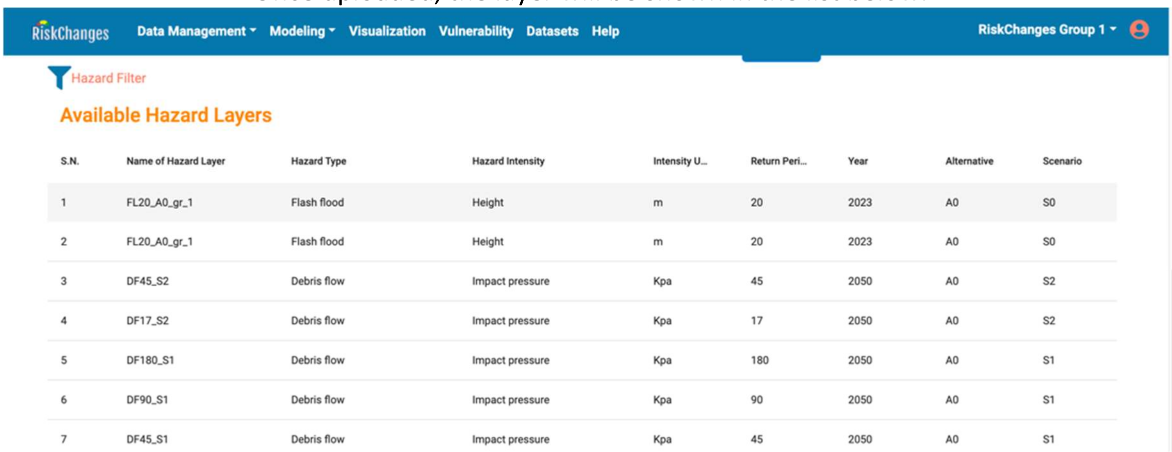

Figure 6.3.9: 6Hazard Layers uploaded

This table shows the list of available hazard layers within the project. User can visualize it, edit the information, or delete it as per necessary.

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Uploading Elements-at-Risk data

In this section, users can define the elements at risk in reference to the chosen hazards. Building footprints, land parcels, linear features (road, railway) and point data are the elements-at-risk that can be added in the system.

Step 1: Upload Data

The data on elements at risk can be added by one of the three different methods: File Upload, OGC service or Database Connection. The data upload process will be completed in four steps (upload data, metadata, column connection and vulnerability connection).

Option1: File Upload

In this method, the user can simply upload the shapefile (zipped format) directly that represents the chosen element at risk.

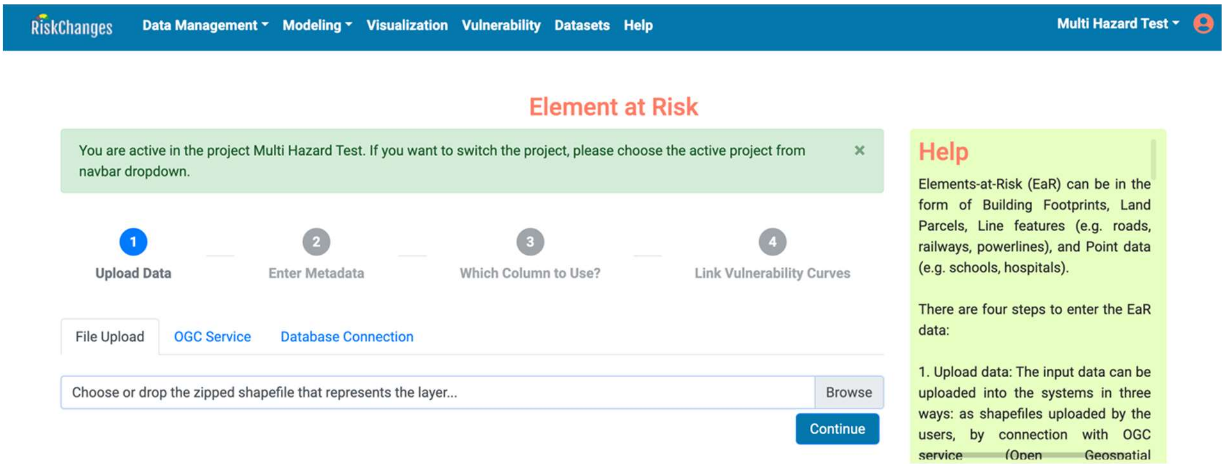

Figure 6.3.10: Uploading Element at risk maps as zipped shapefile.

Option2: OGC Service. In this approach, users can add EaR layer through OGC services for web map. For this user first need to make a connection with Geoserver by adding Geoserver URL and exact name of the layer which is in vector format. User can check the connection by clicking on "Test Connection" button and will see a prompt message informing that "Layer is available" if the connection is successful. Then, user can continue to the metadata section.

Option 3: Database Connection. In this approach, user can add EaR layer through database connection. For this user first need to make a connection with database by entering the details: Database name, schema, database user, password, host name, port, and layer (table name). User can check the connection by clicking on "Test Connection" button and will see a prompt message informing that "Layer is available" if the connection is successful. Then, user can continue to the metadata section. Then, user can continue to the metadata section.

Step 2: Enter Metadata

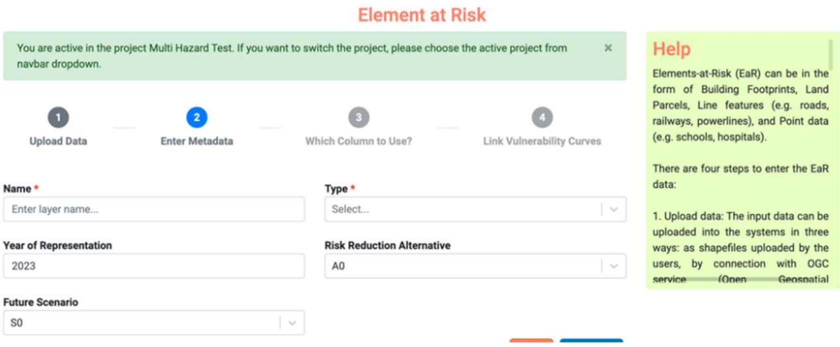

Figure 6.3.11: Element at risk -metadata

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In this section, user will add the details of the EaR layer in which layer name and EaR type are mandatory fields. By default, risk reduction alternative and future scenario are set to A0 and S0 respectively however user can select the other alternative and scenario from the dropdown options if it is defined within the specific project.

Step 3: Which Column to Use?

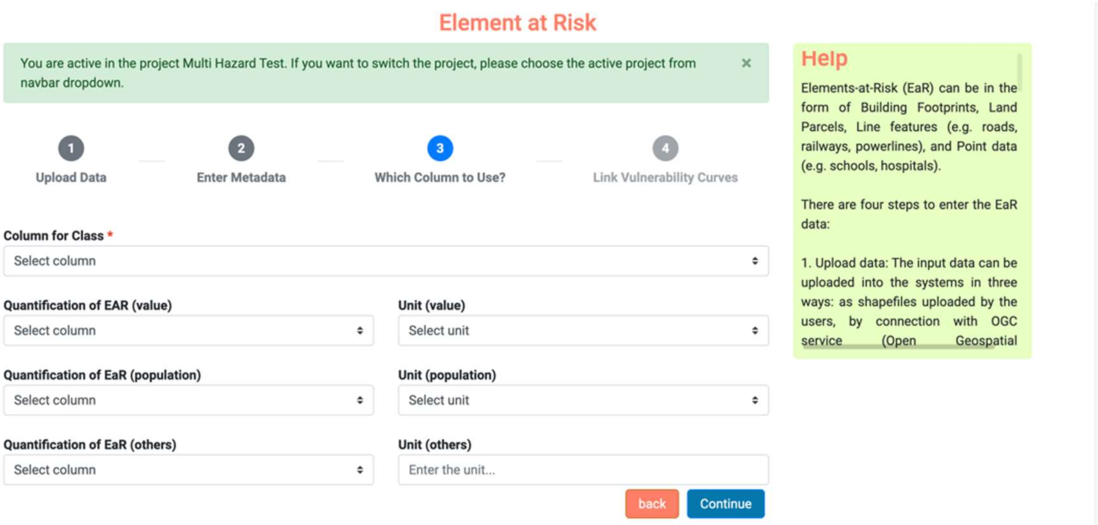

Figure 6.3.12: Element at risk -columns

In this step, user needs to select class column which links the EaR with the vulnerability curve and without this the calculation cannot be performed. User can also select the column that represents the value(cost), population and other classes, if possible, associated with EaR along with their corresponding units. Then, user can proceed to the step 4 (Link Vulnerability Curves)

Step 4: Link Vulnerability Curves

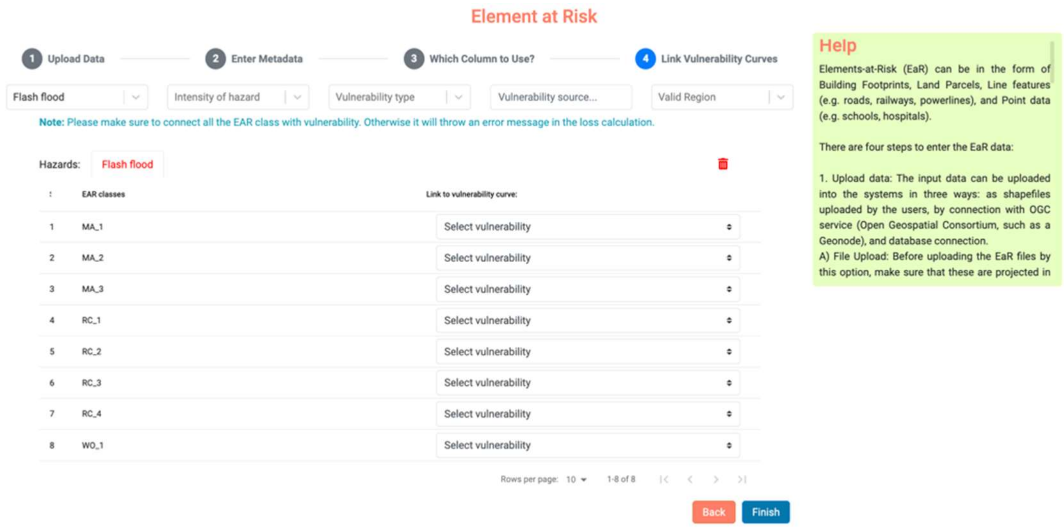

Figure 6.3.13: Link Elements-at-Risk with Vulnerability Curves

In this step, user needs to define the linkage with vulnerability. First, user needs to select the hazard type you are working with in the project from this drop-down menu. Here in the EAR class, you will see the categories that have been defined in the attribute table for classes column. For each class then you will be able to select the suitable vulnerability function from the drop-down list. These are all the functions that have been created within the system for your chosen hazard type (even outside your organization). If you wish to create a new function, you must do so from the Vulnerability under the Data Management tab. While you are making the selection, you will also be able to view the details of that vulnerability function. For the same element at risk, it is possible to make this connection of vulnerability function for multiple hazard type. For that you must

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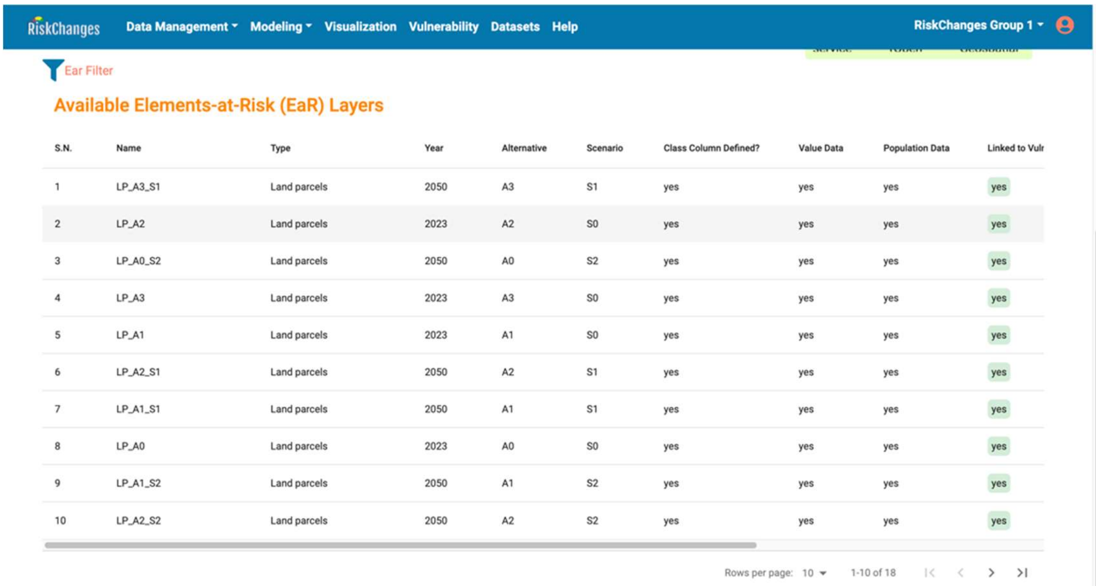
simply select a different hazard and repeat the same process. Once all the details are filled in, user can then click the submit button and see the new EaR data added to the table below.



S.N.	Name	Type	Year	Alternative	Scenario	Class Column Defined?	Value Data	Population Data	Linked to Vul
1	LP_A3_S1	Land parcels	2050	A3	S1	yes	yes	yes	yes
2	LP_A2	Land parcels	2023	A2	S0	yes	yes	yes	yes
3	LP_A0_S2	Land parcels	2050	A0	S2	yes	yes	yes	yes
4	LP_A3	Land parcels	2023	A3	S0	yes	yes	yes	yes
5	LP_A1	Land parcels	2023	A1	S0	yes	yes	yes	yes
6	LP_A2_S1	Land parcels	2050	A2	S1	yes	yes	yes	yes
7	LP_A1_S1	Land parcels	2050	A1	S1	yes	yes	yes	yes
8	LP_A0	Land parcels	2023	A0	S0	yes	yes	yes	yes
9	LP_A1_S2	Land parcels	2050	A1	S2	yes	yes	yes	yes
10	LP_A2_S2	Land parcels	2050	A2	S2	yes	yes	yes	yes

Figure 6.3.14: Uploaded Element at risk layers

This table shows the list of available EaR layers within the project. User can visualize it, edit the information, or delete it as per necessary.

Administrative Units

In this section, user can add the administrative unit layer and the data upload process will be completed in two steps (upload data and column connection). Step 1: Upload Data. A similar interface is made for uploading administrative units, using zipped shapefiles. In this step, a shapefile that represents the administrative data is uploaded in a zipped format. The administrative unit levels are divided into four classes which are national level, state/province level, district level and smaller administrative unit level. After adding the required field in this form, user can proceed to the column connection step. Step 2: Column Connection. 7In this step, user needs to select the column that represents the administrative unit's name. Then, user can click the submit button and see the new admin data added to the table below.

S.N.	Name	Admin Level	Admin Column	Uploaded Date	Updated Date	V...	E...	D...
1	Nocera_adm	County/district/equivalent (I...	ADMIN_UN_1	2023-05-20 09:09:51	2023-05-20 09:09:51			

Figure 6.3.15: Administrative Unit layers

This table shows the list of available administrative unit layers within the project. User can visualize it, edit the information, or delete it as per necessary.

Risk reduction Alternatives

This section allows user to define the risk reduction alternatives that are implemented and how it affects different components of risk assessment (i.e., Hazard, Element at Risk and Vulnerability). User can define the name of the alternative based on its kind for instance "relocation" make a code selection and select the parameters that would change in each risk component. In addition to this, user can also add brief description and the related document if available for the alternative that has been added. The code must be selected respectively later while adding the alternative parameter in Hazard and Element at Risk section. User can create a maximum of four alternatives within one project.

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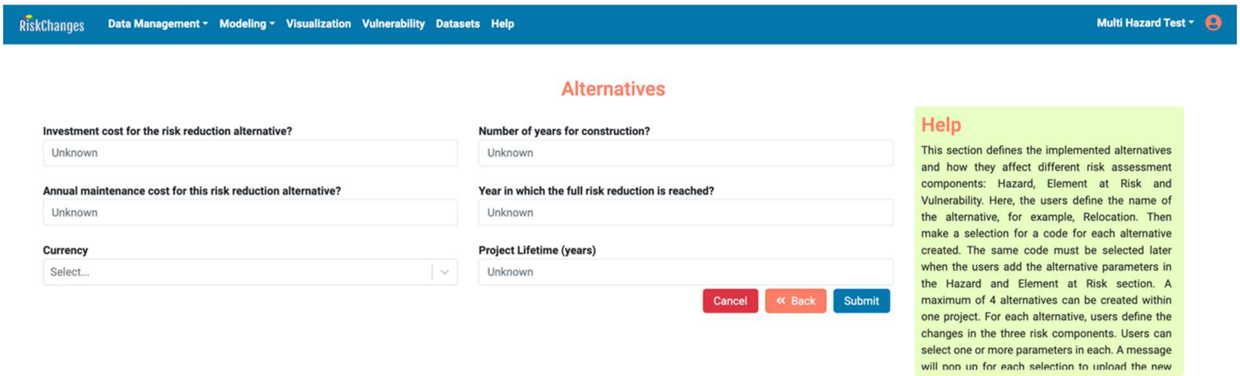

Figure 6.3.16: Risk reduction Alternative dataset upload window

User can add additional information of alternatives by clicking the 'More' button. This is mainly financial information for cost-benefit analysis. It is however not mandatory to add this detail. Once all the details are filled in, user can then click the submit button and see the new alternative added to the table below.

Available Risk Reduction Planning Alternatives

S.N.	Alternative code	Name	Changes Hazard	Changes Element ...	Changes Vulnerabi...	Uploaded Date	Updated Date	E...	D...
1	A2	A2	yes	yes	no	2023-05-20 09:09:51	2023-05-20 09:09:51		
2	A1	A1	yes	yes	no	2023-05-20 09:09:51	2023-05-20 09:09:51		
3	A3	A3	no	yes	no	2023-05-20 09:09:51	2023-05-20 09:09:51		

Rows per page: 10 1-3 of 3

Figure 6.3.17: Example of uploaded Risk Reduction planning alternatives

This table lists all the available risk reduction planning alternatives that have been defined within project. User can modify the details by clicking on "edit" button and delete the data if necessary.

Future Scenarios

8This section allows user to define the future scenarios that are implemented and how they affect different components of risk assessment (i.e., Hazard, Element at Risk and Vulnerability). User can define the name of the future scenario which can be based on its kind like Climate change, Land use change, Population change, make a code selection and select the parameters that would change in each risk component. In addition to this, user can also add a brief description and the related document if available for the scenarios that have been added. The code must be selected respectively later while adding the scenario parameters in Hazard and Element at Risk section. User can create a maximum of four scenarios within one project. Once all the details are filled in, user can then click the submit button and see the new scenario added to the table below.

Available Future Scenario

S.N.	Scenario Code	Name	Changes Hazard	Changes Element ...	Changes Vulnerabi...	Uploaded Date	Updated Date	E...	D...
1	S3	S3	yes	yes	no	2023-05-20 09:09:51	2023-05-20 09:09:51		
2	S2	S2	yes	yes	no	2023-05-20 09:09:51	2023-05-20 09:09:51		
3	S1	S1	yes	yes	no	2023-05-20 09:09:51	2023-05-20 09:09:51		

Rows per page: 10 1-3 of 3

Figure 6.3.18: Example of uploaded Future Scenarios

This table lists all the available future scenarios that have been defined within project. User can modify the details by clicking on "edit" button and delete the data if necessary.

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Vulnerability curves

A physical vulnerability curve database is openly accessible, and any user of the system will be able to view the functions uploaded by any organization without login credentials. The vulnerability values can be uploaded using provided spreadsheet templates. It consists of hazard intensity range, average and standard vulnerability values. These values can be obtained from vulnerability analysis of EAR which generates fragility curves and damage ratios. In absence of such curves, literature and expert opinions can also be used.

Download the vulnerability curve CSV template(1), CSV template(2)

	A	B	C	D
1	hazIntens	hazIntens	vulnAVG	vulnSTD
2	0.1	0.2	0.3	0.23
3	0.2	0.4	0.5	0.24
4	0.4	1	0.91	0.32

	A	B	C	D
1	0	0.1	0.2	0.2
2	0.1	0.2	0.3	0.23
3	0.2	0.4	0.5	0.24
4	0.4	1	0.91	0.32

Figure 6.3.19: Method to upload a Vulnerability dataset using an Excel file.

Once the values in excel template have been uploaded, user can assign the vulnerability name and vulnerability type (economic, physical or population). Information on hazard type and its intensity along with EAR type and class can be added. Different regions have different EAR types, so vulnerability values differ as well. User can also enter the source of the vulnerability curves and possible locations where these vulnerability curves can be used cautiously.

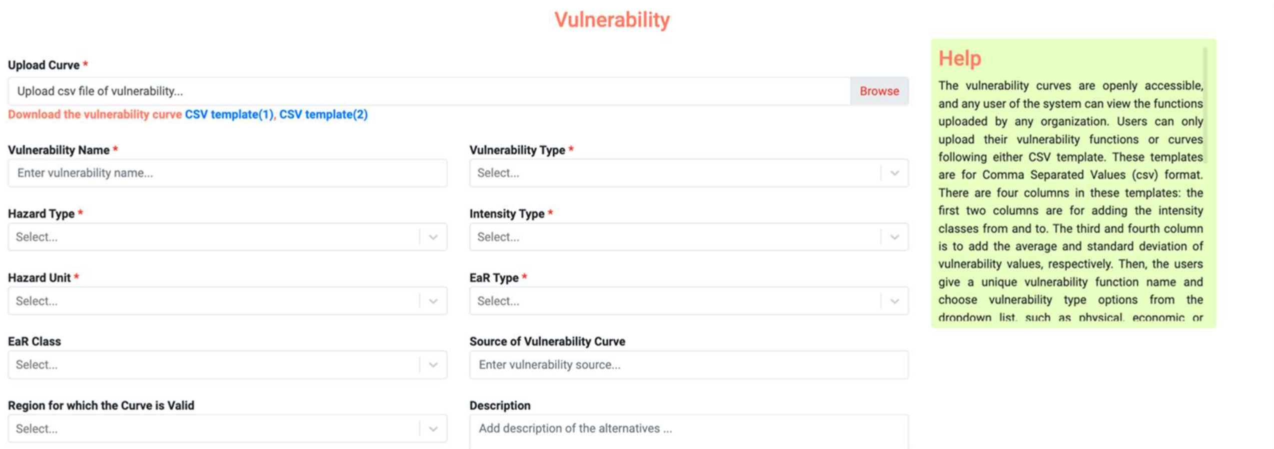

Figure 6.3.20: Vulnerability data upload form

Vulnerability filter

Available Vulnerability Curves

S.N.	Name of Vulnerability Curves	Type	Hazard Type	Hazard Intensity	EaR Risk Type	EaR Class	Uploaded Date	Updated Date	V...	E...	D...
1	test	Physical	Flash flood	Velocity	Building footprints	Masonry, two floors	2022-12-15 07:00:00	2023-04-11 14:28:35			
2	FL_DE_PH_Parkland	Physical	Flash flood	Height	Land parcels	undefined	2022-12-14 07:00:00	2023-04-11 14:28:35			
3	FL_DE_PH_Quarry	Physical	Flash flood	Height	Land parcels	undefined	2022-12-07 07:00:00	2023-04-11 14:28:35			
4	LS_SP_LP_PH_Openspace	Physical	Landslide	Susceptibility	Land parcels	undefined	2022-12-07 07:00:00	2023-04-11 14:28:35			
5	LS_SP_LP_PH_Industry	Physical	Landslide	Susceptibility	Land parcels	undefined	2022-12-07 07:00:00	2023-04-11 14:28:35			
6	LS_SP_LP_PH_Highway	Physical	Landslide	Susceptibility	Land parcels	undefined	2022-12-07 07:00:00	2023-04-11 14:28:35			
7	LS_SP_LP_PH_Grassland	Physical	Landslide	Susceptibility	Land parcels	undefined	2022-12-07 07:00:00	2023-04-11 14:28:35			
8	LS_SP_LP_PH_ForestP	Physical	Landslide	Susceptibility	Land parcels	undefined	2022-12-07 07:00:00	2023-04-11 14:28:35			
9	LS_SP_LP_PH_Culture	Physical	Landslide	Susceptibility	Land parcels	undefined	2022-12-07 07:00:00	2023-04-11 14:28:35			
10	LS_SP_LP_PH_Comm	Physical	Landslide	Susceptibility	Land parcels	undefined	2022-12-07 07:00:00	2023-04-11 14:28:35			

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Figure 6.3.21: Example of available Vulnerability Curves

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User can compare and export the vulnerability curves of desired EAR types with respect to the hazard.

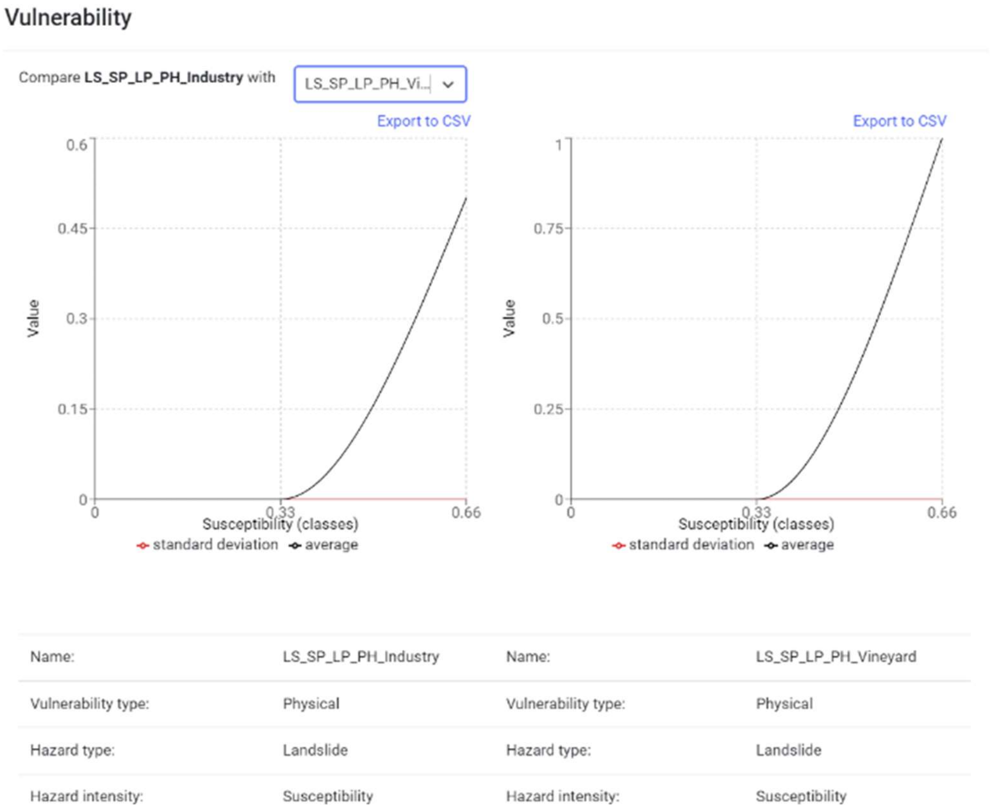

Figure 6.3.22: Examples of vulnerability curves

Outputs

The visualization component is the major output of the system which consists of layer navigation window (left panel), measure distance and area, split screen button and base layer switch button in top right corner in the first load and when user click the layer, map will be rendered, and map legend will be displayed in bottom right. Similarly, when user click the feature on map interface, feature information window will pop up in top right. Users can also filter and search for the uploaded and calculated layers using a filter button. In exposure, there is an additional function to query the exposed results as individual or aggregate, in absolute terms or relative terms, or custom selection of hazard class-EAR class combination. Querying functions shall be implemented in loss and risk in future.

Administrative Unit Layer

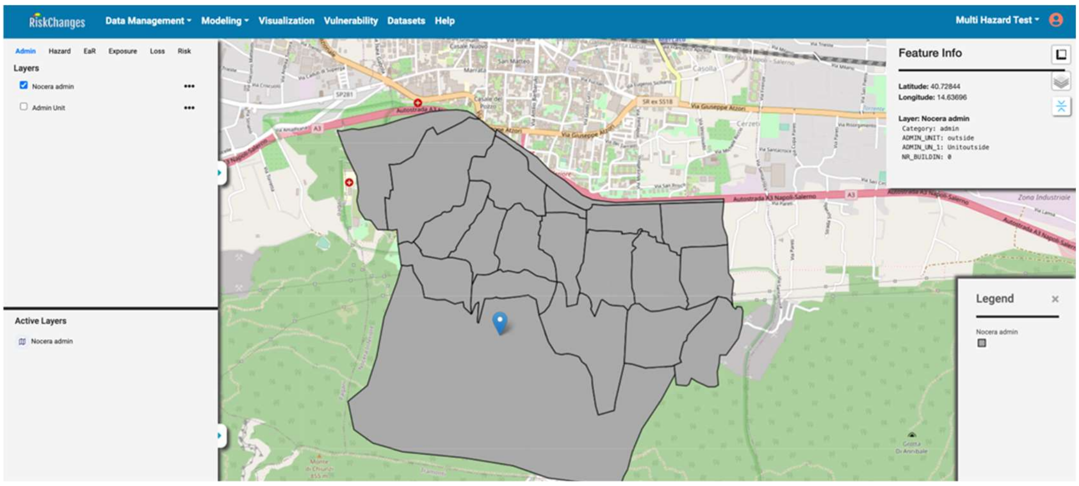

Figure 6.3.23: Administrative unit layer- output view

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This is the rendering of admin unit layer in the map interface. All the available admin layers are listed in the Layers section in layer navigation panel. When user checks the layer, it will be added in active layers section just below the Layers window. User can see the information of individual admin unit associated with it by clicking on the feature.

Hazard Layer display

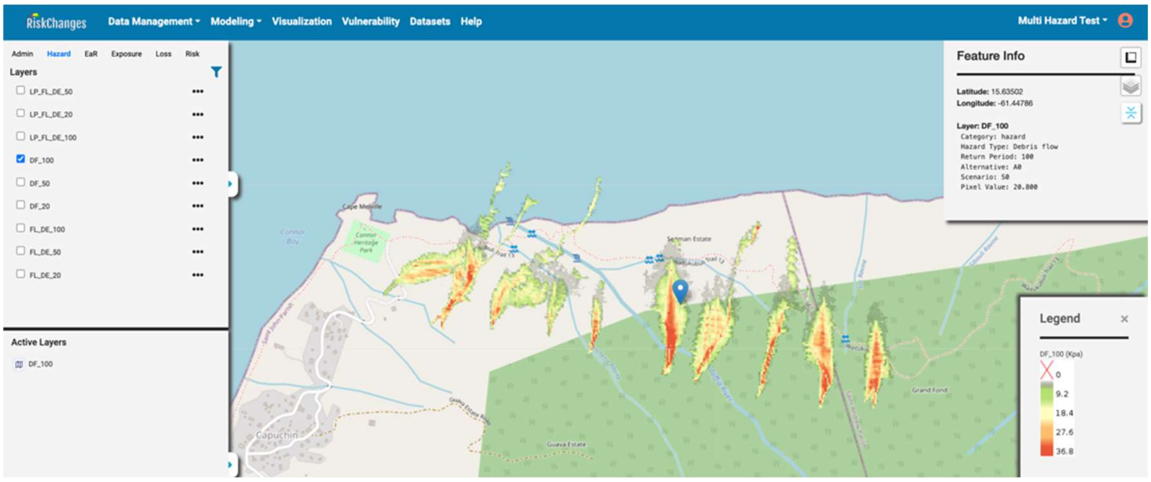

Figure 6.3.24: Hazard Layer - output view

This is the rendering of hazard layer (for example, debris flow with pressure impact as its intensity) in map interface with legend at the bottom right. In feature info window, the information related to pixel is displayed. Different hazard maps can be compared by using a split screen button as well.

Element at Risk Layer display

This is the rendering of Element at Risk layer (for example, land parcel map based on its functional use) in map interface with its legend. In feature info window, the information related to feature is displayed.

Exposure Layer

This is the rendering of calculated exposure layer in the map interface. Exposure map is the combination of hazard classes overlaid over EaR of different types. When user clicks on the feature, the details are shown in feature information window.

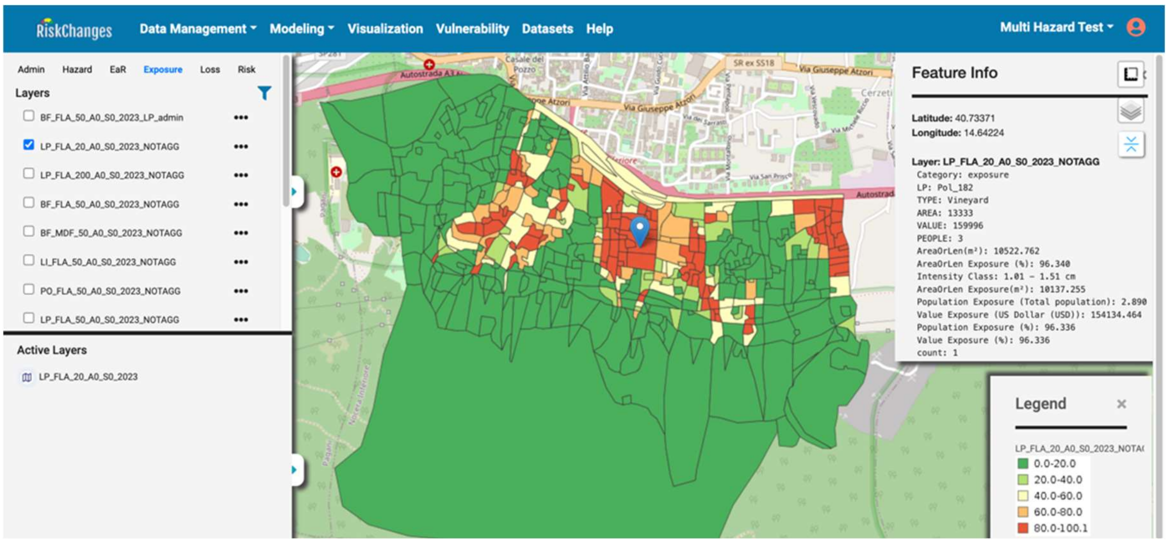

Figure 6.3.25: Exposure layer - output view

It consists of details like geometry (Area or Length) exposure, value exposure and population exposure in both absolute value and in percentage. Furthermore, the intensity class of hazard in which element is exposed can

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also be seen. Results can be queried and visualized based on exposed unit (either geometry or value or population), on absolute or relative terms and as a combination of specific hazard class and Ear type. The queried results can be downloaded as csv or shapefiles for further analysis in GIS software or Excel.

Exposure Query

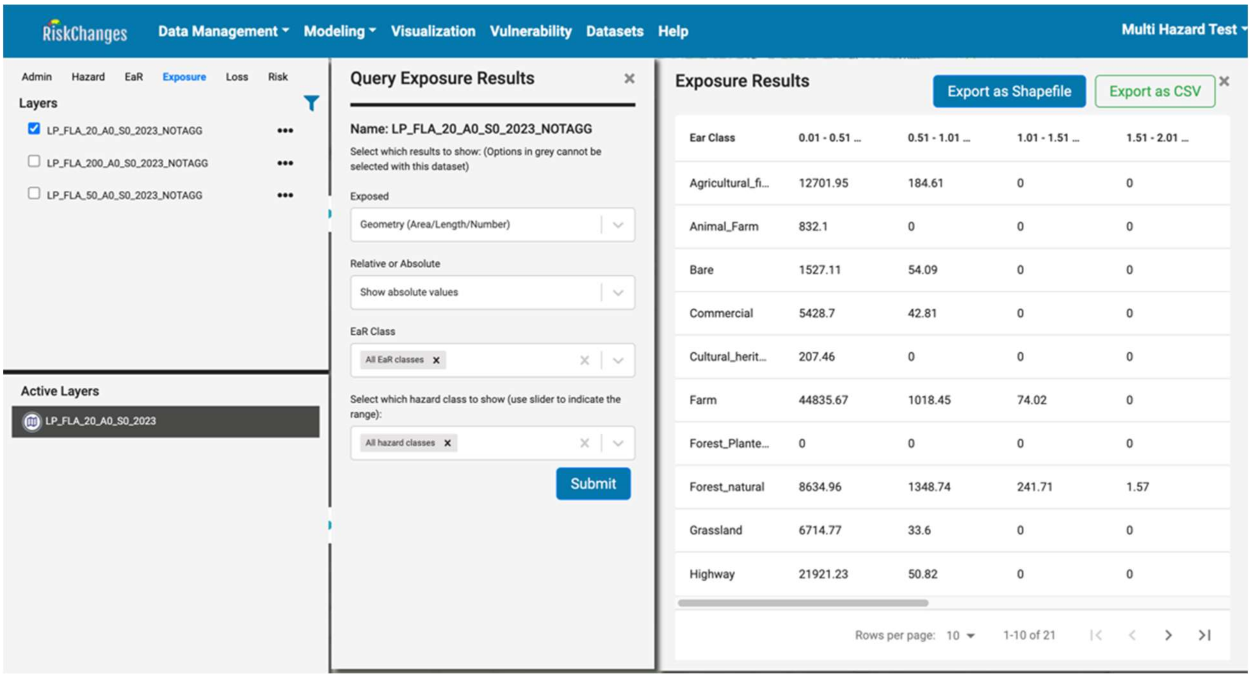

Figure 6.3.26: Example of a query on exposure data

In absolute terms, exposure results are shown in actual monetary values of exposed EaR or number of exposed population or exposed area. In relative terms, exposure results are shown as a proportion of total monetary values of exposed EaR or percentage of exposed population or exposed area.

Loss result display

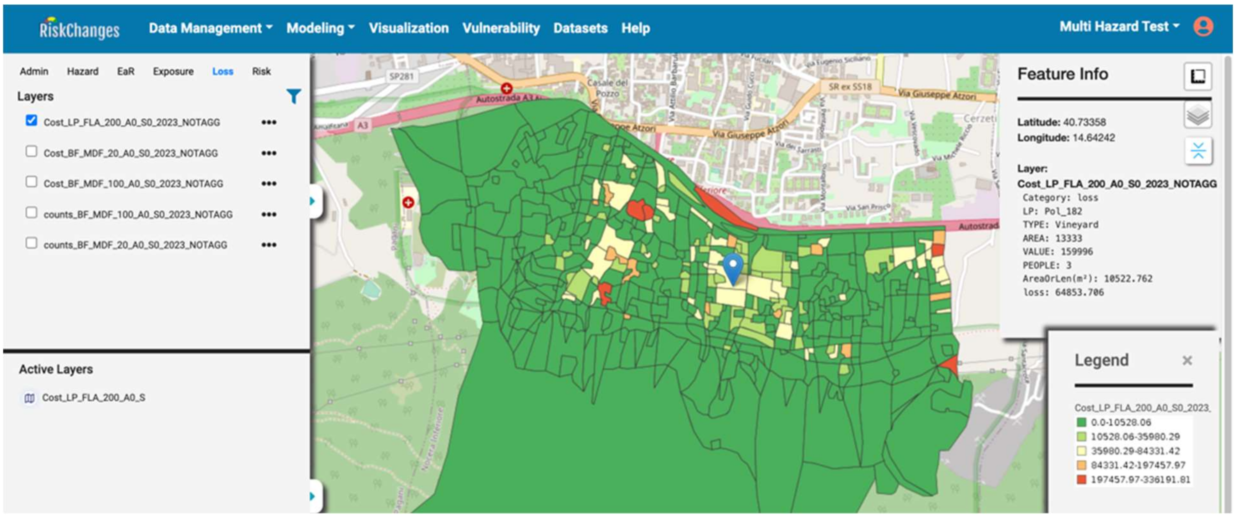

Figure 6.3.27: Loss results display

This is the rendering of calculated loss layer in the map interface. When user clicks on the feature, the details are shown in feature information window. The loss can be calculated based on geometry, value(cost), population and count based on the data available. The results can be shown based on individual EAR loss calculation or aggregated by admin units. The results can be downloaded as csv or shapefiles for further analysis in Excel or GIS software.

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Risk results display

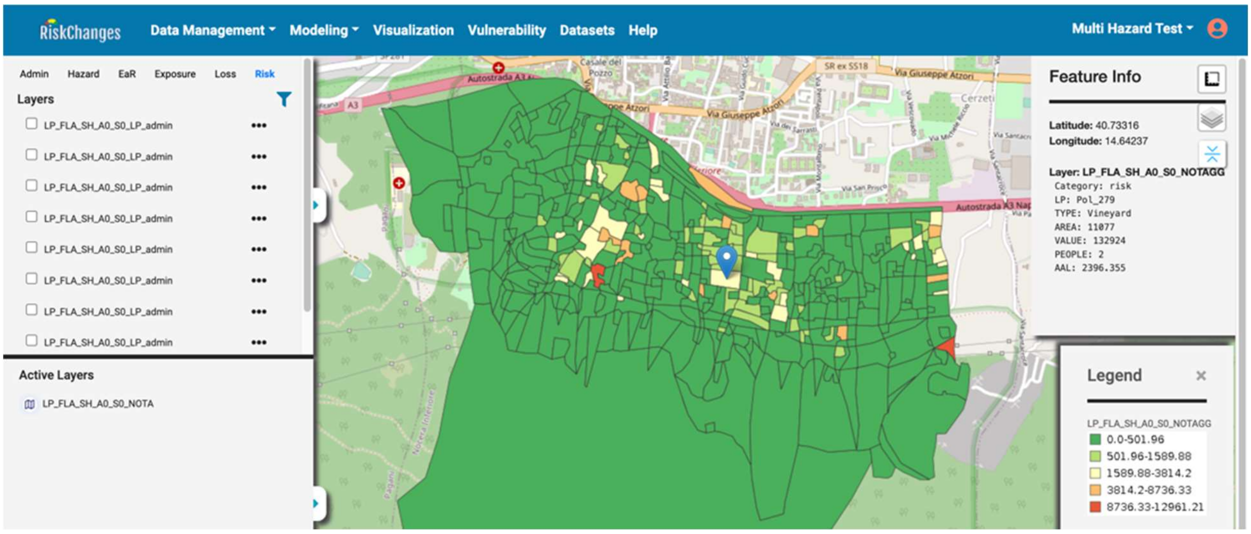

Figure 6.3.28: Risk results display

This is the rendering of calculated risk layer in the map interface. The risk is shown as Average Annual Loss (AAL) values. The AAL values can be shown for either individual hazard risk or multi-hazard risk in aggregated or non-aggregated. When user clicks on the feature, the details are shown in feature information window. The results can be downloaded as csv or shapefiles for further analysis in Excel or GIS software.

Information on the User Interface Design can be found in various sources [105] [106] [107]

[105] https://docs.google.com/presentation/d/1_q-qBZODvh9NeFax0yD-GXL3iKWuYwUG/edit#slide=id.p3
[106] https://docs.google.com/document/d/14FCTP582pj0lgULv4LCZX0DnCu-CArhJ/edi t
[107] https://docs.google.com/document/d/1gt25htnclR-HTeUcRMzAY0UXM9t_uiBz098-bLZ0ojE/edit

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6.4 Resilience indicator tool

With the RiskChanges component it will not be possible to quantify all the direct and indirect impacts of disaster events. Many of these components of impact chains can only be described in qualitative terms, or described using indicators or proxies. One of the least designed components of the PARATUS platform is the so-called Resilience Indicator Tool. The aim of this tool is to show which of the impacts (direct and/or indirect) is the most relevant for stakeholders to address. This could be for example:

- The blockage time of a transportation corridor (e.g. Brenner corridor) resulting from a compounding event (e.g. rain & sub zero temperatures) resulting in traffic accidents in multiple places, which leads to losses due to longer delivery times;
- Unpassable roads due to debris after a major earthquake (e.g. in Bucharest or Instanbul) leading to longer periods before people can be rescued from buildings, which leads to a higher number of casualties.
- Interrupted lifelines (e.g. communication, transportation) on and between Caribbean islands after the passing of a major hurricane or after a volcanic eruption, leading to multiple losses in terms of food shortage, tourism interruption etc.

In all these examples the impact of the compounding and multi-hazard events is determined by the resilience of the system (Dolan et al., 2016). Resilience is defined as “The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.[108]”. Resilience can be visualized and modelled as a triangle (See Figure 6.4.1), with time as x-axis, and a predefined quantity (such as the number of intact buildings, economic production, biodiversity etc.) as y-axis (Zobel and Khansa, 2014). The triangle represents the resilience as time to recovery multiplied by the losses, divided by half. An essential component in this is the recovery time, which depends on many factors, such as the level of preparedness, available resources, magnitude of the impact, external support etc. This can generally only be considered in terms of scenarios. Through the use of impact chains (with additional quantified information on the direct damages, indirect losses, and the timeline of the recovery, it is possible to develop such scenarios).

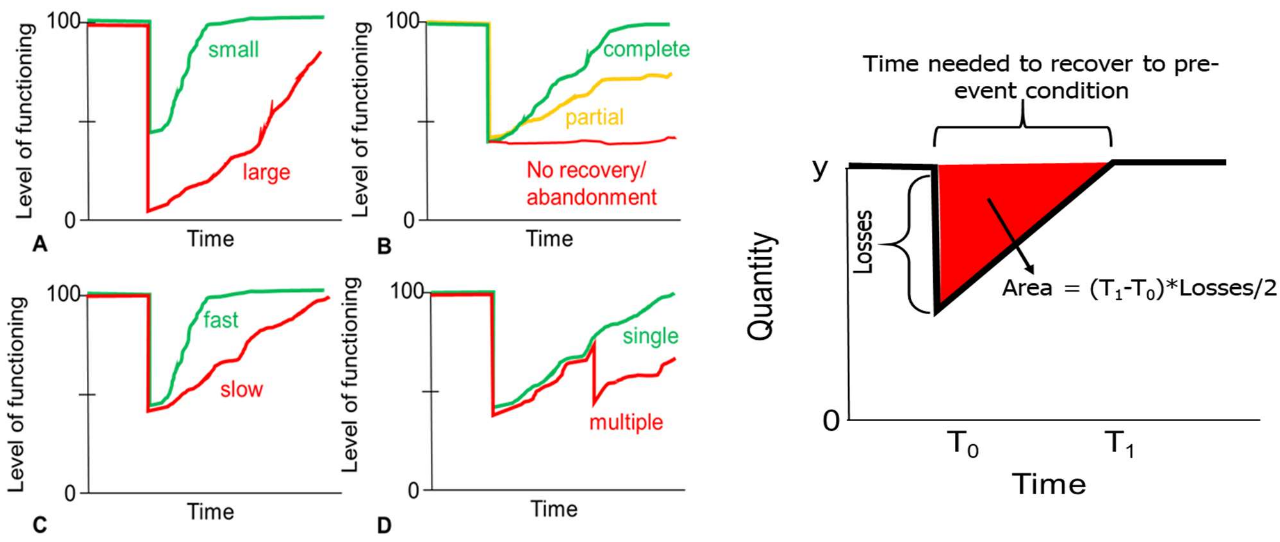

Figure 6.4.1: Resilience curve. Examples of differences in recovery and resilience. A: recovery from large or small impacts; B: complete, partial or no recovery after a disaster; C: fast or slow recovery; D: recovery from

[108] https://www.undrr.org/terminology/resilience

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multiple disaster events occurring in sequence. Right: Possible quantification of resilience (Zobel and Khansa, 2014)

We will develop a method where it will be possible to use the criteria analysis in two different ways.

Using indicator maps in combination with Spatial Multi-Criteria Evaluation (SMCE). One of the most known applications is the method that is known as INFORM Risk[109] where indicators for hazard and exposure, vulnerability and capacity are collected per administrative unit. Here we also want to add indicators that reflect the recovery and resilience components. The indicators can be collected for administrative units, or for different components of a system. This could be different sections of a transportation network, different sectors etc. Indicators are standardized and weighted using a multi-criteria evaluation method, such as AHP[110].

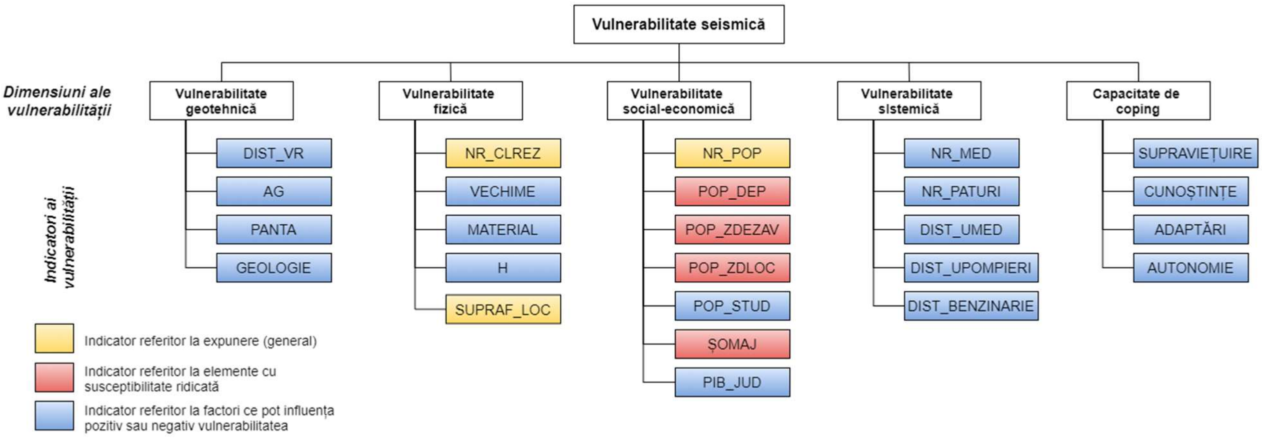

Figure 6.4.2: Example of the use of indicator-based approach for addressing different components of vulnerability (geotechnical, physical, socio-economic, systemic) and coping capacity for settlements in Romania (Albulescu et al., 2022)

Linking to impact chains. The other approach would be to develop indicators that would lead to a score for the impact components within the impact chains, by selecting indicator that would measure the severity of the relations leading to the impact components, their certainty, and the severity of the impact components themselves. This would not be a spatial multi-criteria evaluation as the impact chain component do not necessarily represent spatial units. Through this method we would be able to qualitatively describe the severity of the direct and indirect impacts in impact chains for those situations where we cannot quantify the impact or where we don't have the data to do that.

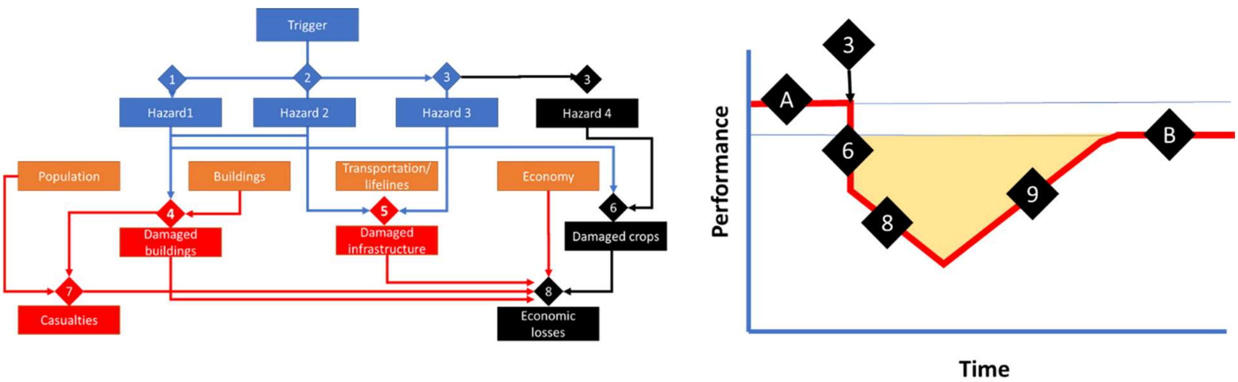

Figure 6.4.3: translating impact chains into resilience curves. A= performance before disaster; B= performance after disaster; A-B= long term effect; 3= Hazard; 6= Direct impact; 8= Indirect impact; 9 = Recovery

109 https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk
110 https://doi.org/10.1080/00401706.2021.1904744

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6.5 Scenario & Alternative definition tool

PARATUS will co-develop context-specific decision-making tools suitable for stakeholders in different sectors and risk governance settings. They will consider the specific needs of stakeholders (including especially vulnerable groups), incorporate the uncertainty of the scenarios, and compare different alternatives for risk reduction.

- **The Learning Labs** are a series of interactive and deeply participatory workshops to facilitate the co-creation of adaptation and DRR measures. This approach has been developed and tested by the Climate Centre and University of Cape Town in the FRACTAL[111] project - testing the City Learning Lab approach in 9 African cities. In *PARATUS* the Learning Lab approach will be used to facilitate deep stakeholder engagement with a range of stakeholders using an action research process. The Learning Labs will take place in the four case study sites and will actively draw on outputs of components 1 & 2.
- **Climate Risk Narratives.** Drawing on *PARATUS* results, the Learning Labs will also present a Climate Risk Narrative approach - allowing participants to explore different long term climate scenarios while assessing the possible future impact on a variety of sectors acknowledging the complexity of the challenges. This approach will allow participants to look at both short term adaptation options and long-term adaptation pathways.
- **Stress Testing.** The stress testing workshops will be integrated into the Learning Lab process and aims to support *PARATUS* partners across the various sectors in integrating climate-related risks in their projects and equip stakeholders with operational climate knowledge. These workshops address questions about what the hazards and climate projections (and uncertainties) are, what these mean for their project (impacts) and what can be done to reduce vulnerability (actions). It aims to move discussions from hazards to impacts to actions. The workshop consists of interactive components about the main concepts of climate risk and regional projections, a reflection on the potential impacts of climate hazards on their respective projects and planning and joint collaborative work on a predefined case study. This approach focuses on cross-sectoral learning through the exchange of challenges and solutions. Interaction, visualization, and engagement will be core focus points – drawing on the extensive experience of the Climate Centre in innovative online facilitation and creative learning[112].

With the PARATUS project we aim to develop the following tools:

- **A risk reduction alternative library:** Local governments can select from a range of structural and non-structural risk mitigation measures. This module will build a library of such measures, linked to specific hazard types, and classifying them into main groups, such as engineering measures, nature-based solutions, exposure reduction options, etc. This module will help local governments to select combinations of mitigation options that are most suitable for their situation. These will then have to be translated into changes in exposure and vulnerability.
- **Future scenario translation tool:** How to translate climate scenarios to local changes in hazard frequency, intensity, and interactions. For floods this could be done using link to climate modelling results and link this to FastFlood. Also link to population and land use scenarios according to different SSPS. Calculating changes in return periods would be another option: when calculating return period per pixel (rainfall intensity per pixel for return periods). CIMP5 dataset (45 models), code is already in GGE at 30*30 km at the equator.

[111] https://www.fractal.org.za/wp-content/uploads/2020/03/IS1-FRACTAL-city-learning-lab-approach.pdf

[112] https://www.climatecentre.org/priority_areas/innovation/

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6.6 Quantifying Multi-Hazard Impact

Section 6.6. presents an important overview of methodological and practical challenges relevant to the analysis, assessment, and management of catastrophic multi-hazard (dependent, cascading, compound) systemic risks. Systemic risks and losses in interdependent systems can be defined as the risks of a subsystem (a part of the system) threatening the sustainable performance of other systems and achievement of their security goals, e.g., food- energy-water-environmental (FEWES) security.

The main challenge is the development of a multi-hazard impact chain analyses and assessment service based on past observations and current conditions, and its application for modelling the impact under future socio-economic, technological, environmental scenarios, with a special focus on adequately incorporating and representing uncertainties. Uncertainty propagates in the various stages of the risk assessment, from single to multi-hazard assessment, exposure analysis, vulnerability assessment, direct and indirect loss estimation.

The challenge is not only to identify and quantitatively and qualitatively analyse those uncertainties, but also to present and convey them in a way that is comprehendible and meaningful to stakeholders. A specific challenge in this context is translating regional climate scenarios into locally usable ones that indicate changes in the frequency of extreme events and using them in multi-hazard models. Global trends (e.g., hyperconnected (internet, financial, communication, transport) systems, national and cross-border migration, etc.) should be translated into local effects on exposure and vulnerability (i.e., with the assessment of socio-economic development, focusing on disadvantaged groups, usage of the territory and properties and maintenance of the built environment including historical sites).

The PARATUS project open-source PARATUS SIMULATION SERVICE platform for dynamic risk assessment allows to analyse and evaluate multi-hazard impact chains, risk reduction measures, and disaster response scenarios in the light of systemic exposure, vulnerabilities, and uncertainties. To develop such a platform, PARATUS collects, analyses and compiles the available evidence and data on historical disaster events, augment historical disaster databases with hazard interactions and sectorial impacts, catastrophe modelling results, socio-economic and demographic projections/scenarios, and exploit remote sensing data.

Building on these insights, the PARATUS SIMULATION SERVICE will incorporate novel exposure, vulnerability and risk analysis methods and tools such as, for example, The Dynamic Risk Scenarios (DRS) tool, that enable systemic risk assessment across sectors (e.g., households, infrastructure, transportation, communication, etc.), geographic settings (e.g., islands, mountains, megacities) and temporal resolutions (current and future hazard patterns, exposure, and vulnerability scenarios). These methods will be used to analyse risk changes across space and time and to develop new exposure and vulnerability scenarios and risk mitigation and adaptation options together with stakeholders, using innovative serious games and social simulations.

In what follows, we discuss methods and approaches relevant for spatially and temporally explicit integrated decision support systems (DSS) to be integrated into the PARATUS SIMULATION SERVICE platform. The DSS links various sub-models of the involved stakeholders, (reduced) stochastic catastrophe scenario generator models and DRS tools, stochastic optimization solution procedure for the design of robust feasible combinations of interdependent ex-ante and ex-post risk reduction and coping measures. A proper robust combination of ex-ante strategic mitigation and ex-post operational adaptive measures can reduce the post-event burden, relax the tightness in various systemic supply-demand relations and lessen chances of critical imbalances, exceedances of vital thresholds, which could otherwise lead to systemic failures with potential catastrophic cascading consequences and the lack of securities. The occurrence of a disaster (catastrophe losses) for each agent is often associated with the likelihood of some processes abruptly passing individual "vital" thresholds. The analysis and the design of risk management strategies therefore requires the introduction and regulation of the safety constraints of the agents within integrated DSSs and catastrophe management models. The safety constraints allow to control the actions within admissible norms, say, land transformation, environmental degradation, pollution, wellbeing, historical values, and cultural preferences restrict the growth of the wealth in risk prone areas. Evaluation of ex-ante structural mitigation measures requires proper approaches to discounting (Ermoliev et al., 2010). The need for the coexistence of both, ex-ante and ex-post, measures is dictated by the potential disastrous losses. This decision-making framework

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implies that the capacity for the adaptive ex-post decision making must be created in an ex-ante manner. In the discussed approaches, specific attention is paid to the modelling of endogenous extreme events (scenarios) and unknown catastrophic risks, i.e., events and risks induced by new decisions for the analysis of which there is no real observations available. Properly designed robust insurance programs, for example, based on an PPP and engaging various stakeholders can be an essential part of the risk management. Such a program can (i) share the risk across actors, locations and time and assure funds available for loss compensation, (ii) induce investments into structural ex-ante mitigation measures, (iii) increase public awareness of disaster risks, (iv) improve land use safety, (v) contribute to the fulfilment of FEWE security goals. A public-private partnership (PPP) can comprise of a financial layer of contributions from property owners (households and businesses), a layer of private insurance, a risk transfer layer through reinsurance or/and catastrophe bonds, and finally a layer of government contribution in a form of a cap or reinsurances of extreme losses. Next section describes these challenges with more details.

6.6.1 Disaster Support System for integrated and financially effective DRM

Catastrophes produce severe consequences, characterized by mutually dependent in space and time socio-economic and environmental impacts, structural and agricultural damages, losses of human lives, failures in energy and water production and supply systems, etc. The multivariate distribution of these losses is in general analytically intractable due to systemic interdependencies and interactions among various systems and policies. The distribution depends on the clustering of values and activities in the region and the patterns of catastrophes. Besides, it may also depend strongly on policy variables. For example, a dam fundamentally modifies the flood conditions downstream and along the site. This creates favourable conditions for new developments, infrastructure investments, land-use transformations, and insurance activities. On the other hand, a failure of the dam may lead to rare but more devastating losses in the protected area. Such interdependencies of decisions and risks restrict the straightforward “one-by-one” evaluations of feasible risk management decisions and regional development strategies. Robust combinations of feasible ex-ante and ex-post structural and financial strategic and adaptive measures must be identified to decrease vulnerability and achieve sustainable developments.

In what follows we discuss several important components of **an integrated multi-hazard disaster risk decision-support system (DSS)** being developed and applied by PARATUS project in a number of case studies. The DSS is a part of the PARATUS SIMULATION SERVICE platform.

The integrated DSS aims to aid communities in integrated disaster risk management (DRM) and disaster risk reduction (DRR). This is done through the evaluation and the decision support for the implementation of robust combinations of ex-ante mitigation and ex-post adaptation financial and structural measures, geared towards the fulfilment of various security goals. For the development of the DSS we use specific (two-stage or multi-stage) stochastic optimization methods and approaches to the evaluation of the ex-ante structural mitigation measures. These methods are based on the notion of safety and security constraints, which we introduce and discuss, also in relation to the relevant public risk perception, equity, and ethical considerations. The one-by-one evaluation of the ex-ante and ex-post measures can run into infinite number of feasible combinations. It can be also misleading and lead to even high catastrophic losses.

The DSS enables the design of proper spatially and temporally explicit integrated catastrophe risk analysis and management modelling frameworks (Ermolieva et al., 2023; Ermolieva and Komendantova et al., 2023; Ermoliev et al., 2022, 2021) linking various sub models:

- Sub models of the involved stakeholders (e.g., land use and agriculture, energy, water sector models),
- Stochastic catastrophe models and tools for future scenario generators (Dynamic Risk Scenarios (DRS) tool), and solution (stochastic optimization) procedures to design robust combinations of interdependent ex-ante and ex-post risk reduction and coping measures.

The holistic design of the DSS considers several aspects, listed here, and expanded and complemented in the following subchapters:

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- **Multi-agent multi-criteria analysis of disasters**: Analysis of catastrophe losses and feasible mitigation and adaptation measures is a multi-disciplinary task, which requires to account for goals and constraints of the involved agents, frequency and intensity of location-specific hazards, stock and ownership of capital at risk, infrastructure characteristics, economic activities and interdependencies in the region, feasible decisions, FEWES goals, and different measures (in particular, engineering, financial) of vulnerability.
- **Catastrophe models and tools for future loss scenario generation and analysis**: The efforts to estimate potential future catastrophe losses require the development of the so-called stochastic catastrophe models (catastrophe scenario generators). The aim of such models is to generate potential scenarios (samples) of mutually dependent losses for a given vector of feasible ex-ante and ex-post policy variables and elements at risk. When there is a lack of historical data, such models can simulate and even estimate multivariate distributions of losses and gains for different concerned agents, e.g., locations, households, industries, insurers, governments. This is critically important in the case of rare events or new policies that have never been implemented in practice. The endogeneity of systemic catastrophic losses on decisions calls for the design of integrated approaches combining stochastic catastrophe models with specific decision support procedures.
- **Integrated multi-disaster multi-agent multi-criteria DSS**: The integrated DSS includes and links together the necessary data and models, representing the multitude of the involved agents and their activities (multi-agent accounting systems) in the exposed region (regions), e.g., energy, agricultural, water sectors, infrastructures, economic, financial, insurance, households' activities, etc. Such a DSS (combining catastrophe generators with interlinked sectoral models) allows to map catastrophe scenarios into direct and indirect impacts, i.e., losses and gains of concerned agents (governments, consumers, producers, households, industries, farms, firms, insurers, investors, etc.). In other words, the DSS investigates the exposure and the vulnerability of the involved agents as a function of potentially implemented strategies. This can tailor the decisions accounting for complex interplay between possible spatially detailed hazard patters (earthquake intensities, the rainfall patterns, floods, windstorms, heat waves, etc.), structural measures in place, towards safety and stability of agents.
- **Spatio-temporal aspects**: The DSS addresses the spatial and temporal aspects of disasters patterns and management as catastrophes have different spatial and temporal characteristics and affect locations quite differently, directly, and indirectly. For example, the location of properties or infrastructure with respect to the centre of an earthquake is an extremely important piece of information. Deforestation at a particular location modifies the flood conditions only downstream and affects losses and respective risk management decisions, e.g., flood protection measures and insurance claims, only from specific locations. In other words, management of complex interdependencies among catastrophic risks, losses and decisions is possible only within a geographically explicit framework.

6.6.2 Feasible risk reduction measures

The development of the DSS, among other critical issues, requires the identification of feasible mitigation, adaptation, response, preparedness, and recovery measures, which can aid in dealing with risks of all kinds, including multi-hazard compound dependent systemic risks. These measures can be classified as structural and financial ex-ante and ex-post risk mitigation, adaptation and risk sharing strategies. Also, the measures can be distinguished according to their costs, horizons of the implementation, pay-back periods, reversibility. For example, a multipurpose water reservoir (to protect against floods, supply water to agriculture, energy, industrial systems) must be designed in view of possible climate change and future water availability. If the water retention area is too big, there may be no sufficient water to fill it up in the future. To build reservoir is a very costly decision, the investments can be lost, land use transformation can be irreversible, environmental damage immense, etc. Instead of a water reservoir, the decision could be to build a system of channels in combination with relocation of activities.

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Mitigation strongly depends on **structural measures** in place. Structural measures are any physical construction to reduce or avoid possible impacts of disasters, or the application of engineering techniques or technology to achieve hazard resistance and resilience in structures or systems. Structural measures can be identified as long-term, rather costly, with long implementation horizons and pay-back periods. Although costly, structural measures are vital for increasing societal robustness, sustainability, and resilience to catastrophic events. Their role is to consider and address the issues associated with structural resilience and structural adaptation focusing on preparation to withstand event scenarios, quickly recover, bear minimal losses, etc[113].

Depending on the hazard risk (earthquake, heavy precipitation, windstorm, heat wave) structural measures can be, e.g., retrofitting of buildings to better withstand earthquake shaking; construction of dams, dikes, water retention areas and channels to protect against overtopping and/or flooding; policy of a better land-use planning to preserve forests protecting against hurricanes and strong winds; discourage building in areas prone to catastrophes, etc.

Structural measures reshape the risks. On the one hand, the measures can induce additional benefits, for example, additional developments. On the other hand, without proper evaluation, the measures can transform the risks and make them more severe and compound. For example, dams and dikes are built to provide protection from floods, but they also create a possibility of rare high consequences floods from a dam or dike break. If not managed properly, e.g., due to the lack of proper evaluations and maintenance, dam failure can induce catastrophic floods causing property and human losses. Alternative to a dam, a water retention area or a system of channels can be more costly measures, however their failure would lead to less losses than the dam failure.

In this situation, the important questions to address with the DSS are:

- What risk is better? What is the optimal and robust combination of structural (and financial) measures?
- How much of possible losses can be prevented strategically ex-ante and how much can be managed adaptively ex-post?

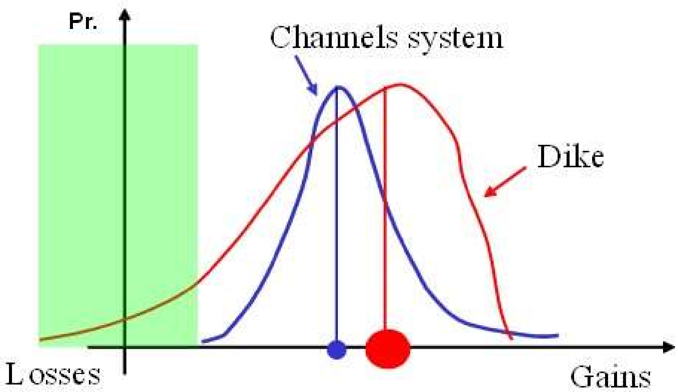

Figure 6.6.1: Loss distribution dependents on policies regarding dike or channel flood protection system: what risk is better? A dike can protect larger region and stimulate economic growth nearby, however if it breaks, the losses can be much heavier than from a disaster. Channel system can inspire less growth and would result in less average benefits; however, it is safer in the sense that it cannot cause extreme losses as in case of a dike break.

Financial measures: The DSS will help to design robust financial measures for multi-hazard risk management. The financial management of catastrophe risks (through insurance, reinsurance, at bonds, credits, various types of catastrophe funds) presents an important public policy challenge for governments across the world[114].

[113] https://www.istructe.org/resources/resilience/
[114] https://www.oecd.org/finance/disaster-risk-financing.htm

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The financial management can be accomplished through public, private, or various combinations of public-private partnership (PPP) schemes and financial markets. Insurance companies accumulate funds through the collection of premiums to create reserves for paying out future losses. Depending on the potential future risk scenarios (designed by PARATUS tools), insurance companies can study optimal policies on their premiums and coverage in risk exposed regions. Transferring some part of the losses to international reinsurance and capital markets can diversify the risk of insurance companies or mutual funds, increase their solvency, and reduce the impact of disaster losses on local, regional, and also national economies. For example, 95% of insured losses incurred as a result of the Maule earthquake in Chile in 2010 were reinsured in international markets (Aon Benfield, 2011), which likely reduced the overall level of economic disruption from what was one of the largest ever recorded earthquake events.

If and where insurance premiums are risk-based (and risk reduction is rewarded with lower insurance premiums), insurance can also provide an important incentive for ex ante risk mitigation actions which could reduce the overall level of damage from major earthquake events.

In what follows we discuss essential differences between insuring traditional independent frequent risks and dependent systemic rare-high impact risks. These differences are being accounted for in the PARATUS project modelling tools.

Insuring traditional risks

Traditional insurance deals with well-defined frequent independent risks. For example, automobile and life insurance are types of insurance where decisions on premiums, estimates of insolvency and possible losses are calculated using rich data bases collected over long periods.

Traditionally insurance companies operate only with what is called "pure risk", which must satisfy certain conditions (Daykin et al., 1994):

- The risk must be predictable. That means there should exist sufficient data to permit actuaries to predict the number and average size of insured losses for a given period.
- Each risk must be measurable.
- The premium charged on the risk must be low enough to attract a sufficient number of insured people, yet high enough to support the numbers of probable losses.
- The risk must be free of any potential catastrophe that could produce loss in excess of the ability of the insurer to respond.
- Homogeneous units must be independently exposed to loss. That is, a loss of one should not lead to a loss of another.

The existing insurance risk theory gives reliable results for dealing with such risks.

Catastrophe risk insurance

Insurers are currently concerned with the possibility of claims even higher than already experienced due to increasing losses from dependent catastrophic risks. The principal problem in ensuring catastrophic risks is insufficient historical data for predicting events at any location, although rich data may exist on their occurrence and magnitude on an aggregated (say regional) level. Potential damages in a particular location may be unlike anything that has been experienced in the past. Catastrophes produce highly correlated damages and claims, which depend on the region of occurrence, coverages at different locations, mitigation measures, reinsurance agreements and so on. The long-term stability of an insurance company dealing with catastrophe risks depends on the risk portfolio, type of coverages, distribution of claims, volumes of premiums, reinsurance contracts, financial market, credits, mitigation measures.

Robust insurance programs

As catastrophe risks grow worldwide, the design of a robust insurance program to deal with dependent catastrophic risks can be based on a public-private partnership (PPP) and engaging various stakeholders. The robust insurance program is a vital instrument in the risk management. A well-designed catastrophe risk

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insurance program will: (i) spread the risk across actors, locations and time and assures funds available for loss compensation, (ii) increase public awareness of disaster risks, (iii) lead to price discounts which reflect capitalized risks, (iv) promote damage mitigation measures, and (v) improve land use efficiency. A PPP may assume, for example, a financial layer of contributions from property owners (households and businesses), a layer of private insurance, a risk transfer layer through reinsurance or/and catastrophe bonds, and finally a layer of government contribution in a form of a cap or reinsurances of extreme losses. This collective effort involving multiple stakeholders requires the analysis of their mutually dependent risk exposures. For example, if an insurer wants to decrease the chances of bankruptcy which may happen if they face a loss greater than a certain level, they may decrease the chances by imposing higher premiums or decreasing coverage, take reinsurance or buy a catastrophe bond. The burden of losses is shifted away from the insurer but may be unevenly redistributed among other stakeholders, i.e., individuals, government, reinsurance companies, and lead to their instability or ruin.

Thus, the success of a loss-sharing program depends on the mutual stability and safety criteria of the involved heterogeneous stakeholders as well as the interplay with other existing and feasible ex-ante and ex-post structural and financial measures.

6.6.3 Evaluation of structural measures

In the integrated decision support system for dealing with dependent catastrophic risks, there are several aspects related to the evaluation of structural (critical infrastructure) measures, their "robust" combinations (CETS 1985; Jansen 1988), and secure functioning. First, of course, these are the engineering considerations when constructing the infrastructure with specific safety requirements (Bowles 2007; Bowles 2001; IAEA 1992). The use of the safety requirements (or constraints) is a rather standard approach for coping with risks in nuclear industries, dams' construction, insurance, finance (Ermolieva et al. Ermoliev et al., 1999-2021; Amendola et al.). For example, the safety regulations of nuclear plants assume that the violation of safety constraints may occur only once in 10^7 years (IAEA 1992).

Equally, there are many non-engineering aspects to influence the evaluation of structural projects, that require more detailed investigation and research on public perception, risk communication, socio-economic data, and processes in order to provide reliable advice. This relates to the so-called equity and ethical considerations, whereby the concerned parties are those who evaluate the projects, pay for them, and those who would be primarily harmed if the infrastructure is not in place or if it fails.

There is an essential dilemma which stems from the following. A "critical" structural (infrastructure) measure is designed to protect against and withstand a specific return period event, for example probable maximum flood (PMF) or "maximum limit level of risk" (Bowles 2007; Bowles 2001; IAEA 1992) criterion, which have become rather standard criteria for flood protection of major dams over the past decades (CETS 1985; Jansen 1988). However, the PMF is, first, a hypothetical flood based upon a set of assumptions. The calculation of the PMF is based on a combination of facts, theory, and professional expert judgments. Alternative groups of experts may arrive at different evaluations (CETS 1985; Jansen 1988). Therefore, the precise analysis and prescription of related measures are impossible. There are not always available and sufficient data and evidence to support the selection of appropriate probabilities, in particular, for PMF.

In this situation of large uncertainty and risks, the problem faced (by the evaluators of the project, designers of the measure, investors, governments, owners, households) is to determine how much investments, protection and maintenance should be provided to the measure considering that rare but high impact event can but may not occur during the prescribed "life" of the measure (dam). How to explain to the stakeholders (public) that the extremely costly infrastructure project may not bring complete safety? The reference events (such as PMF) are usually described as the very improbable event for which there is almost no chances to happen. Floods, however, happen. The objective of the risk reduction and management activities is to reduce any risks to acceptable levels (safety constraints and/or norms) through a set of various feasible structural and financial risk mitigation, adaptation, and sharing measures rather than through only one structural measure. It is impossible to provide absolute safety against all hazards.

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Evaluation of the risk coping measures can be subdivided into three broad categories: risk reduction (loss reduction), economic efficiency, and equity or ethics. Risk reduction aims at complete or partial (within acceptable level) protection against losses, economic objective seeks to maximize benefits over costs, while equity objectives seek to find a balance of expenditures bared by the investors, governments, infrastructure owners (for dams construction and reinforcements) and the other parties, namely, those who may benefit from the infrastructure and those who would be primarily harmed by the infrastructure if not in place or it fails. Building-up public understanding and perception of the catastrophic dependent risks requires proper approaches as the public may have different than technical or economic criteria of safeness.

Investments into new and reinforcement of old structural measures can be effectively supplemented by insurance (robust insurance schemers), which provides an ex-ante financial solution to cover or transfer the losses further to financial markets. Also, the need for mutual sharing of the risks calls for the cooperation between the agents and motivates early investments into the structural risk mitigation. In this case, individual involvement of each agent in the loss sharing program can be analysed with the DSS based on their individual and joint (systemic risks) exposure and safety constraints. The analysis of the exposures and the dependencies of exposures on newly implemented strategies is possibly only with model-based approaches combining generators of stochastic scenarios of potential catastrophes jointly with goals and constraints of the agents (including the dam owners, e.g., government).

6.6.4 Cooperation between stakeholders, safety constraints and endogenous discounting

High potential compound (systemic, dependent) impacts from natural hazards in combination with infrastructure failures (e.g., dam breaks, floods, failures of electricity networks) call for the cooperation of various agents such as governments, insurers, investors, and individuals that must be represented in the DSS. The issues of ethics relate to possible disagreements between the agents, their goals, constraints, and the level of their individual and joint involvement in risk management. These primarily stem from the individual unique assumptions about the facts associated with natural hazards, potential systemic risks and losses, the lack of knowledge and perception of structural measures (building retrofitting, channels, dams) as measures that are on the one hand costly and can be unnecessary if the event does not happen; on the other hand, the structural measures can be of high economic value and protect against catastrophic consequences.

6.6.5 Vital thresholds and safety constraints

The occurrence of a disaster (catastrophe losses) for each agent is often associated with the likelihood of some processes abruptly passing individual “vital” thresholds. For example, an insurer can become insolvent if a catastrophe claims exceed accumulated risk reserve, i.e., capital reserve to cover the claims. The analysis and design of risk management strategies therefore requires the introduction and regulation of the safety constraints of the agents within integrated DSSs and catastrophe risk analysis and management (CRAMM) models. For example, for the insurance business, the vital risk process is defined by flows of premiums and claims, which should be in balance. Critical thresholds or imbalances are defined by insolvency constraints. A similar situation arises in the control of environmental targets, in private incomes and losses, in the design of disaster management programs (Ermoliev and Hordijk 2003; Ermoliev and von Winterfeldt 2012; Ermolieva and Filatova et al., 2016; Ermoliev and Robinson, et al., 2018; Ermolieva et al., 2023; Ermolieva, Komendantova et al., 2023).

The ethical question regarding structural measures (water retention areas, channels, dams, bridges, roads, etc.) concerns not only economic evaluation of the associated risks (risk reshaping), benefits and costs. It also relates to human and environmental values, which are often difficult to be appraised in monetary terms. The safety constraints allow to control the actions within admissible norms, say, land transformation, environmental degradation, pollution, wellbeing, historical values, and cultural preferences restrict the growth of the wealth in risk prone areas.

Therefore, in the DSS model the ethical issues can be resolved by evaluating and introducing the overall safety constraints coherent with spatio-temporal goals, constraints, and indicators of involved agents - whether these are households, farmers, governments, investors, insurers, businesses, producers, consumers, suppliers of

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water and energy, those living downstream of a large dam, or and insurance covering the losses. The proper representation of safety constraints is a crucial aspect. Catastrophic losses often have multi-modal distributions and therefore the use of standard mean value indicators (e.g., expected costs and profits) can be dramatically misleading.

6.6.6 Traditional discounting and NPV

One of the fundamental parameters in the traditional evaluation of long-term infrastructure projects protecting against hazards is the discount rate (; Ramsey 1928; Weitzman 1999). In particular, the social discount rate reflects the level to which we discount the value of future generations' well-being in relation to our own. A lower discount rate emphasizes the role of distant costs and benefits. The flat discount rate of 5-6% traditionally used in projects evaluation (Bowles 2001, 2007; CETS 1985, Jansen) orients the analysis on a 20-30-year time horizon. Meanwhile, the explicit treatment of a potential 200-year disaster would require at least the discount rate of 0.5% instead of 5%. Otherwise, it can easily illustrate that damages do not matter. For the evaluation of truly long-term projects, e.g., "catastrophic" or economic developments projects, say, long-term investments into a dike system, the discount factors must be relevant to expected horizons of potential catastrophes. The expected duration of projects evaluated with standard discount rate obtained from traditional capital markets does not exceed a few decades and, as such, these rates cannot match properly evaluations of projects oriented on 1000-, 500-, 250-, 100- year catastrophes (Ermoliev and Hordijk, 2003; Ermoliev and von Winterfeldt, 2012).

There are several aspects of discounting in relation to critical infrastructure evaluation. For example, traditional approaches (ANCOLD, Bowles, CETS, Harrald, ICOLD; Jansen, Netherlands Ministry of Housing) to the evaluation of flood protection infrastructure (dams, dike, channels) efficiency and safeness often use principles of the so-called Net Present Value (NPV) or Modified Net Present Value (MNPV) to justify the project.

Disadvantages of the standard NPV criterion are well analysed (Ermoliev et al. 2010; Newel and Pizer, Ramsey, Weitzman). In particular, the NPV critically depends on some average interest rate, the application of which for evaluation of a practical project may not be easily implementable. For example, the problem that arises from the use of the expected value and the discount factor implies additional significant reduction of future values in contrast to the real expected discount factor

In addition, the NPV does not reveal the temporal variability of cash flow streams. Two alternative streams may easily have the same NPV even though in one of them all the cash is clustered within a few periods, but in another it is spread out evenly over time. This type of temporal heterogeneity is critically important for dealing with catastrophic losses which occur suddenly as a "spike" in time and space.

6.6.7 Catastrophic risks management

The explicit treatment of extreme catastrophic events and related uncertain time horizons and risks induce dynamically adjusted discount rates, conditional on the degree of social commitment to mitigate risk. In general, risk affects discount rates, which alter the optimal mitigation efforts that in turn, change the risk.

It can be shown, that the NPV under constant and declining discount rates equals the average undiscounted (in the agreement with Ramsey's concerns) random sum of expected cash flows with a random stopping time defined by the given discounting (Ermoliev et al., 2010). Therefore, discount rates can be associated with the occurrences of irreversible "stopping time" events (from safety constraints, exceedances of thresholds, occurrences of catastrophes) determining a finite "internal" discount-related horizon of the NPV criterion. The expected duration of the stopping time and its standard deviation under modest market interest rates of 3.5% is approximately 30 years, which may have no correspondence with expected, say, 300-year extreme events. Also, any stopping time induces a discounting. A set of mutually exclusive stopping time events even with geometric probability distributions, e.g., 1000-, 500-, 250-, and 100- year floods, induces discounting with time-declining discount rates.

Thus, extreme events pose new challenges to the evaluation of long-term infrastructure projects. They often create so-called endogenous, unknown (with the lack and even absence of adequate observations) catastrophic risks, which may potentially affect large territories and communities and, on the other hand, are

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dramatically affected by risk management decisions. Consequently, these risks generally make it impossible to use traditional economic and insurance models (see, e.g., the discussion in (Arrow, 1996; Arrow et al., 1996; Ermolieva, 1997; Ermolieva, Ermoliev, 2005; Ermoliev et al., 2000).

The concept of the stopping time, safety constraints, and the equivalent undiscounted random criteria allows to induce social discounting that focuses on arrivals of catastrophic events rather than the lifetime of market products (Ermoliev et al. 2010). Since risk management decisions affect the occurrence of disasters in time and space, the induced discounting may depend on spatio-temporal distributions of extreme events and feasible sets of related decisions.

The induced discount factors can be analysed within the DSS by solving relevant stochastic optimization problems (Ermoliev et al., 2020; 2011). The misperception of time inconsistency associated with induced discounting may dramatically effect – delay or provoke – the possibility of a catastrophic collapse.

Assessment versus robust solutions

Many infrastructure owners undertake safety (failure) analyses to varying degrees of detail with respect to various possible event scenarios. However, the exact evaluation of all interdependencies between potential strategies and related outcomes is very time consuming or even impossible. It evaluation process may easily run into an extremely high number of alternatives. For example, with only 10 locations, alternative decisions, say, insurance coverages of potential losses at 10%, 20%, …, and 100%, the number of "if-then" combinations for a single location is 10^{10}. Also, a strategy optimal for one scenario may not be optimal against multiple scenarios.

In this situation the most important task seems to be the design of management strategies robust with respect to all (or a certain percentile of) potential scenarios. The straightforward assessment is never exact, while the preference structure among different decisions may be rather stable to errors. This is similar to the situation with two parcels: to find out their weights is a much more difficult task than to determine the heavier parcel. The evaluation of the robust optimal decisions can be achieved without exact evaluation of all possible alternatives (Ermoliev et al., 1999 -2023; Ermolieva et al.,).

The underlying assumption of the robustness accounts for safety, flexibility, and optimality criteria of all agents against multiple potential scenarios of catastrophic events. Foremost, the robustness is associated with the safety criteria, which deal with the Value-at-Risk considerations. This type of risk indicators is a key for regulation of low probability-high consequences risks.

Trade-offs between the ex-ante precautionary and the ex-post adaptive measures

The future losses highly depend on currently implemented strategies. The ex-post decisions may turn to be much more expensive and, obviously, these costs often come unexpectedly in wrong time and place. The need for coexistence of both measures is dictated by the potential disastrous losses. This decision-making framework implies that the capacity for adaptive ex-post decision making must be created in an ex-ante manner. In the discussed approaches, specific attention is paid to the modelling of endogenous extreme events (scenarios) and unknown catastrophic risks, i.e., events and risks induced by new decisions for the analysis of which there is no real observations available.

Disaster damages and cost depend heavily on the policies. In many cases, proper policies established beforehand can avert a significant part of the cost. Traditionally, disaster costs have fallen on various groups, including individuals (property owners), local governments, insurance and reinsurance companies, charity institutions, national governments, and international organizations.

Most of the catastrophic costs (losses) have been paid ex-post (adaptively) by insurers and reinsurers, state and federal agencies and taxpayers with only some of these payments being explicitly arranged ex-ante by long-term strategic decisions (Froot, 1997). Frequently, there has been little or no prior agreement as to who should bear what portions of the cost. Responsible agencies, in anticipation of a need to cover potentially large losses in an ad-hoc way, block certain resources in the budget for this purpose. This however reduces the

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number of options for profitable investment and hence, in case of large funds being affected, it can potentially reduce the rate of economic growth.

Prior modelling of the likely costs, both investments into disaster risk reduction measures and the post-disaster costs for recovering after a catastrophe, would not only make the payment process more orderly but could also actually reduce the expected cost, for example by incentivizing local and/or national governments to regulate land use so as to reduce the risk of catastrophic destruction (Ermolieva et al., 2003; Ermolieva, Filatova et al., 2016; Ermoliev, Robinson, et al., 2018; Ermolieva et al., 2023; Ermolieva, Komendantova et al., 2023).

We claim that intensifying strategic long-term ex-ante measures together with a more intelligent way of putting resources aside for adaptive ex-post compensations can significantly reduce the overall burden to national economies and hence can strike a good balance between the economic growth and security. Effective decisions in this context could be made based on integrated long-term approaches to risk management and economic growth with an explicit emphasis on a possibility of rare high-consequence catastrophes.

The balance between the precautionary and adaptive decisions depends on financial capacities of the agents: how much they can invest now into ex-ante risk reduction measures, say, reinforcement of bridges, dams' safety, improving building quality. Or for how much they can buy insurance; and how much they are ready to spend for covering losses if a catastrophe occurs. As mentioned by many insurance authorities, infrastructure failure may cause losses that not every insurance or reinsurance will be able to absorb.

The introduction of safety constraints of various agents in the integrated DSS model regarding their threshold activities and critical imbalances induces risk aversion among the agents and identifies trade-offs between the ex-ante precautionary and the ex-post adaptive measures. This concerns the trade-off between structural and financial measures, i.e., between expenditures for infrastructure maintenance, reinforcement, and insurability of property in the region exposed to the catastrophe event. Definitively, the reinforcement increases the insurability.

6.6.8 Integrated Catastrophe Risk Analysis and Management modelling (ICRAMM)

For this reason, and as a necessary component of the integrated DSS, IIASA (International Institute for Applied Systems Analysis, PARATUS partner) developed an Integrated Catastrophe Risk Analysis and Management modelling (ICRAMM) approach (Ermoliev et al., Ermolieva et al. 1999-2023) enabling to design robust combinations of strategic ex-ante and adaptive ex-post measures, both financial and structural, for managing catastrophic dependent risks. The model has been tested in a number of case studies on floods (Ermolieva et al., 2003; Compton et al., 2009; Ermolieva et al., 2016), earthquakes (Ermolieva and Ermoliev, 2005), windstorms (Liu et al., 2009), energy and information infrastructure networks (Ermoliev et al., 2010), homeland security (Ermoliev and von Winterfeldt, 2012), etc.

The ICRAMM model "links" several modules or sub models. Many authors (for instance, Baranov et al. 2002, Boyle 2002, Clark 2002, Walker 1997) consider three main modules in catastrophe modelling: A hazard module comprising an event generator; an engineering module for damage estimation; an insurance business module for the analysis of insured losses vs. insurance premiums.

Linkage of models

In more general models, in addition to an engineering module for structural (infrastructure) damage estimation, sectoral (agricultural, energy, water production and provision) modules can be incorporated for calculating plausible impacts from disasters to food, energy, water (FEW) production and provision systems, thereby representing the aspects of food, energy, water security. Agricultural impacts can be estimated by land use and agriculture production planning models (Bielza Diaz-Caneja et al. 2009, Glauber 2015, Ermolieva et al. 2016, Ermolieva et al., 2016, 2021). These models incorporate the main crops and livestock production and management systems, characterized by systems-specific production costs, water and fertilizer requirements, emission factors, and other parameters. Catastrophic damages in agricultural systems can be caused by natural extreme events such as prolonged droughts, heat waves, seasonal variations in precipitation, windstorms, heavy precipitation, etc. The events affect crop and livestock yields, destroy agricultural land, diminish water infrastructure and supply, and cause production depletion, price volatility, market instability, trade bans, and tariff increases, to offset the impact of increasing world prices and cope with production shortages.

In addition to exogenous shocks, endogenous policy-driven impacts in the agricultural sector can be caused by catastrophic damages (failures) in other sectors, trade bans, supply-demand imbalances. For example, linkages between the agricultural and energy markets become more tightened because of climate change concerns and the rapid energy sector transition towards renewable energy sources. Agricultural commodities become important energy resources because of biofuel mandates. Increasing frequency and variability of natural disasters, the vulnerability of crop yields, grain demand and price volatility influence, directly and indirectly, markets for transportation fuels and transportation costs. At the same time, crude oil, gas and electricity markets and prices have indirect effects on agricultural production costs and prices. Additional interactions between FEWE systems emerge due to the uncertainties inherent to the introduction of new technologies, e.g., intermittent renewables, advanced irrigation, hydrogen production, water desalination, etc. For example, water desalination for agricultural water provision requires vast amounts of electricity. Therefore, a failure in the energy system due to an extreme event causes propagation of losses in interdependent FEWE systems.

Energy impact can be estimated by energy production and supply planning models. These models include the main stages of energy flows from resources to demands energy extraction from energy resources, primary energy conversion into secondary energy forms, transport, and distribution of energy to the point of end, and conversion into products for end users to fulfil specific demands. The models can incorporate various energy resources as, e.g., coal, gas, crude oil, and renewables; primary energy sources include coal, crude oil, gas, solar, wind, etc.; secondary energy sources are fuel oil, methanol, hydrogen, electricity, ammonia, etc.; final energy products are coal, fuel oil, gas, hydrogen, ammonia, methanol, electricity, etc. Demands for useful energy products come from economic sectors: industrial, residential, transport, agricultural, water, and energy. Each technology is characterized by unit costs, efficiency, lifetime, emissions, etc. Catastrophic damages (failures) in energy systems can be induced by exogenous natural hazards such as, for example, windstorms, hurricanes, floods, and earthquakes, and by endogenous systemic failures, which can be triggered beyond the energy system. For example, intensive water pumping by farmers in water-scarce regions can cause water shortages for energy system cooling and lead to enforced energy production termination (Abrar 2016).

Interdependent agricultural, energy, and water sectors are connected through joint cross-sectoral relations (im-balances) capturing, e.g., the requirements and limitations on the natural resource use and availability, and investments. Incorporation of joint food, energy, water, environmental (FEWE) security constraints require satisfaction of food, energy, and water demand by users in all potential scenarios of catastrophic shocks. In general, joint constraints impose restrictions on total “security”, production, resource use, emissions by all sectors/regions. The constraints can establish supply-demand relationships between the systems. In addition, the balances can impose limitations (quotas) on total energy production by the energy sector (electricity, gas, diesel, etc.) and land use sector (biodiesel, methanol); total energy use by energy and agricultural sectors; total agricultural production by distributed farmers/regions, etc.

6.6.9 Systemic risks

Increasing interdependencies among Food, Energy, Water, Environment (FEWE) systems involving interactions between nature, humans, and technology resemble a complex chain network connected through supply-demand relations. Disruption of such networks triggered, for example, by a disaster, induces systemic risks associated with critical imbalances and exceedances of vital thresholds, affecting FEWE security at various levels with possible global spill overs. Risks of disruptions and failures in such systems may be unlike anything, which has been experienced in the past. These risks can be induced by human decisions in combination with natural shocks. For example, an extra load in a power grid triggered by a power plant or a transmission line failure can cause cascading failures with catastrophic systemic outages (Abrar 2016). In financial networks, an event at a company level can lead to severe instability or even to a crisis similar to the global financial crisis of 2008. A hurricane in combination with inappropriate dams’ maintenance and land use management can result in human and economic losses, similar to those induced by Hurricane Katrina. Another example relates to an increase of biofuels production, which affects crops and food prices, destabilizes food and water provision, and worsens environmental conditions. Systemic risks in interdependent systems can be defined as the risks

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of a subsystem (a part of the system) threatening the sustainable performance and achievement of FEWE security goals. Thus, a shock in a peripheral subsystem induced (intentionally or unintentionally) by an endogenous or exogenous event, can trigger systemic risks propagation with impacts, i.e., instability or even a collapse, at various levels. The risks may have quite different policy-driven dependent spatial and temporal patterns. While standard risks analysis and assessment can rely on historical data, systemic cascading risks in FEWE systems are implicitly defined by the whole structure and the interactions among the systems, in particular costs, production and processing technologies, prices, trade flows, risk exposure, FEWE security constraints, risk measures, decisions of agents.

Prediction of systemic risks in complex natural and anthropogenic policy driven FEWE systems is a rather tedious task. The main issue in this case is robust management of the risks, which can be achieved by equipping the systems with precautionary and adaptive strategies enabling the systems sufficient flexibility and robustness to maintain sustainable performance and fulfil joint FEWE security goals independently of what systemic shock occurs (Ermolieva et al. 2016, Ermolieva et al. 2021).

Therefore, catastrophe analysis and management in interdependent food, energy, water systems require an integrated approach to understand and deal with the numerous interactions between the systems and potential catastrophic losses due to exogenous and endogenous systemic risks. This approach, compared to independent analysis, contributes immensely to sustainable development within and across sectors and scales.

6.6.10 Catastrophe generators

The lack of historical data on catastrophic losses and the absence of analytical forms of joint distribution create a rapidly increasing demand for integrated catastrophe modelling (See Amendola et al. 2013, Amendola et al. 2000, Amendola et al. 2000, Baranov et al. Digas et al. 2002, Boyle 2002, Clark 2002, Ermolieva et al. 2003) incorporating catastrophe (hazards) models and socio-economic sectoral models. GIS-based computer catastrophe modelling attempts to simulate samples (scenarios) of mutually dependent catastrophe losses on the levels of a household, a city, a region, or a sector, from various natural hazards, e.g., floods, droughts, earthquakes, and hurricanes. These models are used as a tool for planning, emergency systems, lifeline analyses, and estimation of losses.

Most of the models involved in the analysis produce outputs that are distributional. That is, the results of catastrophe simulations are typically not simply an expected loss, but rather a set of geographically detailed loss scenarios enabling it to obtain of a multidimensional probability distribution, which may be analytically intractable and not follow a particular statistical distribution.

Natural hazards models have been developed for a wide range of catastrophic risks and geographic territories worldwide. All major natural hazards are modelled, including earthquakes, hurricanes, winter storms, tornadoes, hailstorms, and floods. The seismic hazard module simulates actual earthquake shaking. It uses or simulates locations and magnitudes of earthquakes. This module often comprises other physical phenomena associated with an earthquake including subsequent fires, and landslides. The movement of the seismic waves through the soil is modelled by attenuation equations. Seismic effects at a site depend on earthquake magnitude, distance from the source, and site characteristics, such as regional geology and soil types. The vulnerability module relates seismic shaking to structural and property damage. It determines the extent of damages to buildings and content at a site. In the general case, it calculates sectoral damages. The financial module assigns a cost to these damages and calculates the maximum potential and/or expected losses for either individual sites or regions. It calculates losses to structural damage, damage to property and content, agricultural losses, losses due to business interruption for example due to energy system failure, etc. This module includes data on building locations, building types, building contents, power sector values at risk, agricultural properties, etc.

From Monte Carlo simulation of natural catastrophe scenarios, histograms of aggregate losses for a single location, a particular catastrophe zone, a sector, a country or worldwide can be derived from the catastrophe

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modelling. But catastrophe modelling has only marginal benefits when it is used in a traditional scenario-by-scenario manner for obtaining estimates of aggregate losses.

Although catastrophe modelling is considered to be a decision-making tool by many researchers and insurance companies, however, the decision variables are not explicitly incorporated in the existing catastrophe models. Following Amendola et al. 2000a, 2000b, Baranov et al. 2002, Ermoliev et al. 1997, 1998, 2000a, 2000b, 2001, 2010, 2018, Ermolieva et al. 1997a, 1997b 2003, 2004, 2005, 2013, 2018, Amendola et al. 2000a, 2000b, we can admit that the currently existing form of catastrophe modelling can only be a necessary element/subset of more advanced extensive decision-support models enabling simultaneous integrated analysis of the catastrophic risk portfolios/scenarios and the optimization of catastrophe management policies within the same modelling framework. The explicit introduction of decisions in such models opens a possibility for integrated catastrophic risks management based on the contribution of individual risks to aggregate losses.

Example: a catastrophe flood analysis model.

Let us consider an example of a catastrophe model developed for the analysis and management of flood losses in several case studies, i.e., a catastrophe flood model. The aim of the model is to generate potential samples of mutually dependent losses for a given vector of policy variables. For example, when there is a lack of historical data, models can estimate distributions of losses and gains for different locations, households, farmers, energy providers, water authorities, insurers, and governments. This is critically important in the case of rare events or new policies that have never been implemented in practice.

As is shown in Figure 6.6.2, the model for catastrophe flood analysis links, in general, five sub-models (modules): the "River" module, the "Inundation" module, the "Vulnerability" module, the "Multi-Agent Accounting System", and the "Variability" module.

The “River” module calculates the volume of discharged water to the pilot region from different river sections for given heights of dikes, given scenarios of their failures or removals, and rains. The latter are modelled by upstream discharge curves. Thus, formally, the “River” module maps an upstream discharge curve into the volume of water released to the region from various sections. The underlying sub-model can estimate the discharged volume of the water into the region under different conditions, for example, if the rain patterns change, if the dikes are heightened, or if they are strengthened or removed.

The next module is the spatial GIS-based “Inundation” sub-model. This module maps water released from the river into levels of standing water at fine resolutions (of e.g., 10 m^2) and thus it can estimate the area of the region affected by different decisions.

The “Vulnerability” module maps spatial patterns of released water into economic losses. This module calculates direct losses and may include possible cascading effects, such as floods causing fire and its consequences. It may also include loss reduction measures, e.g., new land-use modifications and flood preparedness measures. This module can indicate changes in economic losses from changes in risk reduction measures.

The “Multi-Agent Accounting System” module maps spatial economic losses into losses and gains of the involved agents. These agents are central and/or local governments, catastrophe insurance funds, investors, and “individuals” (cells) representing households, farmers, producers, consumers, etc.

Given sufficient data, the above-mentioned sub-models can generate scenarios of losses and gains at different locations for specific scenarios of rains, dam failures, risk reduction measures and risk spreading schemes. But there are significant uncertainties and a considerable variability in the simulated losses and gains. A 50-year flood may occur in 5 days or in 70 years, which may induce considerably different losses depending on regional economic growth scenarios. Governments, mutual catastrophe funds, and insurers are especially concerned about the variability since they may not have the capacity to cover large losses. To maintain their solvency, they may charge higher premiums and taxes, which may result in overpayments by the insured (households, farmers, producers, consumers, etc.). Alternatively, they may undercharge contracts.

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There may be alternative opinions about loss-reduction measures. A higher dike may fail and cause more damages in comparison to a dike without modification. The “Variability” module, a Monte Carlo model, transforms spatial scenarios of losses and gains among agents into histograms of probability distributions. For example, it derives histograms of direct losses at a location or a subregion. It also calculates histograms of overpayments and underpayments for different agents as explained in the following section.

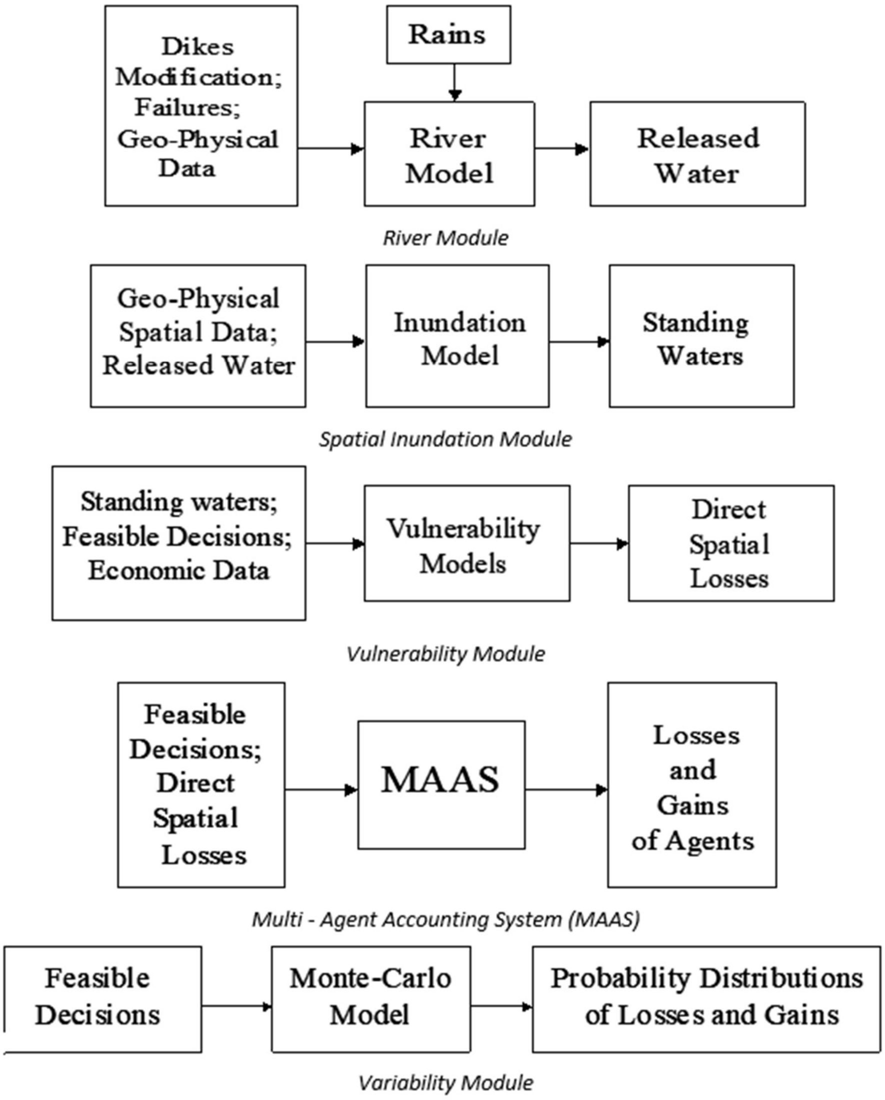

Figure 6.6.2: Modules of the Integrated Catastrophe Flood Analysis Model.

6.6.11 Adaptive Monte Carlo procedures

Catastrophe modelling and analysis discussed in previous sections opens the possibility for "if - then" scenario analyses, which allows the evaluation of a number of policy alternatives. These analyses may run quickly into an infinite number of possible combinations. For example, an insurer in a certain region can have different policies regarding the extent of coverage that it offers, say 0%, 10%, 20%, 100%, i.e., altogether 11 alternatives. For 10 locations the number of possible combinations is 10^{11}. With 100 locations, the straightforward "if - then" analysis runs into enormous number of scenarios leading to “curse of dimensionality” (i.e., increasing problem dimension and computational efforts). The same computational complexity arises in dealing with location-specific land use management decisions, flood protection measures, dikes, channels, improvement of building codes, premiums, investments in different critical infrastructures, etc.

The fundamental question concerns the evaluation of a desirable policy without the evaluation of all the

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options. The complexity of this task is due to analytical intractability of stochastic catastrophe models, often precluding the use of standard optimization methods, e.g., genetic algorithms. Therefore, in general cases we must rely on the stochastic optimization methods (Ermoliev et al. 2000; Ermoliev et al., 2018) on the so-called Adaptive Monte Carlo Optimization. “Adaptive Monte Carlo” means a technique that makes on-line use of sampling information to sequentially improve the efficiency of the sampling itself.

We use “Adaptive Monte Carlo Optimization” in a rather broad sense, i.e., the efficiency of the sampling procedure is considered as a part of more general improvements with respect to different decisions and goals. The “Adaptive Monte Carlo Optimization” model consists of three main interacting blocks: “Feasible Decisions”, the “Monte Carlo Catastrophe Model”, and “Indicators”.

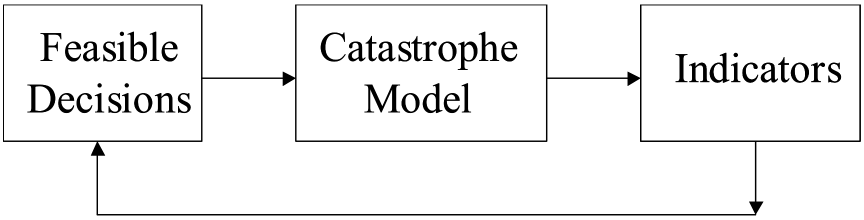

Figure 6.6.3: The Adaptive Monte Carlo Optimization Model

For floods management, the block “Feasible Decisions” represents all feasible policies for coping with floods. They may include feasible heights of dikes, capacity of reservoirs, water channels, insurance coverage, land use modifications, etc. These variables affect performance indicators such as losses, premiums of funds and insurers, underpayments or overpayments by the insured, costs, insolvency, and stability indicators.
The essential feature of the “Adaptive Monte Carlo Optimization” model is the feed-back mechanism updating decisions towards specific goals and the improvement of insolvency and stability indicators. The updating procedure relies on Stochastic Quasigradient (SQG) optimization techniques. Losses are simulated by the catastrophe model, causing an iterative revision of the decision variables after each simulation run. In a sense, the Adaptive Monte Carlo optimization simulates in a remarkably simple and evolutionary manner the learning and adaptation process based on the simulated reversible history of catastrophic events. This technique is unavoidable when the outcomes of the catastrophe model do not have a well-defined analytical structure.

Example: Application of the integrated catastrophe flood management model in the outside dike areas in Rotterdam, the Netherlands

The integrated catastrophe flood management model has been revised and applied in a case-study of potential floods in a Rotterdam area outside the main flood protection system (i.e., outside dike areas) in the Netherlands (Ermolieva et al., 2016). In this case study, among other goals, two alternative ways of calculating insurance premiums were compared: robust premiums computed using the proposed model, and premiums obtained by the traditional actuarial average annual loss approach[115] (). In the Netherlands, flood safety standards in protected areas vary between 200- and 10.000-year floods return periods. Although floods may happen rarely, their abrupt occurrence in time and space comes as “spikes” that cannot be properly modelled “on average”, say a 100-year flood may occur any year in the future. For example, in Dordrecht, a flood with a return period of 2000 years may cause damage of about 1.5 billion euro. According to the Average Annual Loss (AAL) approach, which is currently adopted by insurance industry, an expected damage is 0.75 million euro per year including damage to private (households and businesses) and governmental actors. This is a reasonable affordable amount except that this damage is not going to occur in small annual portions – all 1.5 billion will come at once. Thus, annualization of expected damages and evaluation of insurance premiums based on that average may be misleading and could undermine the financial stability of an insurance program and overall

[115] https://www.verisk.com/insurance/visualize/5-things-cat-modeling-every-reinsurer-know/

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flood risk management. The numerical experiments demonstrated significant advantages of the robust premiums. First, robust premiums can be calculated so that they guarantee the insurer's solvency in all or almost all (depending on the trade-off between α and β flood scenarios. In contrast, the traditional AAL approach, by definition, generates a premium that is optimal in response to the average flood magnitude. Such a premium on the side of the insurance program can lead to its insolvency; on the side of insured, it can lead to lower loss coverage. Case studies in (Ermolieva et al., 2016; Ermolieva et al., 2003) demonstrated essential advantages of the robust premiums, namely:(1) they guarantee the program's solvency under all relevant flood scenarios rather than just one average event, and they produce sharp increases in insurance coverage, adjustments of mitigations, and decreases in cost; (2) they establish a trade-off between the security of the program and the welfare of locations; and (3) they decrease the need for risk transfer and risk reduction measures compared with the actuarial approach.

6.6.12 Conclusions

Section 6.6. presents important overview of methodological and practical challenges relevant to the analysis and management of catastrophic multi-hazard (dependent, cascading, compound) systemic risks. Systemic risks and losses in interdependent systems can be defined as the risks of a subsystem (a part of the system) threatening the sustainable performance of other systems and achievement of their security goals,, e.g., FEWES security. In front of uncertainties and dependent risks, the strategies (decisions) to increase systems' resilience and robustness against the risks can be of the two main types: the ex-ante strategic precautionary mitigation anticipative actions before the event (shock) occurs (construction of dams, bridges, building reinforcement, resource allocation, new technologies, irrigation infrastructure, water reservoirs, grain storage, catastrophic funds) and the ex-post adaptive adjustments (insurance claims, reinsurance, credits, financial markets, marketing, inventory control, subsidies, prices, costs) that are made after the information about the event becomes available or the events occurs (after observing the event and receiving actual information about real losses, damages, failures, etc.). We discussed methods and approaches to the evaluation of ex-ante structural mitigation measures, introduced the notion of safety and security constraints, discussed relevant public risk perception, equity, and ethical considerations, traditional and risk-based (induced) approaches to discounting, etc. The one-by-one evaluation of the ex-ante and ex-post measures can run into an infinite number of policy combinations and in the end can be misleading and lead to even high catastrophic losses. Therefore, we argue for the design of proper spatially and temporally explicit integrated catastrophe risk analysis and management Decision Support Systems and models (Ermolieva et al., 2023; Ermolieva, Komendantova et al., 2023; Ermoliev et al., 2022, 2021) linking various sub-models of the involved stakeholders, (reduced) stochastic catastrophe scenario generator models, and a (stochastic optimization) solution procedure to design robust feasible combinations of interdependent ex-ante and ex-post risk reduction and coping measures. A proper robust combination of ex-ante strategic mitigation and ex-post operational adaptive measures can reduce the post-event burden, relax the tightness in various systemic supply-demand relations and lessen chances of critical imbalances, exceedances of vital thresholds, which could otherwise lead to systemic failures with potential catastrophic cascading consequences and the lack of securities.

While standard risks analysis and assessment can rely on historical data, systemic cascading risks in interdependent systems are implicitly defined by the whole structure and the interactions among the systems, in particular risk exposure to different hazards, supply-demand relations, costs, production and processing technologies, prices, trade flows, FEWE security constraints, risk measures, infrastructure in place, feasible decisions of agents. Therefore, the systemic risks in interlinked natural and human systems cannot be characterized and evaluated analytically by a single probability distribution. This requires the development of integrated Decision Support System(s) linking subsystems of the involved agents and enabling the analysis of complex systemic interaction and multivariate joint probability distributions of possible losses dependent on the frequency and intensity of natural hazards, feasible decisions, risk perception, risk measures, etc.

Catastrophic risks have skewed, often analytically intractable, distributions exhibiting "fat" (extreme or heavy) tails, characterized by distribution's quantiles. Recent advances in physics suggest that due to climate change one should expect "fat" tails to become even "fatter". In case of catastrophic risks, normal distribution defined

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by mean and variance, which is the most popular distribution used for the assessment, policies appraisal, and modelling in economics and finance, is not an appropriate model for pricing and for devising strategies to manage the risks.

As it is not possible to totally prevent disasters, many concerned organizations are now considering as a priority to strengthen the societal or social disaster resilience through various combinations of ex-ante and ex-post mitigation and adaptation measures. The resilience towards disasters can be understood as the capacity of a social entity (e.g., a group or community), "the ability of individuals, communities, organizations and states to adapt to and recover from hazards, shocks or stresses without compromising long-term prospects for development".

High potential compound (systemic, dependent) impacts from natural hazards in combination with infrastructure failures (e.g., dam breaks, floods, failures of electricity networks) call for the cooperation of various agents such as governments, insurers, investors, and individuals that must be represented in the DSS through their goals, vital constraints, thresholds, etc.

The occurrence of a disaster (catastrophe losses) for each agent is often associated with the likelihood of some processes abruptly passing individual "vital" thresholds. The analysis and design of risk management strategies therefore requires the introduction and regulation of the safety constraints of the agents within integrated DSSs and catastrophe management models.

The safety constraints allow to control the actions within admissible norms, say, land transformation, environmental degradation, pollution, wellbeing, historical values, and cultural preferences restrict the growth of the wealth in risk prone areas.

Evaluation of ex-ante structural mitigation measures requires proper approaches to discounting (Ermoliev et al., 2010). Regarding long-term catastrophe risk mitigation projects, discount rates can be associated with the occurrences of irreversible "stopping time" events (from safety constraints, exceedances of thresholds, occurrences of catastrophes) determining a finite "internal" discount-related horizon of the NPV criterion. The expected duration of the stopping time and its standard deviation under modest market interest rates of 3.5% is approximately 30 years, which may have no correspondence with expected, say, 300-year extreme events. Also, any stopping time induces a discounting. A set of mutually exclusive stopping time events even with geometric probability distributions, e.g., 1000-, 500-, 250-, and 100- year floods, induces discounting with time-declining discount rates.

Thus, natural disasters pose new challenges to the evaluation of long-term infrastructure projects. They can create endogenous, systemic, unknown (with the lack and even absence of adequate observations) catastrophic risks, which may potentially affect large territories and communities and, on the other hand, are dramatically affected by risk management decisions. Consequently, these risks generally make it impossible to use traditional economic and insurance models. In this situation the most important task seems to be the design of ex-ante and ex-post risk coping strategies robust with respect to all (or certain quantile) potential scenarios. The need for the coexistence of both, ex-ante and ex-post, measures is dictated by the potential disastrous losses. This decision-making framework implies that the capacity for the adaptive ex-post decision making must be created in an ex-ante manner. In the discussed approaches, specific attention is paid to the modelling of endogenous extreme events (scenarios) and unknown catastrophic risks, i.e., events and risks induced by new decisions for the analysis of which there is no real observations available.

Properly designed robust insurance programs, for example, based on an PPP and engaging various stakeholders can be an essential part of the risk management. Such a program can (i) share the risk across actors, locations and time and assure funds available for loss compensation, (ii) induce investments into structural ex-ante mitigation measures, (iii) increase public awareness of disaster risks, (iv) improve land use safety, (v) contribute to the fulfilment of FEWE security goals. A public-private partnership (PPP) can comprise of a financial layer of contributions from property owners (households and businesses), a layer of private insurance, a risk transfer layer through reinsurance or/and catastrophe bonds, and finally a layer of government contribution in a form of a cap or reinsurances of extreme losses.

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6.7 Impact-Based forecasting tool for the Caribbean

6.7.1 Impact-Based Forecasting Portal

The Impact Based Forecasting (IBF) Portal takes the theory about risk, vulnerability and exposure and transforms it into actionable practice for local users such as disaster managers (see **section 3.1**). It is meant to be the one stop shop for disaster managers to find all the relevant information for them to respond adequately to an upcoming hazard.

IBF is a process of predicting the impact of impending disasters on vulnerable people living in areas prone to these disasters.

- Turning forecasts from descriptions of what the weather will be into assessments of what the weather will do
- Enables organizations to anticipate and take action to mitigate the impacts brought by the events.
- Release funds to vulnerable communities and individuals ahead of potentially devastating events, enables anticipatory actions that save lives, livelihoods, and property.

IBF portal by 510 is currently implemented in 9 countries and supports 6 different types of hazards. The IBF Portal has been developed and implemented in the countries Zambia, Uganda, Kenya, Ethiopia, Philippines, Egypt, Malawi, Zimbabwe, and South Sudan. The hazards that are covered in one or multiple countries are Floods, Flash Floods, Heavy Rainfall, Infectious diseases (malaria, dengue), Tropical Storms (Typhoons) and Droughts. An example of the IBF portal can be seen in Figure 6.7.1.

510 can provide data & digital support for the development of impact-based forecasting for different extreme weather events, and epidemics. This includes trigger modelling, the IBF Portal (information visualization), and as needed support in EAP development.

In this project we will explore the needs to implement the use of the IBF Portal for multiple islands in the Caribbean and for multiple relevant hazards.

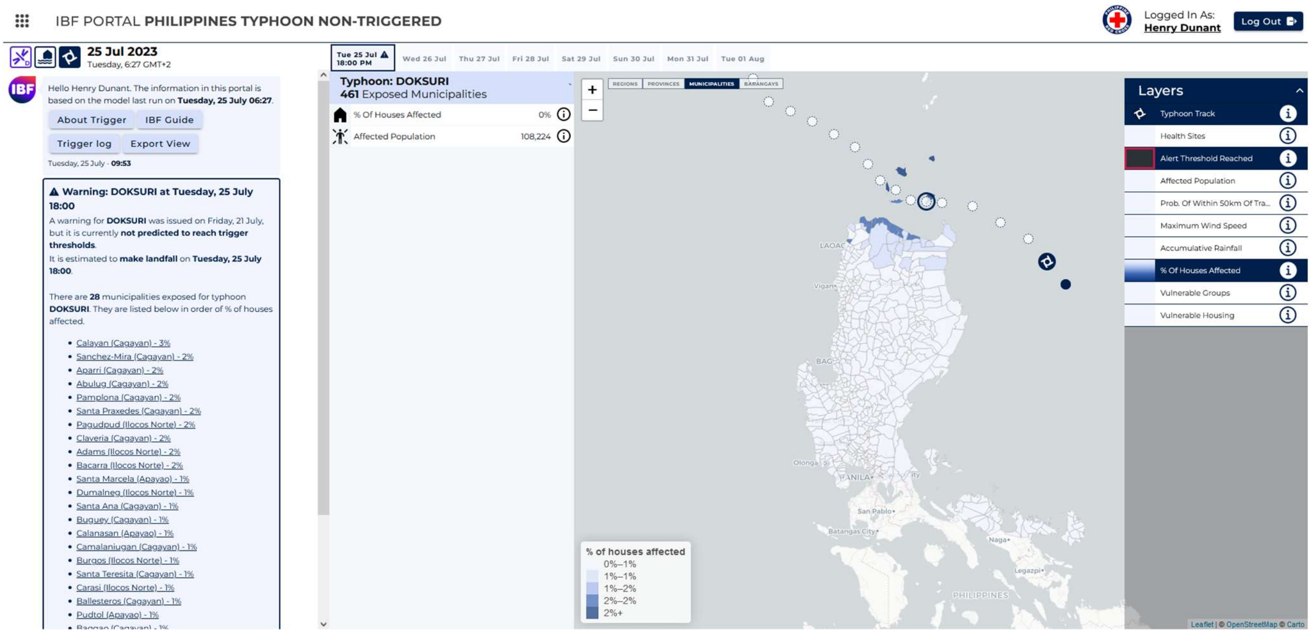

Figure 6.7.1: Example of the IBF Portal for the Philippines

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6.7.2 Functionality

Knowing *when* to act to mitigate the effects of a hazard is core to anticipatory action. For this, trigger models are used as the basis of an IBF portal. One way the trigger model works is by constantly monitoring the forecast of one or more biophysical or meteorological indicators that are used to predict a hazard. The magnitude of the upcoming hazard can be matched to that of an historical event by correlating historical impacts to historical events. The trigger model can be set up as a sequence of automated tasks feeding into each other and that runs on a computer.

Whenever the pre-defined threshold of the indicators is exceeded, the trigger model issues a warning. The outcome of the model is 1. an alert is sent to the end-users via email and/or WhatsApp and 2. information and data about the upcoming hazard event that will be automatically uploaded to the interface. The warning urges the end-user to take specific pre-defined anticipatory actions to mitigate the effects of the hazard.

The impact chains that will be developed in PARATUS could potentially be used to improve the way the impact is modelled in the trigger model, in this case specifically for the Caribbean.

Functionality: multi-hazard

The IBF Portal can be used for multiple hazards. In the case of the Caribbean area and based on an initial and hypothetical scenario in which the users need an interface that will allow them to analyse the impact of different hazards each of which will be coupled to a trigger model. A possible similar implementation of the interface that would allow the user to switch views between hazards is shown in figure 6.7.2. We would like to validate with the users and explore the possibility that the interface will also include some information on the impact chains. The assumption is that it could allow the user to understand what the impact of the hazard is, in a form of an impact chain, whenever hazards occur simultaneously. Based on the users' needs we will explore the possibility to depict each hazard individually as well as in different combinations.

Figure 6.7.2 Possible depiction of the multi-hazard portal that would allow switching the view between the hazards by clicking on the corresponding icon.

Functionality: background risk data

The central component of the IBF Portal is a map of the Area of Interest. It is possible for the user to turn on and off several map layers. Some of the map layers are meant as background information that is also useful when there is no upcoming hazard event. They contain information on risk and specifically about vulnerabilities of the population to a specific kind of hazard, as shown in Figure 6.7.3.

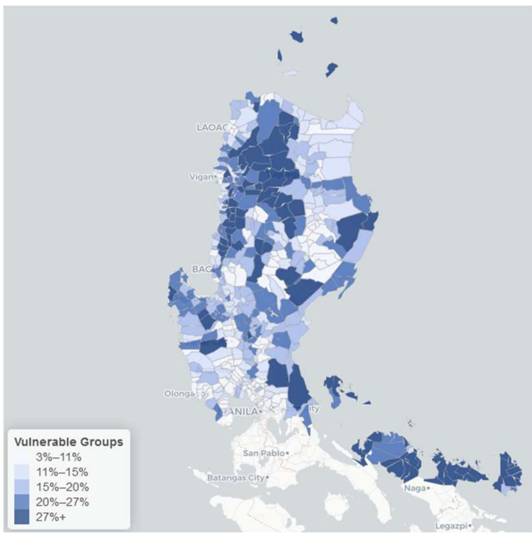

Figure 6.7.3: Example of a background layer about vulnerable groups.

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Functionality: information about the upcoming hazard event

Whenever the trigger model indicates that the set threshold is surpassed, the probability of an upcoming extreme event increases. In this case the portal is in 'trigger mode' and draws the attention of the user to the details of the upcoming event. General information about the event is then shown in text (on the left side of the portal), in a timeline (on top) and in several map layers. The text guides the user in what is happening as shown in figure 6.7.4. It shows the date that the last model was run and the date for which the event is forecasted to take place. It also shows which areas are likely to be hit. Depending on the hazard the timeline will show upcoming days, months or hours and it shows for which timeframe the hazard will strike. When there is a flood, it is possible to show the forecasted river or discharge levels as well as the expected inundated area. For tropical storms it shows the path of the storm and the wind speeds and category of the storm that it will take in the near future.

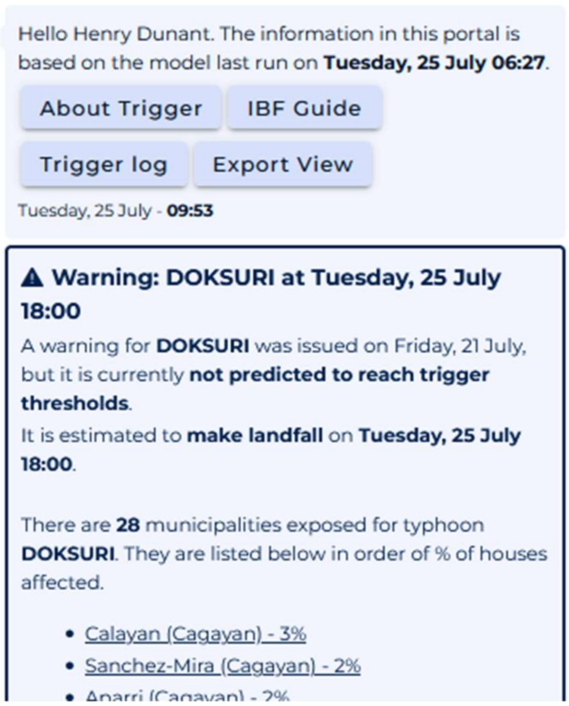

Figure 6.7.4: Messages that guide the user through the information about the upcoming event.

Functionality: anticipated impact of the upcoming event

For first responders and disaster managers the primary focus is the potential impact of an upcoming hazard. A hurricane that hits an uninhabited island will likely have no or very small impact on people's lives and thus is also less important for disaster managers to act on.

The kind of impact changes for different hazards and can be visualised in the IBF portal as shown in figure 6.7.5. For floods, the impact is mostly how many people will be exposed to the floods. For hurricanes, it might be essential to know the exposed population as well as how many houses are likely to be damaged. Apart from the direct impact on people it is also important for first responders to know the impact on infrastructure, hospitals and evacuation centres. Which roads will stay operational? Are there hospitals that need to be evacuated and which evacuation areas will be the right ones to use for the local population?

Depending on the needs of the specific users in the Caribbean and the availability of data and forecasts we will select the most important impacts, calculate their magnitude and visualize their geographic distribution.

Functionality: guide on early actions to take

The goal of early warning is to be able to take early actions to mitigate the effects of the upcoming hazard event. Choosing the most suitable early actions depend on the users, often the local disaster managers. This

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will be discussed with the users in the Caribbean to develop a suitable feature. In other areas where the IBF Portal has been implemented together with the national Red Cross / Red Crescent Society it has been often developed together with an Early Action Protocol[116] . This is a document that specifically describes which early actions are coupled to specific trigger requirements. Once this approved, the IBF Portal can implement the EAP together with the trigger model. This means that when the specific requirements (or thresholds) are reached, the portal will guide the users through the early actions that need to be taken, as shown in figure 6.7.5. Often the actions depend on the lead time of the forecasted hazard event. For example, a flood that is forecasted a week in advance allows for a wide range of early actions to be undertaken: such as cleaning drainage channels, community mapping and training volunteers on response. A hazard event that is forecasted to hit in a day's time, is coupled to other types of early actions such as evacuations, cash transfers to vulnerable people, reinforcing houses and distribution of water treatment products.

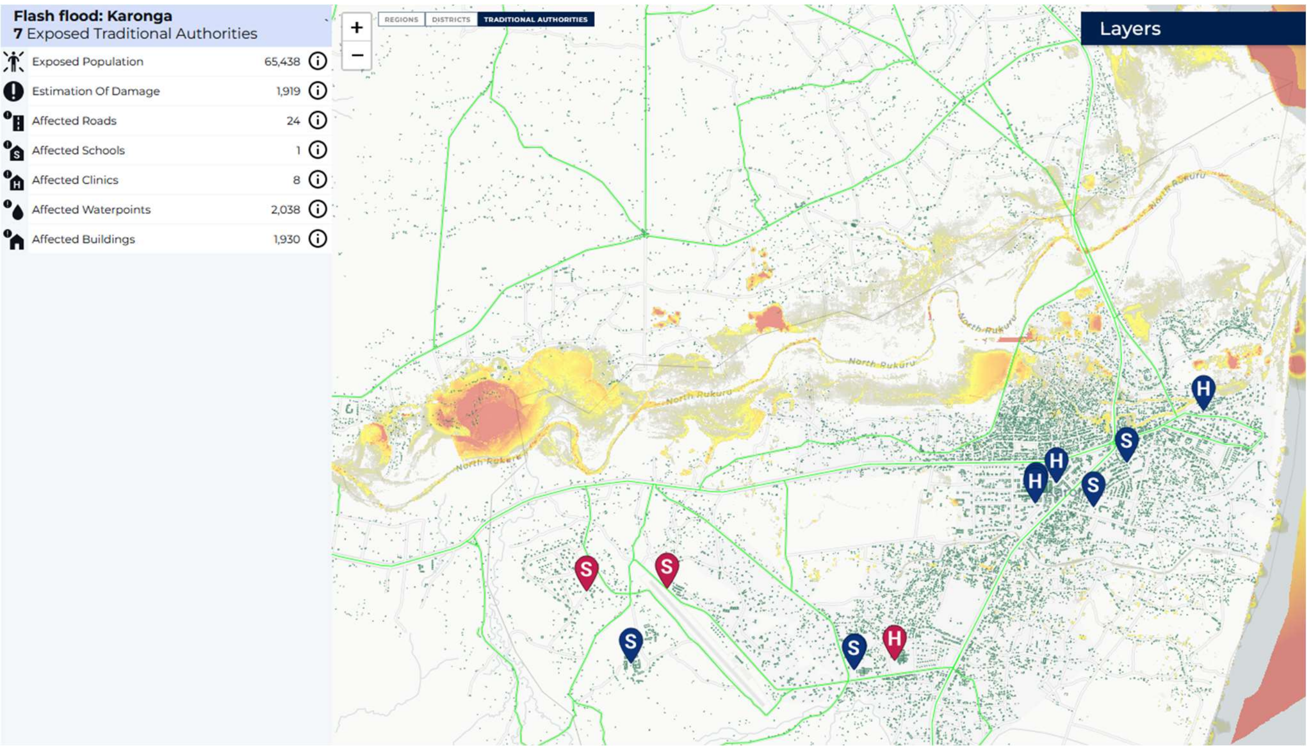

Figure 6.7.5: The impact of a hazard can be visualized in the IBF Portal. The example shown is for Flash Floods in Malawi (simulated data). It shows the number and locations of affected roads, schools, clinics, etc.

Other functionalities

Next to the functionalities described above, other, non-core yet important functionalities can be added to the portal. For example, a page where a user can see all historical triggers for that specific area of interest in the form of a table. This could show the historical trigger events from the trigger database with name of the area, start date, end date, numbers for the exposure indicator, etc. Another functionality that could be added is an IBF Guide which can be accessed by clicking on a button in the main screen as seen in figure 6.7.6. This would open a popup with multiple options for receiving guidance on how to use the IBF Portal. When a user is logged in there is also an option to change their password by clicking the button in the top right. In every implementation of the IBF Portal a link to the background of the trigger model is included, which can be accessed through the "about trigger" button. This is usually a document describing the trigger model.

[116] https://www.ifrc.org/happening-now/emergencies/anticipatory-pillar-dref https://www.ifrc.org/happening-now/emergencies/anticipatory-pillar-dref

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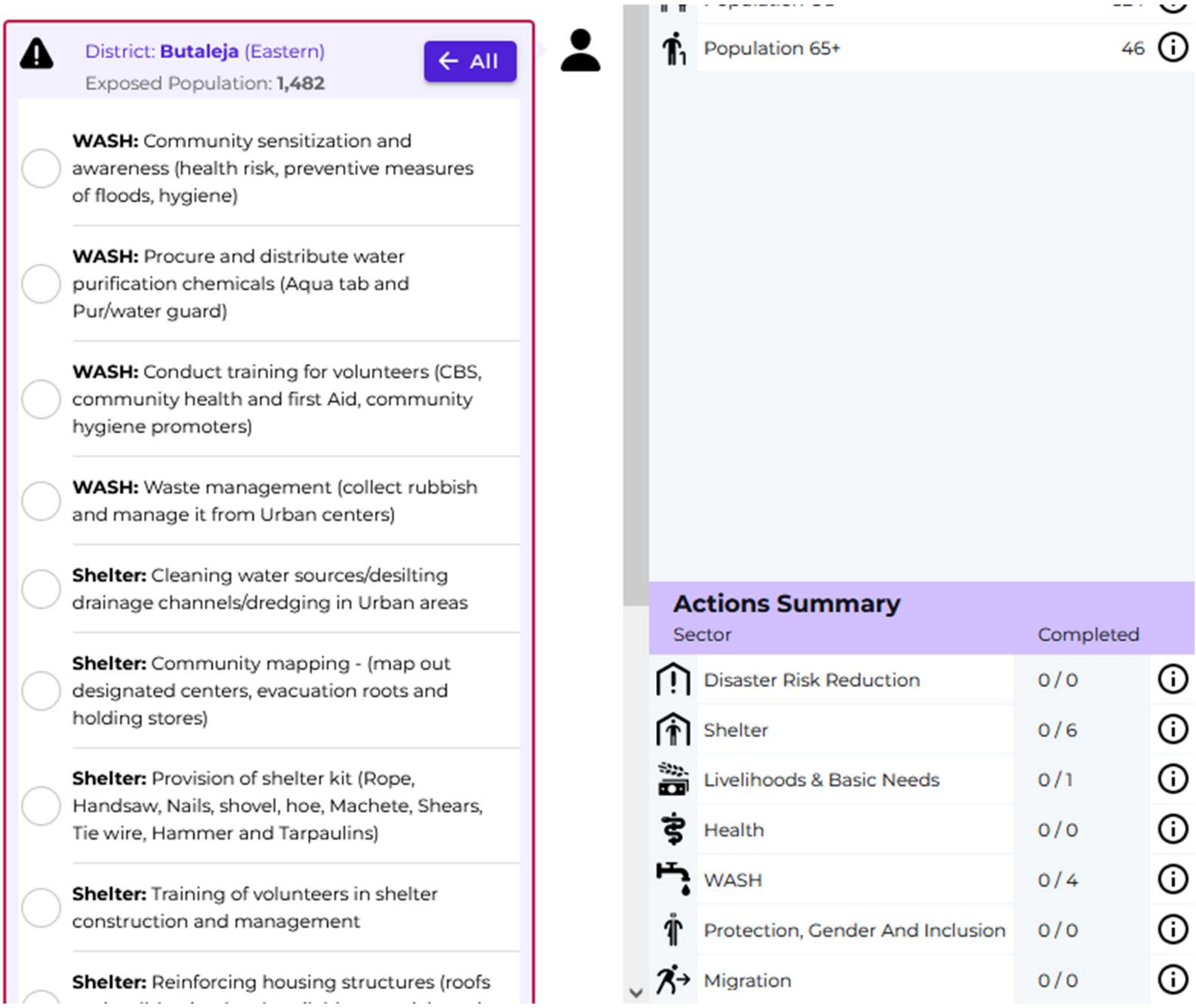

Figure 6.7.6: Example of a list with early actions. The user can check off which actions are done (per area) and the summary shows how many have been done across the whole Area of Interest.

Apart from the abovementioned general functionalities of the IBF portal, depending on whether there is a specific functionality that is needed by the local users of an IBF Portal implementation, we consider adding new functionalities to the portal. We base the decision on the compatibility of the functionality to the overall IBF product vision and use across different countries. For the Caribbean we might consider certain adaptations depending on the user input and the viability of implementation globally in IBF.

6.7.3 Assumptions / Constraints / Risks

Impact Based Forecasting is only possible if there are (accurate) forecasts available and if we find that the end users are able to support the implementation. Supporting both in term of the availability and participation in the development and research, and with the required data and digital literacy to operate and use the platform. In this implementation the Netherlands Red Cross/510 will work together with local users and KNMI to identify hazards and forecasts that can be used for these hazards. For the Caribbean, the most important hazards are hurricanes, earthquakes, tsunami’s and flash floods. Earthquakes are difficult to forecast accurately, but the forecasts of the other three hazards could provide possibilities to create accurate trigger models.

A risk with digital platforms developed in projects is that their long-term sustainability is not guaranteed after the project ends. This is also a risk for the IBF Portal in the Caribbean. To avoid this risk and guarantee that the platform will stay operational the following issues will need to be addressed fully:

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- identify the stakeholders that benefit from the portal staying online
- understand who can provide the funds for hosting and maintenance
- identify who has the technical ability to perform the hosting and maintenance. There are several options for this, as the experience of the 510 team of the Netherlands Red Cross has shown in our collaborations on IBF Portal implementations to date, but this needs to match with the specific stakeholders in this project.

Lastly, the IBF portal is recommended to be implemented if there is also an Early Action Protocol or Early Actions linked to it. If deciding to do so, such a protocol will need to be set up and approved by the International Federation of the Red Cross and Red Crescent societies (IFRC). This process needs to be taken into consideration in the planning and timing.

6.7.4 Design Considerations

Way of working

The platform potentially implementing an IBF Portal for the Caribbean will be developed by following Human Centered Design methodology as described in section 3.2. The process of human center design and development is based on users' needs and problems to solve and is an essential part of the product development process that is instrumental to take place before building any platform within the PARATUS project.

The software development of IBF Portal is done using the Scrum Framework. This means that value will be added to the product in short iterative cycles by using empiricism. After every cycle (sprint) the product will be inspected with the stakeholders and decided which adaptations are needed to be done for the next sprint. Good inspection is only possible with good transparency. This means that there will be a demo environment open for key stakeholders to try out the new functionalities. There will also be a product backlog with new functionalities to be added which will be open to stakeholders.

Technical software architecture

The interface of the general IBF Portal is a web app, developed with the Ionic, Angular and Leaflet libraries. In the background there is a geoserver instance that serves (some) map layers to the interface. The data is hosted in a separate database server running Postgres. The trigger messages are sent via mailchimp (email) and/or Twilio (WhatsApp). The frontend communicates with the backend (and the trigger model pipeline) through a REST API implemented with NestJS. The application is containerized using Docker. The overview of the IBF portal system design can be seen in figure 6.7.7.

The application is hosted in Microsoft Azure. The docker is run on a Virtual Machine and the Postgres database is hosted in a dedicated database server. The trigger model is run in a logic app running a docker image hosted in an Azure Container Repository. The application has three environments. The operational environment, a staging or demo environment and a test environment. Development is done on a local host. The code is open source and is managed through github[117]. The product backlog, sprint backlog and roadmap are on Azure DevOps.

[117] https://github.com/rodekruis/IBF-system

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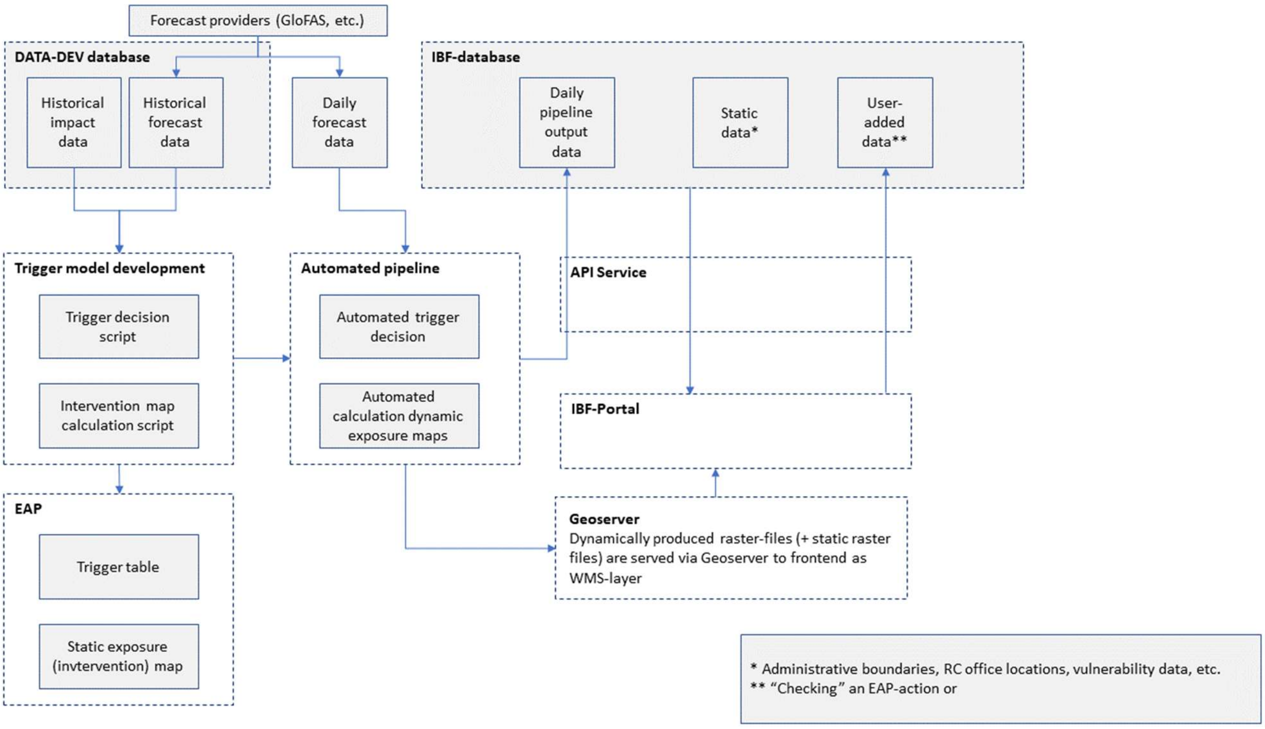

Figure 6.7.7 Schematic overview of the IBF Portal system design.

User Interface Design

The implementation of the IBF Portal for the Caribbean use case will depend on two things, namely the current product offering and the users' needs. The development will be done based on the current product offering as described in section 6.7.1 (including the screenshots of the current design) features and functionalities. The IBF portal is currently implemented in different countries and contexts, so when prioritizing new features and functionalities we must consider the different implementations and use cases. Based on the insights from the user interviews and user tests we will prioritize adding or adapting to the existing features and functionalities to the specific needs of the users in the Caribbean and the relevant hazard (i.e. hurricanes).

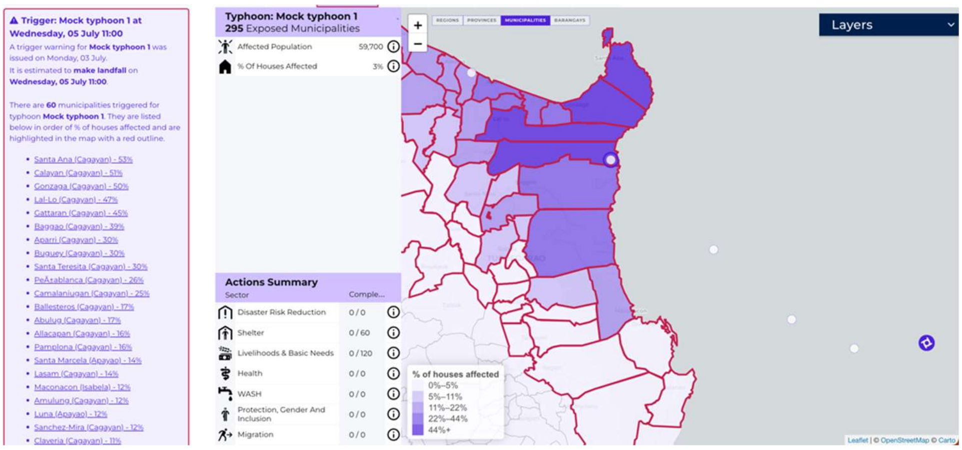

Figure 6.7.8 Example of the tropical cyclone IBF Portal in the Philippines.

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6.8 Serious Games

With stakeholders, we will co-develop two serious games - exploring creativity and experiential learning, using in-person/ video processes and augmented reality. Serious Games are facilitating deeper learning in complex contexts, enabling participants to learn experientially and harness their creativity. The Climate Centre and CRS have been working with serious games for more than a decade[118]. They will collaborate with other groups[119] [120] that have a wide experience with serious gaming, an experiential process rooted in a more active, experiential methodology based on Kolb's cycle[121]. This approach highlights the fact that knowledge acquisition is "created through the transformation of experience" and requires a more interactive environment that the players may explore. The project will use two types of serious games:

- **Social Simulations:** Social simulations are characterized by the social aspect of the tool in which different groups of interest interact in a fictional environment that emulates the real-world system and interlinkages between its key elements. The project will use social simulations to explore possible futures and new pathways towards risk reduction, adaptation, and mitigation, and creating more resilient communities. An important element of the projects' simulation will be the social learning aspect. This will allow people to learn different perspectives and individual challenges, through narration-based gameplay and include them meaningfully in navigating future challenges and testing possible solutions[122]. One of the most important distinctions of this social simulation is that it will be future-oriented. Seeing and experiencing the possible future outcomes of their own decisions, players will be able to confront their hidden assumptions and actively learn from their mistakes within a safe environment. This will build the capacity of stakeholders for actual disaster situations.
- **Augmented reality:** Experiencing future realities to Augmented Reality is a powerful way to inhibit possible futures and to allow the viewer to explore emotions and decision-making options in a new, and more immersive way. The Climate Centre (RCCC) has been working with a range of virtual tools - ranging from Virtual Reality approaches for Early Warning Early Action decision making to designing an Augmented Reality App called Cartoon Graffiti. *PARATUS* thus combines experience in designing and facilitating games and a creative co-production process that will create a balanced experiential product and create learning and networking opportunities during the actual design and testing phase.

Work Package 3 of the PARATUS project will develop tools to support understanding of other tools on the platform (e.g., scenario and alternative development tool or adaptation and DRR alternatives).

This document will talk about the Serious Game and Learning module that will be embedded in the PARATUS Platform. The module will include a self-exploratory online browser-based simulation, a multiplayer online browser-based social simulation, and a serious game using augmented reality.

The module will be co-developed with relevant, local stakeholders that are at the core of the PARATUS project.

6.8.1 Purpose of the Serious Game and Learning Module Component

This module will have three main purposes:

1. To support understanding of the PARATUS platform, its goals, components.
2. Providing additional inputs on the role of worldviews and society pressure on the decision-making processes while using a few pre-made scenarios based on the project case-study areas.
3. Providing stakeholders with immersive and social online experience for exploration of various possible future adaptation/DRR scenarios.

[118] http://www.climatecentre.org/downloads/files/Games/CDKNGamesReport.pdf
[119] https://www.dkkv.org/de/serious-gaming
[120] https://www.fastcompany.com/90323110/these-board-games-play-out-how-climate-change-will-reshape-our-cities
[121] https://www.researchgate.net/publication/235701029_Experiential_Learning_Experience_As_The_Source_Of_Learning_
[122] https://doi.org/10.1016/j.gloenvcha.2020.102204

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The module addresses the needs of users for a more personal and less abstract approach towards scenarios and impact chains, enabling users to observe and consider the impacts of their decisions on various groups of interest, and become exposed to cascading effects and possible solutions to problems also on the personal level, through heightened emotions and experimenting.

6.8.2 General Overview and Design Guidelines/Approach

This section describes the principles and strategies to be used as guidelines when designing and implementing the system. From a technical point of view, the module will contain 3 important components that will be able to function completely separately from one another. The reasons for the separation will be described in more details below.

The components include:

Self-exploratory online browser-based simulation that enables users to experience impact chains and scenarios from a perspective of a decision-maker. The component will also have outbound links to other modules and components of the Platform, providing the necessary context of where and how to explore details of the elements included in the simulation.

Figure 6.8.1. Self-exploratory browser-based simulation: map/storyline view.

Figure 6.8.2. Self-exploratory browser-based simulation: video view.

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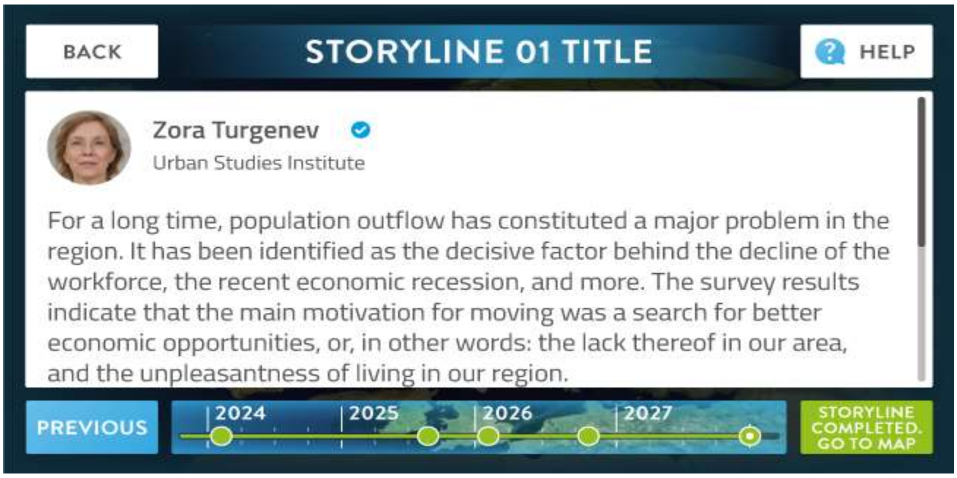

Figure 6.8.3. Self-exploratory browser-based simulation: social media posts view.

Figure 6.8.4. Self-exploratory browser-based simulation: article/ long posts view.

1. **Multiplayer online browser-based social simulation** that builds on the material from component 1, but expands it to allow, through role-play, social interactions and making decisions in a multi-actor environment. The roles will include representatives of decision-makers, civil society organisations or practitioners. A few separate scenarios will be available, with each having a separate setting to reflect real-life differences in places around the world.
2. **Serious game** using augmented reality.

The components might be supported by additional text-based, graphic-based, or video-based materials that could be accessible directly via online platform or as a downloadable. Components 1) and 2) will also include videos and graphics that could be accessible separately if users require it. The substantive content of components 1) and 2) will be developed based on the Com-pleC-Sus (Com-plex-ity-Col-lab-o-ra-tion-Sus-tain-abil-ity; Mochizuki et al., 2021) framework that is built on the concepts of social learning and procedural rhetoric.

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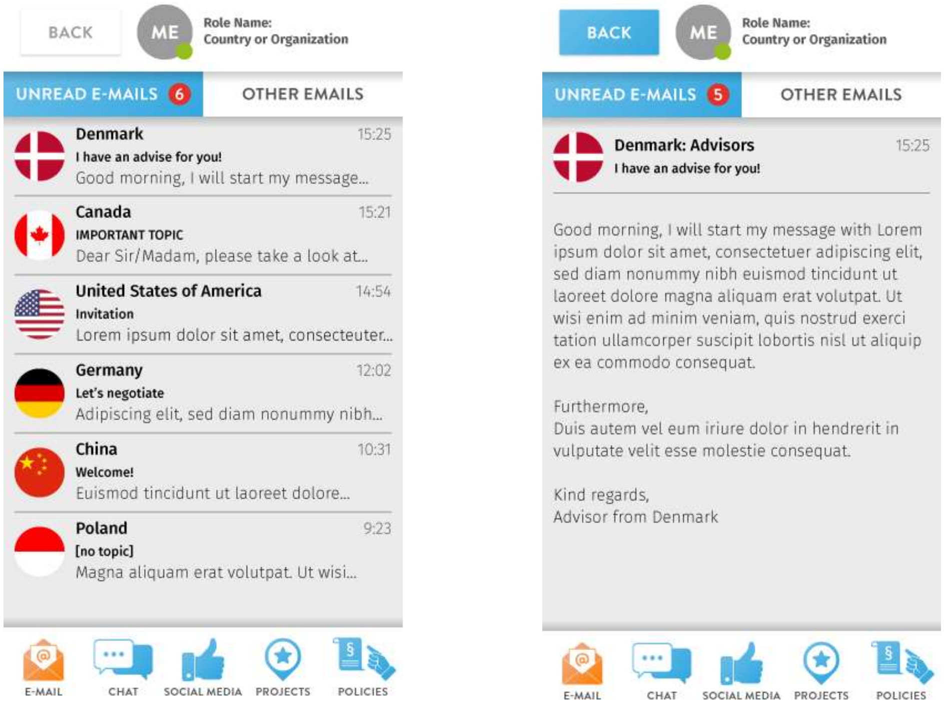

Figure 6.8.5. Multiplayer online browser-based social simulation: email view

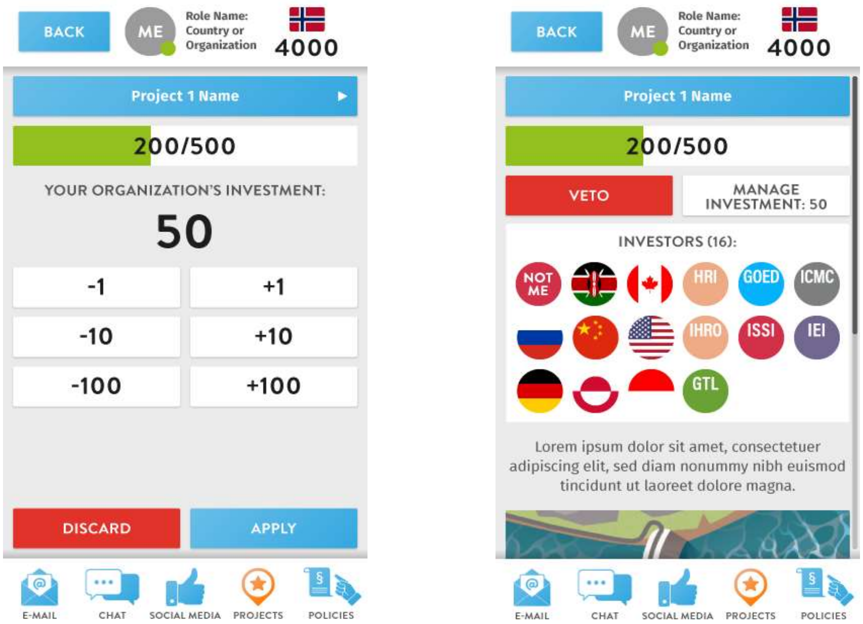

Figure 6.8.6. Multiplayer online browser-based social simulation: sup porting a project proposal view.

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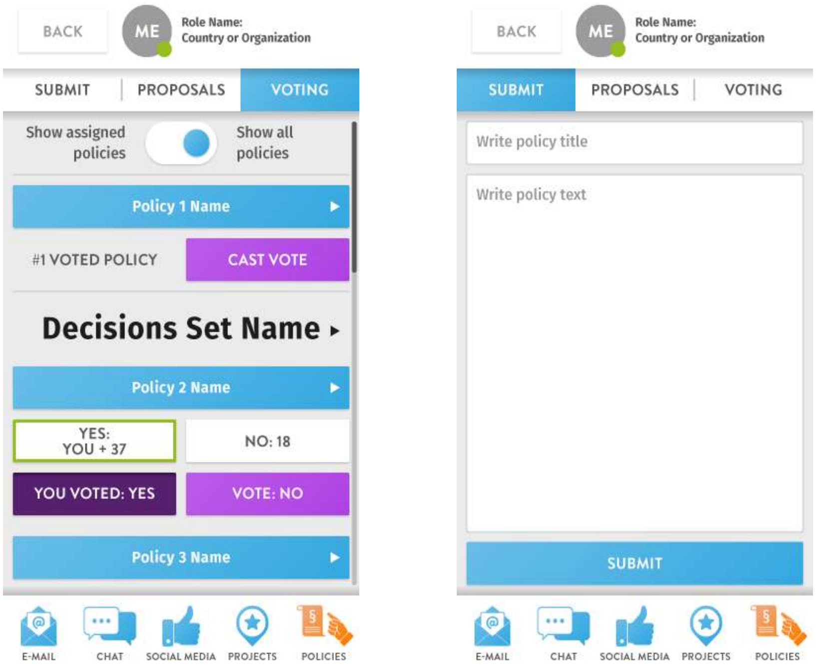

Figure 6.8.7. Multiplayer online browser-based social simulation: policy options (voting and submit).

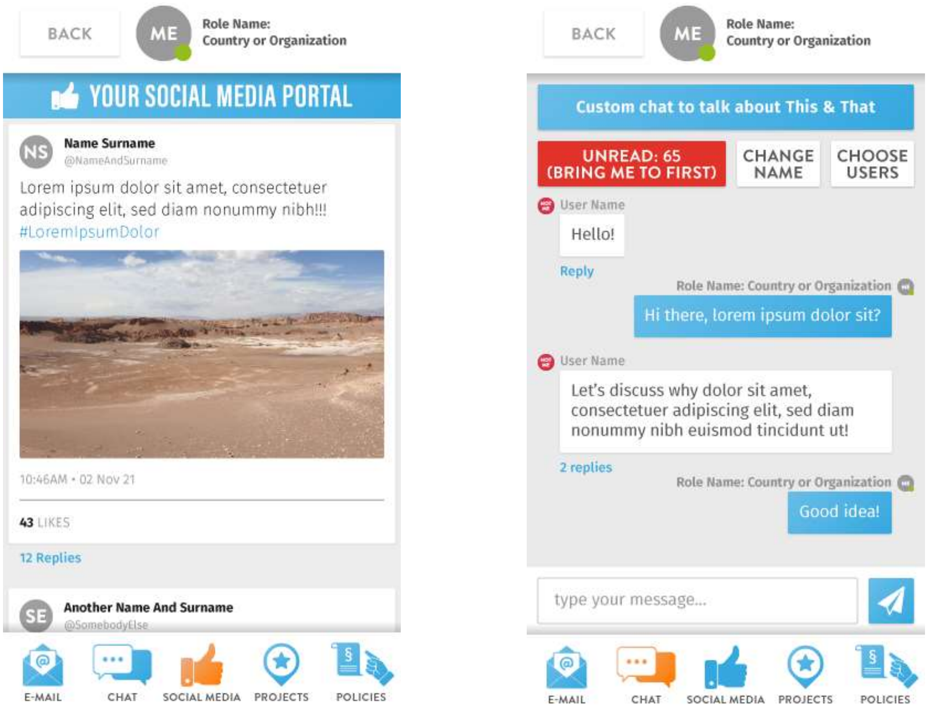

Figure 6.8.8. Multiplayer online browser-based social simulation: social media view and live chat view.

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6.8.3 General Overview of game design

The Work Package 3 Partners: RCCC, UNU-EHS, DBL, with the WP lead CRS, will draw on the existing state of art of serious games to provide stakeholders from application case studies with an immersive and social online experience for exploration of various possible future adaptation/DRR scenarios.

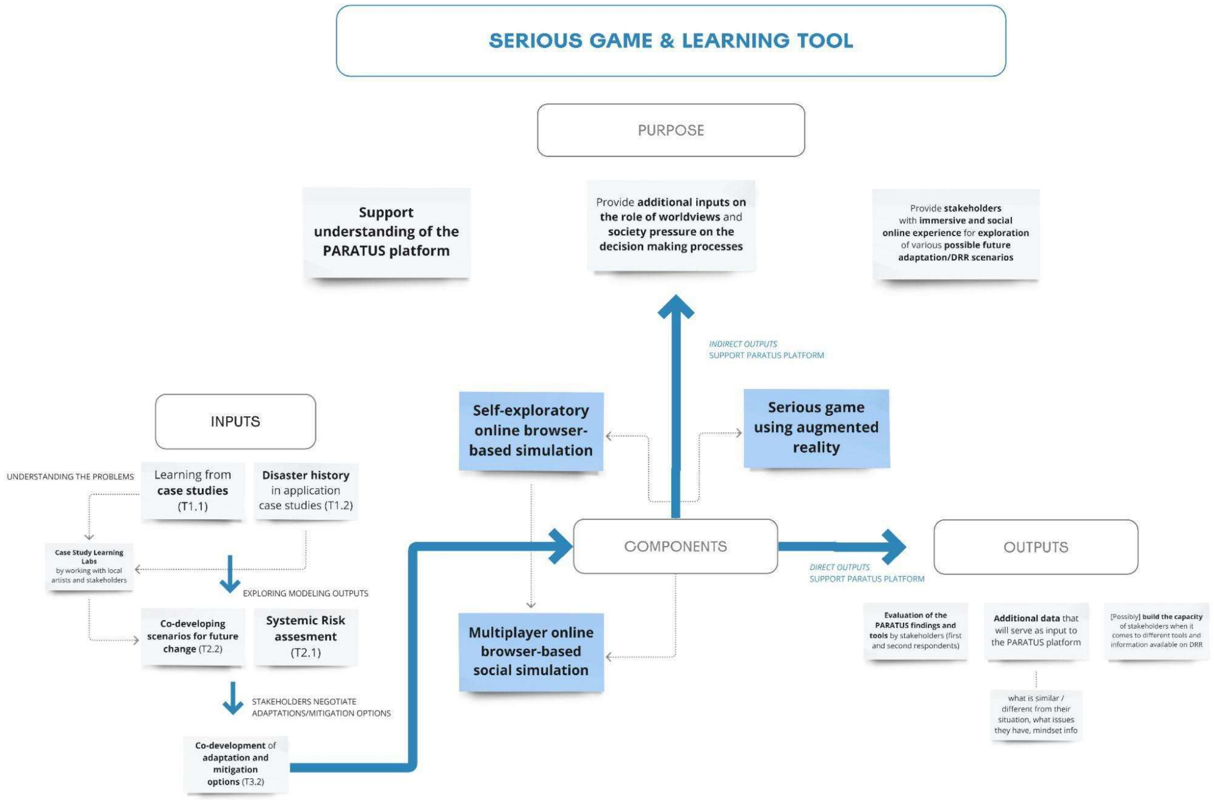

Figure 6.8.9. A general overview of the Serious Game & Learning Tool Module.

Moreover, the module will engage the stakeholders in the co-development process to ensure that the created applications are relevant and useful for the project participants and beyond. Use of the prototypes of the game in the Learning Labs to test the viability of options and keeping a feedback loop to the development of the serious game application in a few language versions (languages of the case studies and English; T3.2), in collaboration with case study leaders.

Another game will directly link to task 3.2 and 3.4 and will explore possible adaptation and DRR pathways in an augmented reality application. The co-development process will also enrich the Case Study Learning Labs by working with local artists and stakeholders to co-create future adaptation and DRR scenarios. The application will allow the user to be immersed in a few future scenarios through experiencing artists' impressions of those.

The development of each component of the module will be described in the deliverables 3.4 and 3.5. The document includes the concept for linking of the components with the PARATUS platform and reasons behind assumptions. The assumptions may change due to the co-design process, and newly discovered needs of the users. Due to the iterative nature of both platform and its components, the document should serve only as the initial concept.

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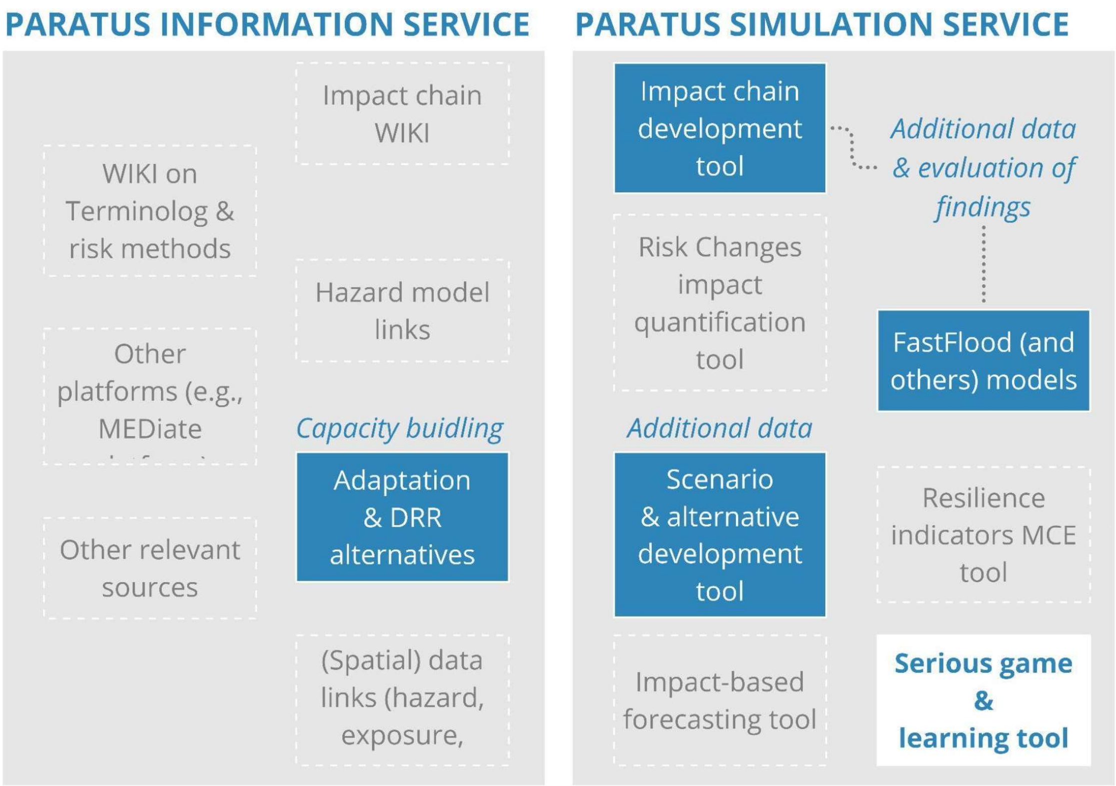

Figure 6.8.10. Outputs linked to other services offered by the PARATUS Platform.

6.8.4 Assumptions/Constraints/Risks

Assumptions

The assumptions for the inclusion of the components on the platform are based on:

- Groups of users targeted by platform and components of the Serious Games module;
- the purpose of the module and its separate components.

Main assumptions for the components of the modules, which will be described in more details in the deliverables 3.4 and 3.5 include:

- Accessibility on mobile devices;
- being able to concurrently use the components of the Serious games modules with other modules of the simulation;
- ability to use the components of the Serious games module during workshops in ad hoc fashion;
- use of pre-existing tools and libraries for the development of the simulations.

Considering the assumptions above, rather than completely merging tools within the platform, the tools will be embedded in the platform and hosted using other servers (for 1) and 2) Centre for Systems Solutions dedicated server, for 3) app service provider.

Main reasons for such decisions are as follows:

- Many tools on the platform are developed using different programming languages, navigating the backend would be difficult for the team working on the games, due to the flow of the development process. More on that in the design considerations.

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- The tools will be designed to work on mobile devices, whereas the platform will be used primarily on desktops.
- The direct interactions between other tools and simulations are limited, and simulations will be using a pre-prepared set of data based on the outputs of other work packages.
- Separation of the simulations from the platform enables Centre for Systems Solutions and Red Cross an easy access and dedicated support to the users of the simulations beyond the duration of the project.
- The simulations will be based on a pre-existing framework that is constantly developed and improved to support newer browsers and devices.
- The components of the Serious Games modules may have a wider target group than the known platform target group. Though primarily developed for stakeholders and decision-makers, they will be usable for citizens and youth. To avoid security problems and enable easier access to other target groups that may not necessarily see the need to access the PARATUS platform.

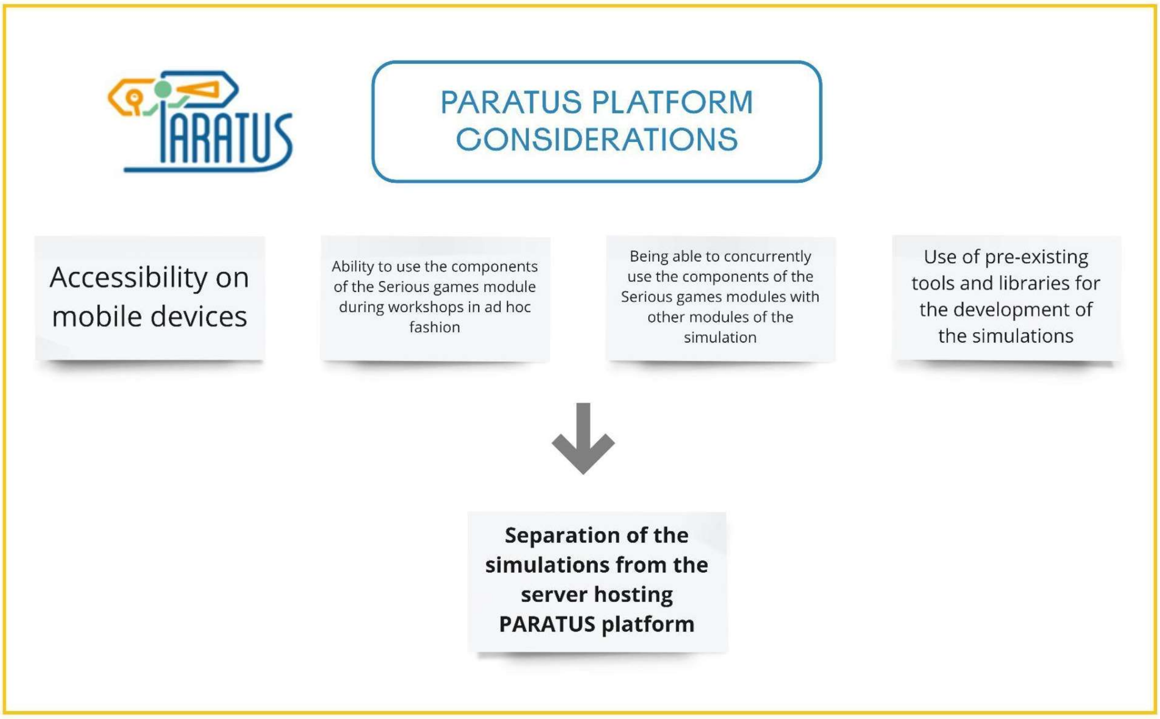

Figure 6.8.11. Consideration regarding the serious games and the PARATUS Platform.

Risks

One of the challenging risks for including this module in such a way is transferring users entering simulation in such a way out of the platform. To mitigate this - all the outgoing links in the platform will open a new tab, rather than opening links in the current tabs. Each downloadable document and simulation will also have an outbound link back to the platform.

The platform will also provide QR codes, so that they can be accessed from mobile devices or other devices while staying within the bounds of the platform. Outbound links from the information services to the simulations could also be provided to enable users to actively experience topics that they are reading about via self-exploratory simulation.

As the simulations wouldn't be hosted on the same platform as the rest of the PARATUS platform, there is a risk of users facing a situation where though the platform is working correctly, they cannot access the simulations. There will be care put into scheduling maintenance of the simulation servers and PARATUS platform to the same time and date to avoid problems like this. For other downtime issues, the platform will provide links to websites or social media channels describing the current status of the servers.

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6.8.5 Design Considerations

The design of the module is based on design thinking and co-design principles where prototyping and extensive testing are key activities. Separation of the simulations from the server hosting the PARATUS Platform enables the game design team to extensively test and prototype the simulation not only internally, but also in the online environment with the stakeholders and project partners on varied devices and in different settings.

Goals and Guidelines

The form of the module is dictated by a few factors, which some are already mentioned above.

- Wise target group
- Use of mobile devices
- Use of pre-existing frameworks and libraries
- Enabling future developments of the simulations, e.g., by localizing them for new languages and contexts

There are three types of users that can be defined for the components of the Serious Games modules:

- User-player
- User-moderator
- User-admin

User-player is a user that plays the simulation, meaning actively engages in it in one of the roles. User-moderator is present only for the component 2). User-moderator is a person that manages the closed environment for the simulation, choses a scenario and settings for the sessions to provide each user-player the experience most suitable for the goal and social interactions. The components 1) and 3) lack this role, as those components provide more freedom in free exploration of the topics and approach the social aspects a bit differently.

User-player and user-moderator can be Platform users, but they can access components of the module from external sources.

User-admin (or user-developer) is a special role that enables inclusion of the changes on the simulation and will be used primarily during the co-design and testing phases by the games development teams. It is mentioned here, as it’s important that the development process also considers needs of the development team, for good workflow and collaboration.

The distinction between these 3 groups of users is important to make the components user-friendly while referring to the design of other modules and tools in the Platform.

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6.9 Collaborative planning tools

The aim of collaborative decision support procedures is to involve stakeholders in decision making to solve conflicting issues. Consensus building methods include developing alternative planning scenarios, brainstorming jointly on evaluation criteria for certain plans, sketching different plan alternatives, or assigning individual priorities and criteria weights during an assessment. Structuring decision making processing following a sequence of converging and diverging steps helps to better integrate consensus building steps into the process.

Various working modes can be used in these steps, i.e., individual activities or large group collaborations, to achieve a consensus decision in the end. Collaborative planning tools is composed of Various hard- and software components can be utilized to support the different phases of spatial decision making.

Figure 6.9.1: A maptable, an example to collaborative planning tools (source [123])

''Collage'' and ''Ogito'' are two examples to collaborative decision making tools that are developed in the University of Twente. The former, COLLAGE – Collaborative Location and Allocation Gaming Environment, is an interactive mapping game that allows various stakeholders to discuss and negotiate about the pros and cons of different paths to a larger supply of local renewable energy together with citizens. During the game workshops, experts provide the local technical, economic and social knowledge with the participants. The overall aim is to co-develop the knowledge to support local pathways to a lower-carbon economy. COLALGE was developed within the EU FP7 funded research project: COMPLEX. The latter, OGITO- Open Geospatial Interactive Tool, is an open-source software tool that was developed following human-centred design and Agile software development principles. The tool was co-developed through iterative development cycles and feedback from the community in Sumatra, Indonesia.

Incorporating Planning Support Systems (PSS) on a maptable is a large horizontal touch screen and provides an interactive environment by supporting and enhancing participation of various stakeholders to the decision

[123] https://www.itc.nl/facillities/labs-and-resources/thedisc/

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making processes. Such an approach facilitate group learning by allowing to exchange knowledge between stakeholders and support building consensus among them. Flacke et al. (2000) state that all kind of Planning support systems succeed to facilitate collaboration of stakeholders intensively. A maptable provides a GI-based visual platform that is easy to understand by the variety of stakeholders regardless of their IT literacy or knowledge background (Aguilar et al., 2020).

The studies show the importance of interactive and collaborative decision making systems, i.e. map-tables, to support social learning, decision making and awareness raising on various societal problems. Additionally, studies also prove that following iterative development cycles and incorporating user feedback throughout the process improve improvement the tool's usability and functionality, and consequently, increase the societal impact.

Figure 6.9.2: The Design and Interactive Space for co-creating (DISC) laboratory in ITC/UT (Source: [124])

[124] https://www.itc.nl/facillities/labs-and-resources/thedisc/#workshops

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7. Conclusions

This deliverable provides the first version of design of the PARATUS platform, which integrates the various tools developed within this project to support first and second responders and other stakeholders in Disaster Risk Management.
The components that are currently envisaged in the PARATUS platform are presented in this document. **The exact number of components, and the final structure of the platform will be determined iteratively through a number of stakeholder consultations, following a use-centred design**, as described in this report. It is important to state here that the design will be a compromise between the stakeholder needs of the stakeholders involved in the PARATUS project as project partners (DSU in Romania, ASFINAG in Austria, IMM in Istanbul and NRC in the Caribbean), and stakeholder requirements of stakeholders outside of the consortium. The platform should be both generic enough to be able to cater for stakeholders that work in different sectors, geographic setting, and interacting hazards, and specific enough to address (several) their needs for analysing the impact of compounding and multi-hazard events, with cascading impacts.

In workshops that will be organized in the period between May 2023 and May 2024 we will present and discuss the platform ideas to a range of stakeholders that participated in the initial workshops in the four application case study areas. The co-development will be done with first and second responders and other stakeholders. This is a wide range of stakeholders. First responders such as civil protection agencies (for example DSU in Romania) will be involved to evaluate the use of the system in emergency response planning. Humanitarian organisation (for example the Netherlands Red Cross and its affiliated organizations on the Netherlands Caribbean islands) will be involved to evaluate the use of the platform in impact-based forecasting, and early actions. Secondary responders (for example the Austrian highway authority ASFINAG) will be directly involved to test the applicability of the platform in evaluation complex impacts under future scenarios and take adaptive actions.

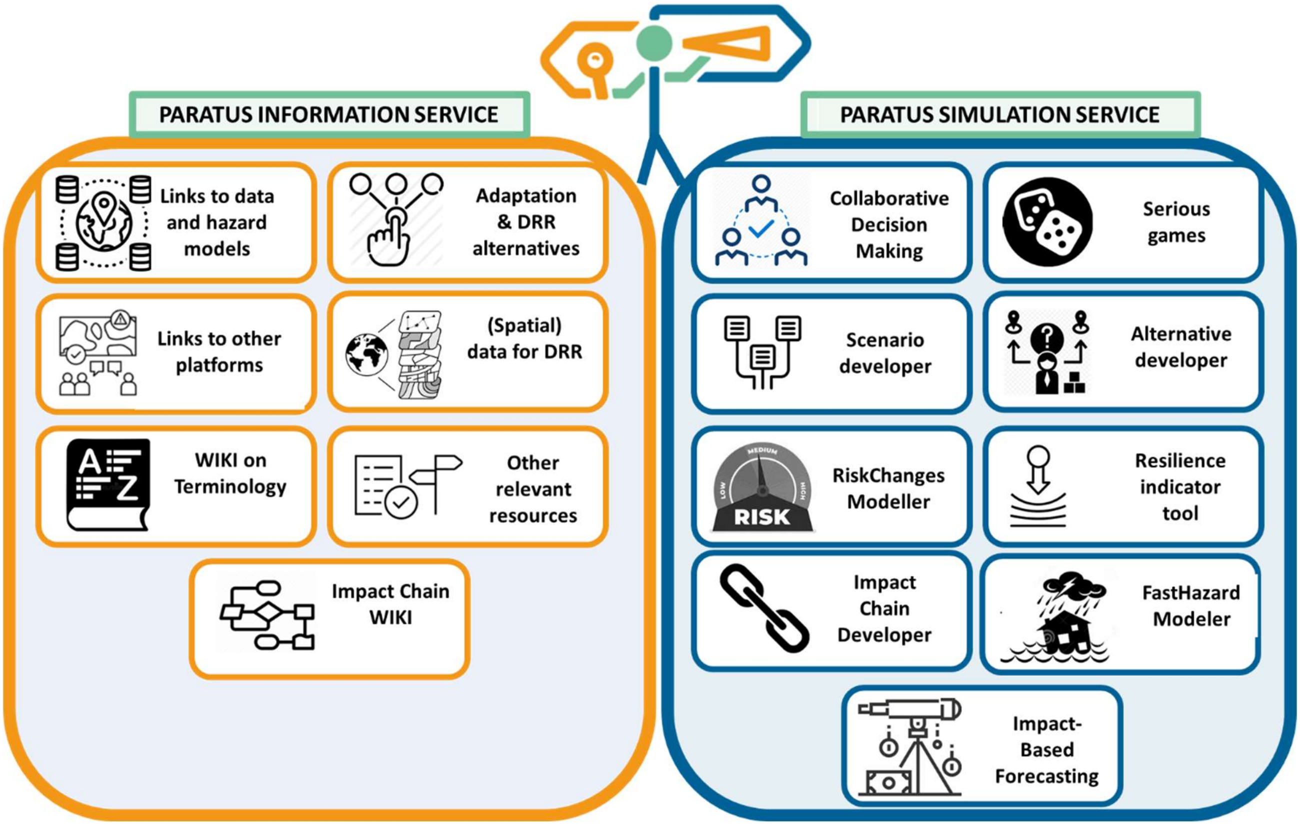

Figure 7.1: Summary of the two sections of the PARATUS platform with the proposed components.

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The description of the components is not equally large, which reflects the different levels of conceptualisation that is ongoing with respect to the various components. As indicated in table 1.1 some of the components of the PARATUS platform will be delivered late in the project. For example:

- Taks 4.3 (Scenario formulation and selection approach and tools), will be carried out between M24-M44) and coordinated by IIASA. The description in section 6.6 of this document is therefore still basic. The aim is that systemic dependent risks will be analysed and characterized by developing specific systemic risk measures based on robust statistical analysis, extreme events data, and machine learning approaches in close cooperation with stakeholders and experts. This task will integrate data farming approaches for the evaluation of scenarios. The approach will provide the capability of executing enough experiments so that both frequent and rare unexpected results may be captured and examined for robust insights and policy recommendations.
- Task 4.4 (Cloud-based Integration of tools for decision-making with respect to adaptation measures under possible scenarios) will be carried out between M30 and M46 and will be coordinated by RCCC. Section 6.5 provides a first idea on this component. The aim is the co-creation of possible adaptation measures for reducing the impact of complex multi-hazard impact chains, and the evaluation of optimal alternatives as a basis for decision making. Selection of a set of adaptation alternatives and a limited number of alternatives that apply for the specific sector and case are selected, modified for the local condition. The most important component is a cost-effectiveness analysis tool, allowing to evaluate changes in social impacts for planning mitigation options. It also includes a Multi-criteria Evaluation tool allowing to develop participatory decision making and the integration of non-quantifiable and qualitative considerations on optimal adaptation measures under uncertain scenarios. It also includes a cost-benefit analysis tool. Also, the tool will incorporate robust decision support models and methodologies based on novel dynamic stochastic optimization approaches incorporating interdependent feasible precautionary (mitigation) and adaptive (operational) actions co-designed with stakeholders and experts.

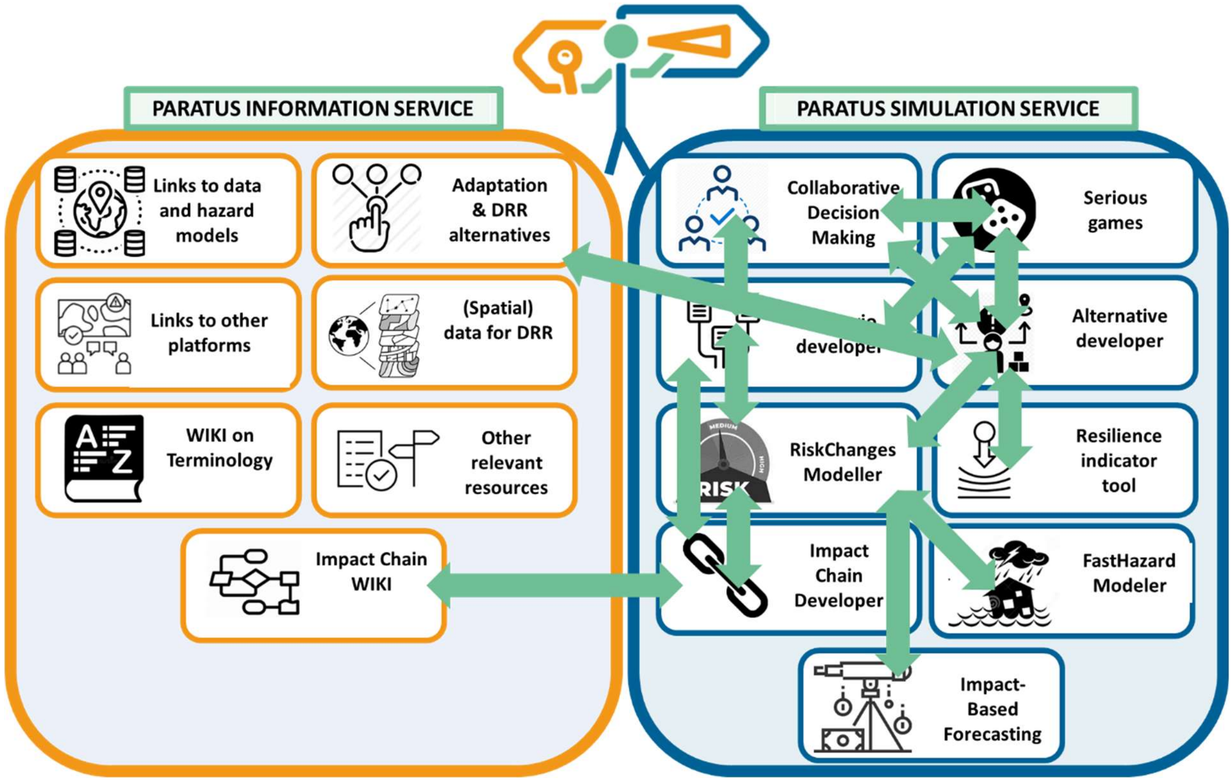

Figure 7.2: Links between the components of the PARATUS platform

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Figure 7.2 provides an schematic overview of the links between the various components of the PARATUS platform. These links could be either direct: data from one component can be directly entered into another component. However, in most of the cases these links will be indirect. The components will be standalone tools, and the output files form one tool can be entered into another tool. So interoperability is an important aspect in the development of the tools.

For the development of the components a number of partner will take the lead and other will contribute . An overview of the responsible project partners for the tools is given in Figure 7.3.

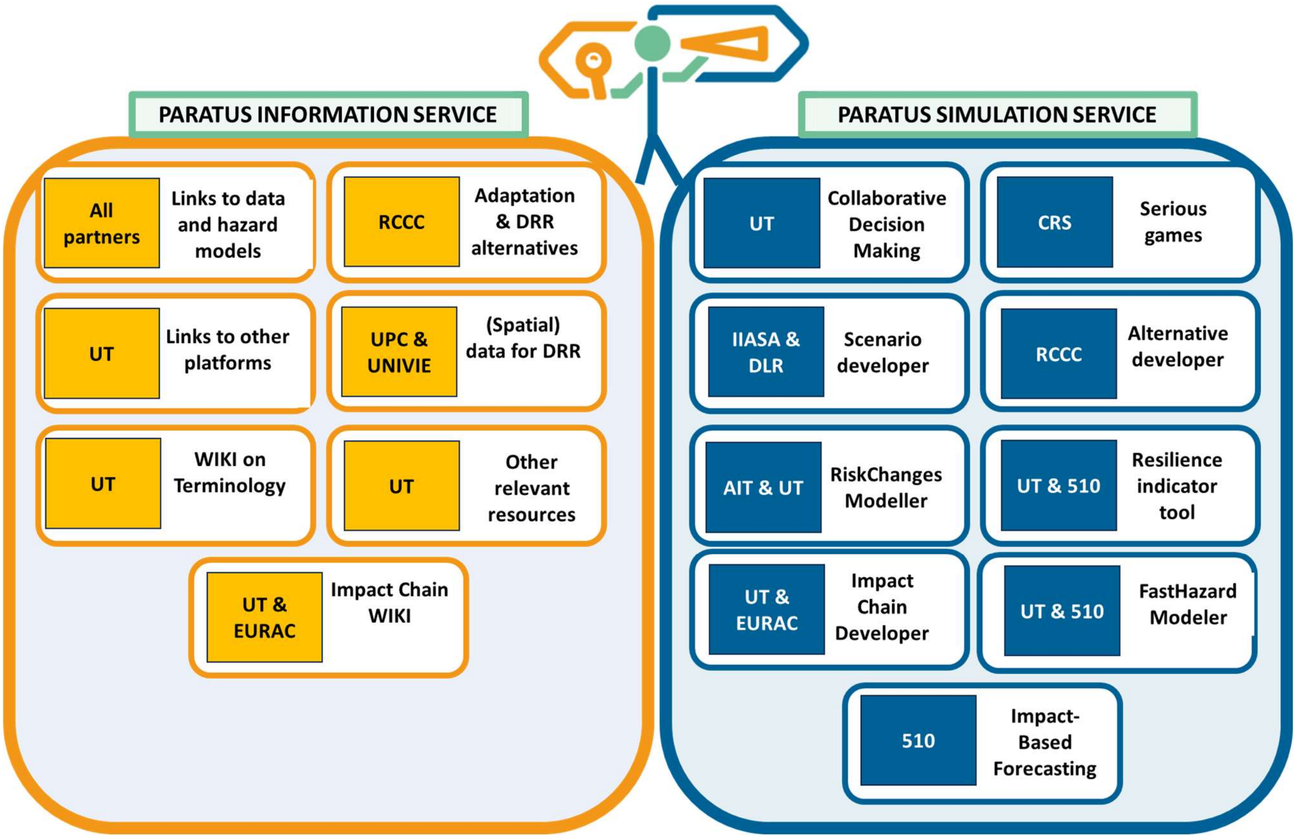

Figure 7.3: Overview of the partners involved in the development of the components of the PARATUS platform.

The final platform will be implemented in two communities of practitioners:

CMINE Development: Rather than recreating a comprehensive platform for internal and external communication and engagement, the project has elected to make extensive use of the community of practice known as CMINE[125] , which was developed as part of the FP7 & H2020 project **Driver+**. The CMINE platform was completed in Summer 2020 and, under a Memorandum of Understanding with the Research Executive Agency, passed to *PARATUS* partners RAN to facilitate and administer on a not-for-profit basis. CMINE will be used as the foundation for the creating a community Hub engaging all users within *PARATUS*. When it migrated out of Driver+ governance, this was seen as a strong component of the sustainability strategy ensuring its future. Since then, membership has almost tripled, and the platform has continued to grow. Using it as proposed within this proposal not only supports that continuation, but it creates a unique element for the sustainability of *PARATUS* well beyond its 4-year horizon. At the end of the project, a legacy will have been created that will be highly beneficial for all stakeholders and sustainable for at least a further three years.

[125] https://www.cmine.eu/

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Multi-hazard Impact-based forecasting Platform: the 510 Data & Digital team[126] supports national societies of the Red Cross Red Crescent movement with data and digital products to make humanitarian aid faster and more (cost) effective. One of the products developed by 510 for disaster managers is a platform for decision making support in the wake of a disaster: the Impact Based Forecasting platform[127]. The IBF platform is a one stop shop of information for decision making during anticipatory action, co-designed with 100+ disaster managers in the Red Cross Movement and partners and currently operational in Zambia, Uganda, Zimbabwe, Ethiopia, Philippines. The platform is multi-hazard and currently developed to include models for forecasting floods, typhoons, droughts, heavy rains, and dengue epidemics. The platform is cloud-based hosted in the 510 data architecture and can be packaged for full handover to the relevant stakeholders. Drawing on this development, a multi-hazard risk assessment platform will be developed to include the risk and impact models developed in *PARATUS*. Human-Centred design methodology will be used to identify end-users, define the problem the platform will solve and gather insights to ensure the platform will be usable and useful to be adopted by the users. Short cycle user testing will keep the user engaged and involved during the development of the platform, introducing innovative training elements to the platform.

[126] www.510.global
[127] https://www.510.global/impact-based-forecasting-system/

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