C2IMPRESS

D.3.5: Implementation of (a) PPCP and (b) integrated mapping tools for risk communication v2

WP3

March 30th, 2025 (M30)

This project has received funding from the Horizon Europe Framework Programme (HORIZON) Research and Innovation Actions under grant agreement No 101074004

DISCLAIMER

Technical References

Project Acronym	**C2IMPRESS**
Project Title	Co-Creative Improved Understanding and Awareness of Multi-Hazard Risks for Disaster Resilient Society
Project Coordinator	Dr. M. Serdar Yümlü Sampas Bilisim ve Iletisim Sistemleri Sanayi ve Ticaret A.S. serdar.yumlu@sampas.com.tr
Project Duration	1 October 2022 – 30 September 2025 (36 Months)

Deliverable No.	D.3.5
Dissemination Level	SEN
Work Package	WP 3 – Multi Hazard risk management, exposure and resilience Framework
Task	T.3.4 – Use of PPCP approach for effective risk communication to the public (building consciousness and resilience) v2
Lead beneficiary	ART
Contributing beneficiary(ies)	All CSA partners
Due date of deliverable	March 30th, 2025
Actual submission date	March 28, 2025

Version	Person	Partner	Date
01	Alexandra JAUMOUILLE	ART	22/02/2025
02	Catherine FREISSINET	ART	24/02/2025
03	M Azizur Rahman, Sifat Islam	TVS	04/03/2025
04	Cenk Gureken	SAM	05/03/2025
05	M Azizur Rahman	TVS	09/03/2025
06	Ana Catarina Zózimo Nurhan TEMIZ Josué Díaz Jiménez	LNEC ORDU GOIB	13/04/2025
07	Catherine FREISSINET	ART	14/04/2025
08	Julia HALL, Rui PERDIGÃO Adem B.	MET IU	21/03/2025
09	M. Azizur Rahman Sifat Islam	TVS	26/03/2025
10	Catherine FREISSINET	ART	27/03/2025
11 (Final)	Cenk Güreken	SAM	28/03/2025

Disclaimer

The information reflects only the authors' view and the Commission is not responsible for any use that may be made of the information it contains.

Table of Contents

List of figures

List of tables

Acronyms

ABM	Agent-Based Model
AI	Artificial Intelligence
APA	Administraçion de Porto (Portugal)
ANN	Artificial Neural Networks
ART	Artelia
C2IMPRESS	Co-Creative Improved Understanding and Awareness of Multi-Hazard Risks for Disaster Resilient Society
CC	Climate change
CSA	Case study area
D&E	Dissemination & Exploitation
D3R	Disaster Risk Reduction & Resilience
DSS	Decision Support System
EC	European Commission
EGL	Egaleo Municipality (Greece)
EU	European Union
GA	Grant Agreement
GOIB	Govern de Les Illes Balears
HBM	Human Behaviour Model
ICT	Information and Communication Technology
IU	Istanbul University
LL	Living Lab
LNEC	Laboratório Nacional de Engenharia Civil
MET	Meteoceanics
MHRIN	Multi-Hazard Risk Intelligence Networks
NCSRD	National Centre For Scientific Research Demokritos
ND	Natural disaster
NGO	Non-governmental organization
ORDU	Municipality of Ordu (Turkey)

PPCP-LL	PPCP Living Lab
PPCP	Public Private Civil Partnership
RDI	Research, Development and Innovation
REX	Return on Experience
RMITE/U	Royal Melbourne Institute of Technology Europe / University
SAM	SAMPAS Holding
SECAP	Sustainable Energy and Climate Action Plan
SMCDA	Spatial Multicriteria Decision Analysis
SoS4MHRIN	System-of-Systems for Multi-Hazard Risk Intelligence Networks
SSH	Social Sciences and Humanities
TVS	Technovative Solutions
UCAM	University of Cambridge
UGA	Université Grenoble-Alpes
UIB	Universitat de les Illes Balears
WP	Work Package

Executive Summary

The overall objective of this deliverable is to present consolidated report on the Public-Private-Civic-Partnership (PPCP) approach in the C2IMPRESS case study areas (CSAs), and to describe the details of the spatial multicriteria decision Analysis (SMCDA) tool for risk mapping with an example study in Portugal CSA. Hence, for the simplicity the report has two sections where section A considers the PPCP study and section B presents the SMCDA tool. It is to be mentioned that this deliverable is the second version of the D3.2: Implementation of (a) PPCP and (b) integrated mapping tools for risk communication v1. In D3.2, the PPCP methodology has been explained in detail where in D3.5 it is rather short. The vice versa approach is considered for SMCDA. In D3.2 only high-level methodology was explained where D3.5 provides the details with an example.

PPCP approach: The Public-Private-Civil Partnership (PPCP) is a collaborative framework that aims at bringing together the public sector, private sector, and civil society organizations to address social, economic, and environmental challenges in a coordinated manner. It is an inclusive approach that recognizes the complementary strengths and resources of different stakeholders in achieving common goals. Therefore, as outlined in D3.2**,** the primary goal of the PPCP approach is to assist each Case Study Area (CSA) in collaboratively developing a polycentric governance system for managing risks associated with natural disasters. This system will be designed to align with the unique environmental, political, societal, and cultural specificities of each CSA. The implementation of each extra-public governance system will be customized to suit the distinct needs of each CSA.

By involving a diverse range of stakeholders and continuously refining the governance framework, the objective is to strengthen resilience and improve responsiveness to natural disasters. The framework seeks to promote a more inclusive, effective, and polycentric governance system for disaster risk management. WP7 provides a detailed outline of this framework in D7.1 and D7.2**.** The complete reports of the PPCP LL3 and PPCP LL4 will be presented in the appendices of the D6.3.

SMCDA tool development and testing: This report outlines the creation and application of integrated mapping tools aimed at assessing and communicating multi-hazard risks. The approach utilizes Spatial Multi-Criteria Decision Analysis (SMCDA) to support decision-making in disaster risk management. By combining hazard mapping techniques that employ both the Analytical Hierarchy Process (AHP) and machine learning methods with vulnerability mapping, the framework evaluates social, economic, and environmental elements that contribute to disaster risk. This system enables decision-makers to systematically analyze various hazard scenarios and develop targeted mitigation strategies to reduce potential impacts. To validate the methodology, a case study is conducted in the Mondego River Basin in Portugal. The hazard evaluation considers critical factors such as slope, precipitation, drainage density, soil type, and the Topographic Wetness Index (TWI). The vulnerability assessment includes socio-economic variables such as household income, literacy rates, emergency management capabilities, and access to clean water. A detailed risk map is created by integrating the flood hazard and vulnerability maps, helping to identify high-risk areas and support proactive disaster preparedness under flooding conditions. In addition, wildfire hazard is evaluated using factors such as elevation, land use, precipitation, and TWI, while vulnerability is assessed using the same socio-economic indicators as in the flood analysis. A wildfire risk map is then generated by combining these layers. These individual risk maps are subsequently integrated to produce a comprehensive multi-hazard risk map for enhanced disaster management and planning. A web-based decision support tool has been developed to improve the visualization, processing, and analysis of spatial data. This interactive tool allows users to process data and apply normalization and reclassification methods for data standardization. It also supports constraint-based adjustments to refine hazard and vulnerability evaluations. The system is incorporated into the C2IMPRESS Decision Support System (DSS), ensuring accessibility and user-friendliness for stakeholders involved in various decision-making contexts, including emergency response planning. Additionally, a map server has been developed to visualize and operate GIS-based results within the DSS platform.

1. Introduction

This deliverable corresponds to Deliverable 3.5. Implementation of (a) PPCP and (b) integrating mapping tools for risk communication. It is to be submitted in month 30 of the project (i.e., in March 2025). This deliverable is the continuity of the D3.2 which was dedicated to presenting the theoretical approach of PPCP, the concepts and tools it aims at using, and the method for implementing this approach for the four pilot sites of the C2IMPRESS project. The main objective of D3.5 is to present and analyze the methodology while the methodology implementation is detailed in the WP6. In fact, the implementation was carried out as part of WP6, and the analyses and conclusions are presented in D6.3 “Validation of models, methods and technology at different case study V2”.

The main outcome of the application of the PPCP approach, which is the co-creation of a new polycentric governance framework to better manage natural disasters (before, during and after), will be the subject of two other deliverables linked to the C2IMPRESS project:

Deliverable D7.1 "Polycentric risk governance framework - mapping and analysis at CSA level", which consists of a mapping and analysis taking societal, ecological and legal issues in consideration.

Deliverable D7.3 "Integrated climate change adaptation policy, multi-hazard risk management framework, legal issues and best practices (national and EU level) and policy recommendations".

This deliverable encompasses the efforts undertaken across two distinct tasks: Task 3.4, detailed in Section A, and Task 3.5, outlined in Section B.

As a reminder, those two tasks are detailed below:

- **T3.4: Use of PPCP approach for effective risk communication to the public (building consciousness and resilience)** (Leader: ART, Partners: all CSA partners) [M3 – M14]:

This task 3.4 was dedicated to collective intelligence, exchange of information on the different approaches for setting up the CSAs (WP6) and the management approaches enabling its achievement. In collaboration with CSA partners, ART defined the operative strategy for the CSAs e.g. identifying local key end-users/stakeholders for further engagement through a social diversity analysis (including the most vulnerable communities), an institutional analysis and a cultural analysis, and setting up the processes of knowledge exchange amongst different stakeholders.

- **T3.5 Integrated, robust and interactive spatial hazard, vulnerability and risk mapping tool and a ‘Map Server’ for visualization** (Lead TVS, partner: all CSA partners) [M14-M30]

TVS has combined the risk and resilience framework to develop a decision support tool that will facilitate the decision-makers to analyze, prioritize and rank options. An interactive and integrated spatial multicriteria decision analysis (SMCDA) tool will be developed that will be tightly integrated with Q-GIS environment. The functionalities of the Q-GIS were extended by implementing the SMCDA within the GIS environment to combine the advantages given by the user interface controls available in the Q-GIS. SAM developed a map server that will be connected to all assessment studies and visual the spatial map.

During the four PPCP Living Labs conducted, a mapping approach was proposed to identify the natural hazards present for each Case study area and the vulnerabilities associated with these hazards. Moreover, risk mapping was one of the supports to help the PPCP-LL participants to draw some scenario to better protect the territories.

The different natural risks, the multidimensional effects of these risks (economic, social, environmental, infrastructure service loss, physical damage, etc.) and the disaster risk management system were discussed during the PPCP LL, enabling stakeholders from different sectors to contribute their knowledge and opinions on these subjects.

A. PUBLIC-PRIVATE-CIVIL PARTNERSHIP (PPCP)

2. PPCP Concept

2.1. Scope

The Public-Private-Civil Partnership (PPCP) is a collaborative framework that aims at bringing together the public sector, private sector, and civil society organizations to address social, economic, and environmental challenges in a coordinated manner. It is an inclusive approach that recognizes the complementary strengths and resources of different stakeholders in achieving common goals.

The three main categories of PPCP stakeholders are:

- Public Sector: This includes government agencies and institutions at various levels, such as national, regional, and local governments. The public sector typically provides policy direction, regulatory frameworks, and public resources to support the partnership.
- Private Sector: This refers to businesses, corporations, and industry associations that operate for profit. The private sector brings in financial resources, technical expertise, innovation, and market-driven approaches. It can contribute to the partnership through financial investments, technology transfer, job creation, and sustainable business practices. The private sector's involvement often leads to the development of new products, services, and employment opportunities.
- Civil Society: This encompasses non-governmental organizations (NGOs), community-based organizations, advocacy groups, and other voluntary associations. Civil society organizations represent diverse interests, including social and environmental concerns, human rights, and community development. They play a critical role in promoting social inclusion, participatory decision-making, and the voice of marginalized groups. Civil society organizations often bring grassroots knowledge, mobilize public support, and advocate for the public interest.

The PPCP model emphasizes collaboration, shared responsibilities, and mutual accountability among these three sectors. It recognizes that no single sector can address complex challenges effectively in isolation. By leveraging the strengths and resources of each sector, PPCP aims to achieve sustainable and inclusive development outcomes.

PPCP initiatives can take various forms, such as joint projects, multi-stakeholder platforms, policy dialogues, and public-private-civil society forums. These partnerships can focus on a wide range of issues, including infrastructure development, healthcare, education, environmental conservation, poverty alleviation, and social welfare.

2.2. Objectives

PPCP Living Labs are one of the most important social learning environments for organizations. However, social learning is often overlooked in analysing the social dimensions of risks and disasters. Ross (2023) concluded in their research that social learning can help change practices by creating more lasting and effective responses for future disasters. In addition, the study found that social learning can help question the "vulnerability narrative" and encourage resilience-oriented approaches. They also noted that social learning provides an opportunity to make sense of changes, create a broader set of strategic options and foster innovation. This is why the PPCP approach is included in the polycentric governance framework (PGF) model to foster social and organizational learning to increase risk reduction and resilience in disaster management.

Therefore, as described in D3.2, the main objective of the PPCP approach is to support each case study area (CSA) in co-constructing a polycentric governance system for the management of risks linked to natural disasters, in accordance with the specificities linked to the CSAs (environmental, political, societal, cultural, etc.). The establishment of each extra-public governance system will be tailored for each CSA.

The specific objectives of the PPCP are to:

- **Incorporate** civil society into decision-making processes at the territorial level;
- **Propose** a new multi-party engagement structure;
- **Increase** acceptability and transparency of governance actions;
- **Improve** collective intelligence and public awareness on disaster risk management and climate change;
- **Foster** the sharing of knowledge and beneficial experiences as well as the reproduction of good practices with regard to risk management and more generally to climate change.

This approach should make it possible to:

- **Develop multi-stakeholder decision support micro-services** as well to improve public awareness and understanding of natural disasters:
    - Develop a co-design and co-creation approach for socio-technical innovations, knowledge generation and validation to empower citizens and society to act on climate considering future resilience in multi-risk crisis.

Induce an evolution towards new forms of governance to increase the participation of all actors in decision-making for a sustainable transition towards a just and risk-resilient society.

2.3. Outcomes

The main expected outcome of the PPCP is to have an operational polycentric governance framework in each territory, capable of governing risk management. The specific outcomes are as follows:

- Solutions adapted to the local context are co-created by local stakeholders;
- An autonomous governance network for each CSA is created;
- The benefits and outreach of project results are maximized;
- Social acceptability of the project is promoted;
- Collective intelligence and public awareness are improved;
- The sharing of knowledge, beneficial experiences and good practices regarding disaster management and climate change resilience is fostered.

2.4. Principles

The principles of PPCP are collaborative thinking, interdisciplinarity and collective intelligence. They allow co-creation, collaborative decision, and policy-making in a **quintuple helix setting** (Carayannis et al., 2012) (e.g. co-creation of local visions, plans for citizen science activities for hazard risk observation and monitoring and a policy action roadmap towards a just and risk-resilient society). The Figure 1 presents the ideation of PPCP concept.

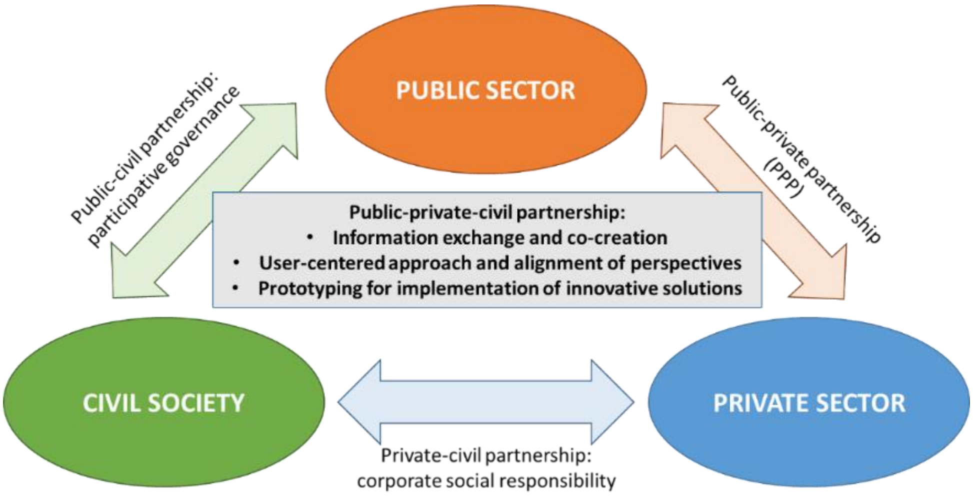


Figure 1: Ideation of PPCP concept (Source: ARTELIA, 2022)

2.5. Methods

2.5.1. Livings labs

A PPCP Living Lab (LL) methodology will be applied as the basis for the stakeholder engagement component of the project. The LL methodology is a transdisciplinary approach that recognizes that complex problems, such as those encountered in disaster management, cannot be solved by a single line of thought, a single discipline, or a single method. This process combines multiple forms of knowledge, including expert, tacit and local knowledge, to better understand the systemic aspects of management challenges and support the co-design of plans and solutions. The approach seeks to bring out ideas for the establishment of a polycentric system of governance, going beyond the State in natural disaster management projects.

The Living Lab methodology allows the creation of a platform promoting inclusion, interaction, collective intelligence and innovation, where the different actors can share their knowledge and create value around a problem, then of a common idea. The strength of the PPCP LL lies in its ability to bring together in the same workspace public authorities (municipal and provincial), NGOs and civil society organizations, researchers and academics, private companies and community organizations. Thus, the PPCP LL makes it possible to initiate a process of cohesion, dialogue and trust between the stakeholders who are a priori not connected to each other.

2.6. Design Thinking

Engineer and Stanford University professor David Kelley and designer Tim Brown developed Design Thinking in the 1990's through their design agency IDEO. This method, marked by its experimental nature, is divided into three main stages - immersion, ideation and implementation, which are subdivided into five phases - empathy with the user, problem definition, idea generation, prototyping and testing. Each of these phases is implemented in iterations.

The method emphasizes the following elements: the approach centred on the user's experience, the principle of multidisciplinarity through co-creation, the absence of a predefined problem, and finally, the notion of prototyping, which allows the right to make mistakes.

Figure 2 shows example of tools.

Why use Design Thinking in governance innovation?

- To transform the way public administrations operate when the service provided is not satisfactory or lacking
- To ensure that a policy or a proposed facility meets all the expectations of the end-users
- To improve the user experience.

→ The common point of these three objectives is to put the user at the centre of the questioning and the project.

Design can be particularly powerful for:

- Questioning the original problem, reformulate it and thus increase the chances of imagining a truly relevant response.
- Integrating all the actors in the project, linking them and thus guaranteeing the technical and economic feasibility of the solutions imagined. The mediation of design will allow to go from an idea to an innovation by making sure that the idea meets its public and will help all the actors to "reposition" themselves by rethinking their respective missions and their relationships.

Figure 2: Design Thinking-inspired toolbox

NB: the tools shown as thumbnails above will be explained in greater detail as the deliverable progresses (Source: ARTELIA, 2023)

2.7. Global view of the PPCP approach for the PGF

The specific objectives of the activities proposed through the PPCP are to:

- **Encourage collaboration and dialogue between public, private and civil society stakeholders.**
- **Stimulate creativity and innovation through adapted Design Thinking techniques.**
- **Develop concrete, visualizable proposals for a new polycentric governance framework.**
- **Propose concrete actions as part of the PG improvement and ensure their sustainability.**

Figure 3 illustrates the insertion of the PPCP approach in the development of a polycentric governance framework (PGF) and the global implication of the CSAs.

Figure 3: Global view of the PPCP approach for the polycentric governance

The overall goal is **to build with participants a shared vision of their territory's improvement.** The Figure 4 below presents the different phases and tools associated with the creation of the polycentric governance framework. All the phases are detailed in the D7.1.

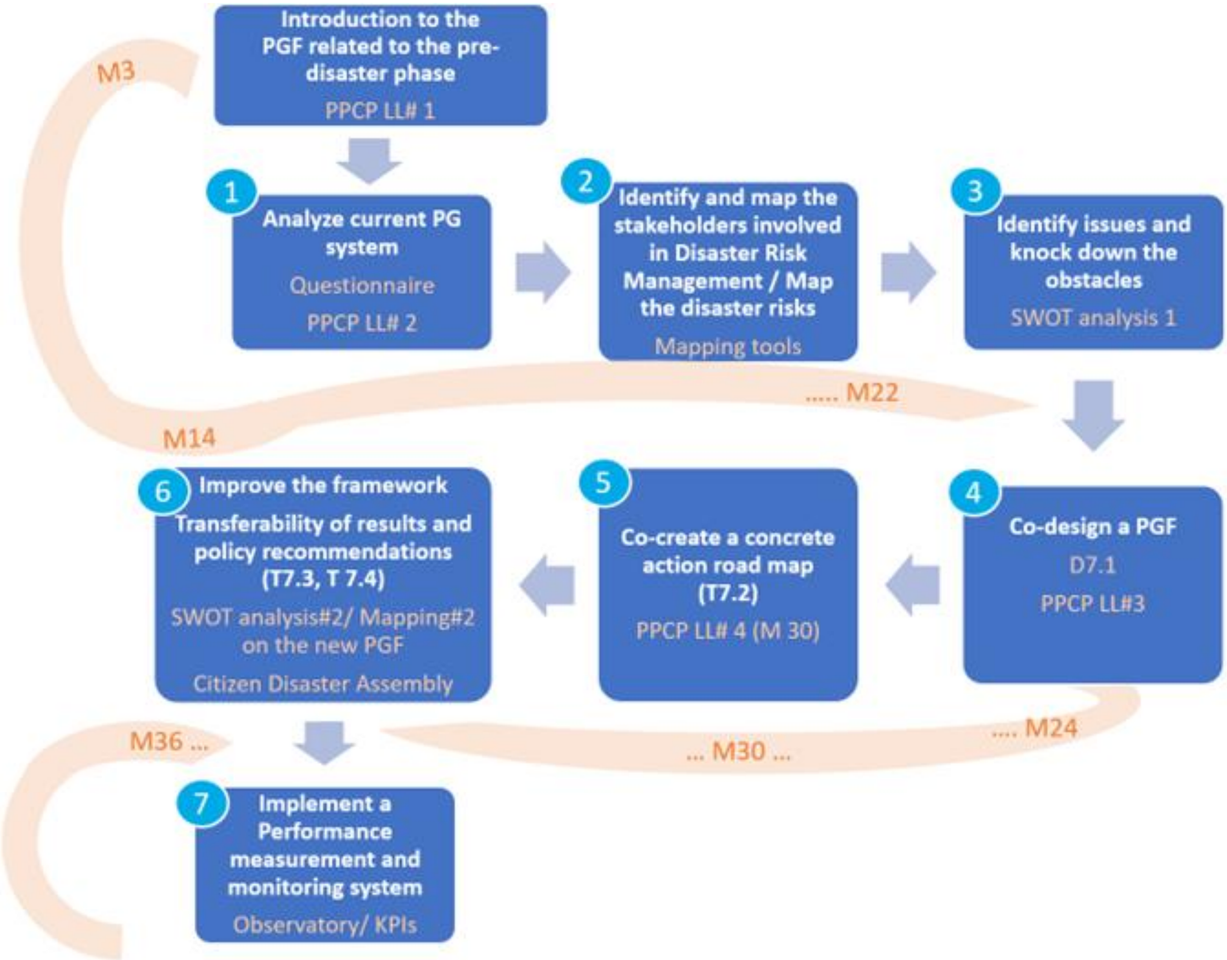


Figure 4: Global view of the different steps and tools associated for the development of the PGF (source: Artelia)

3. Implementation of the PPCP LL in the CSAs

3.1. Global view

Figure 5 below presents the different PPCP LL and their main objectives linked to the tasks associated.

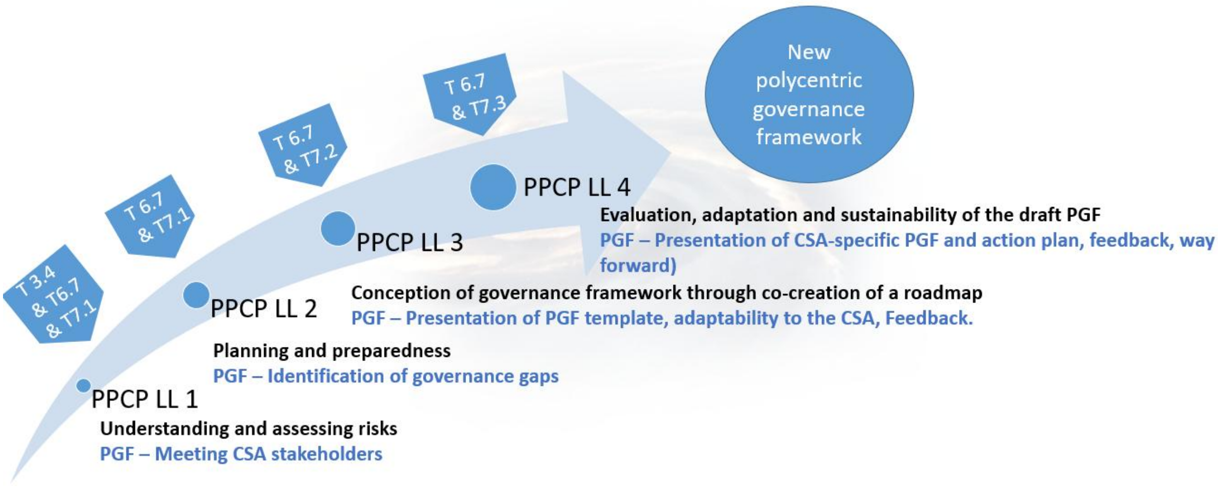


Figure 5: Global view of the different tasks linked to the PPCP LL

3.2. Objectives and outcomes of the different PPCP LL

- ### PPCP LL1

<table>
<tr><th>Global aim</th><td colspan="4">
• Present the C2IMPRESS project as well as the PPCP approach to stakeholders;
• Identify the stakeholders present;
• Understand the perspective of stakeholders on disaster management as well as the strengths and shortcomings of the current governance system;
• Raise the interest that stakeholders have in C2IMPRESS and identify the positive effects of the project for them;
• Emerge work leads for a partnership between stakeholders;
• Facilitate a comprehensive understanding and collaboration among stakeholders to enhance disaster management through the presentation of the C2IMPRESS project and the PPCP approach, identifying potential partnerships and synergies that can strengthen the current governance system.
</td></tr>
<tr><th rowspan="2">Implementation Period</th><th>Egaleo-Greece</th><th>Ordu-Turkey</th><th>Centro region-Portugal</th><th>Balearic Islands-Spain</th></tr>
<tr><td>April 28th, 2023</td><td>October 5th, 2023</td><td>October 16th, 2023</td><td>October 23rd 2023</td></tr>
<tr><th>Outcomes</th><td colspan="4">
• Choice of one disaster and evaluation related to the type of impact and social groups impacted
• Mapping disasters and environmental risks: Location, Severity, Type of impact, Groups and activities affected
• Definition of the strengths of the territory regarding disaster mitigation
• Definition of the measures to be implemented to better mitigate the disasters identified during the mapping
• Discussion about the precautions to apply to reduce the effects of potential disasters
</td></tr>
</table>

	• Discussion about the stakeholders that have an impact on disaster management - Positive aspects of the municipality for disaster mitigation - Measures you would like the municipality to implement to mitigate disasters - What other stakeholders are affected by/have an impact on disaster management - How participants can benefit from networking

- **PPCP LL2**

Global aim	• Initiate co-creation activities around a chosen disaster scenario identified in the PPCP LL1, begin by identifying and analysing the relevant stakeholders. Following this, define a specific scenario to address the problem and propose actions to be taken to strengthen partnerships and cooperation between various stakeholders. • Identify and analyse relevant stakeholders • Collectively define a specific challenge to respond to the problem • Conduct interviews to better define the issues related to their challenge • Preliminary identification of actions (Localisation, Axes of intervention, Vulnerable groups, Infrastructures, Services, Description of the action /Entities involved/ Objective and impact…) • Prototype a solution that meets their challenge.			
Implementation Period	**Egaleo-Greece**	**Ordu-Turkey**	**Centro region-Portugal**	**Balearic Islands-Spain**
	December 4th, 2023	February 29th, 2024	April 19th, 2024	April 19th, 2024
Outcomes	• Discussion on a primary challenge and the themes to be better addressed to achieve this goal. • Compilation of actions and Axis of intervention recommended for the pre-disaster phase. • Co-creation of a prototype to respond to the thread-question and the challenge defined by the group.			

- **PPCP LL3**

Global aim	• Define a common vision for the PGF discussing on the definition of a just risk resilient society and vulnerability. • Create a polycentric and inclusive governance framework for natural disaster management by facilitating the co-creation and collective visualization of stakeholder ideas. • Obtain feedback on the prototype that will have been designed during session 2 and tested between PPCP LL2 and PPCP LL3 and redesign the prototype according to the lessons learned; launch a second test cycle between PPCP LL3 and PPCP LL4. • Define recommendations to improve the governance of disaster risk reduction.			
Implementation Period	**Egaleo-Greece**	**Ordu-Turkey**	**Centro region-Portugal**	**Balearic Islands-Spain**
	October 1st, 2024	December 3rd, 2024	December 2nd, 2024	January 30th, 2024
Outcomes	• Co-creation of one or several polycentric governance models for natural disaster management, integrating various stakeholders and describing their roles and			

	interactions. These models will serve as a basis for developing a governance framework adaptable to the specificities of each CSA. • Discussion on the meaning of a "just risk resilient society" and "vulnerability" • Analysis of individual behaviours when facing a disaster event • Recommendations for the future action road map

- **PPCP LL4**

Global aim	• Co-creation of an action road map corresponding to specific measures related to disaster risk reduction to be implemented in the PGF and linked to specific identified stakeholders. • Co-design a new stakeholder mapping to improve the polycentric governance. • Analyse vulnerabilities to risks related to the gender perspective • Assessing Just Transition for vulnerable communities based on their vulnerability identification, existing action plans and local visions • Feedback on the overall experience regarding the 4 PPCP LLs			
Implementation Period	**Egaleo-Greece**	**Ordu-Turkey**	**Centro region-Portugal**	**Balearic Islands-Spain**
	February 25th, 2025	February 19th, 2025	February 26th, 2025	March 3rd, 2025
Outcomes	• Co-creation of an action road map and stakeholders associated integrated recommendations and solutions conceived during the previous PPCP LL • Analysis vulnerabilities to risks related to the gender perspective • Just Transition visions (linked to T7.2) • Feedback on the overall experience of the PPCP LLs			

All the tools used for these PPCP LL are detailed in the D3.2.

The complete reports of the PPCP LL1 and PPCP LL2 are presented in Appendix D of the D7.1.

Applications for the use of mapping tools in PPCP activities are presented in D6.3, the objective of which is to implement the tools on CSAs. Moreover, the complete reports of the PPCP LL3 and PPCP LL4 will be presented in the appendices of the D6.3.

The complete reports of the PPCP LL3 and PPCP LL4 will be presented in the appendices of the D6.3.

4. Conclusion

Data collected through questionnaires, PPCP Living Labs, stakeholder's relations mapping and SWOT (strengths, weaknesses, opportunities, and threats) analysis, highlight strengths and weaknesses of the current system through key themes such as communication, emergency planning, partnerships, citizen involvement, risk assessment, training, technology, legislation, and system adaptability. Each CSA has unique strengths and weaknesses, with varying degrees of polycentric governance elements. Those specificities require the adaptability of the PGF in each CSA depending on the needs.

By engaging diverse stakeholders and continuously refining the governance framework, the goal is to enhance resilience and responsiveness to natural disasters. The framework aims to foster a more inclusive, effective, and polycentric governance system for disaster risk management. WP7 details the framework through the D7.1 and D7.2.

B. INTEGRATED MAPPING TOOLS FOR RISK COMMUNICATION

5. Integrated Mapping Tools for Risk Communication

5.1. Background

During the early stages of land development and urban planning, individual hazard maps can be helpful, but they cannot accurately represent the complex scenario of multi-hazards. Multi-hazard risk maps provide a comprehensive representation of multiple natural hazards within a unified framework, making them a better option for planners to determine which places are most at risk, evaluate the effectiveness of different adaptation strategies, and create appropriate hazard risk mitigation strategies [1], [2]. Moreover, the multi-hazard risk map can be used for comprehensive and integrated land use planning and watershed management, leading to the sustainable development of the area of interest [3]. Decision-makers can develop effective evacuation plans by integrating socioeconomic data, such as housing and population distribution, which are integrated within a vulnerability map of a region. While this approach is particularly crucial for impoverished areas due to their limited resources and higher susceptibility to disasters, it equally applies to all communities to enhance overall resilience. Efficient evacuation planning can significantly reduce the number of casualties and injuries [2]. Additionally, a risk map can aid in communicating with citizens, especially people in vulnerable conditions affected by hazards [4].

For accurate assessment of hazard mapping, identifying triggering and causal indicators of hazards and their relationships with them is crucial, but there are no established principles for selecting these indicators [5], [6], [7]. These indicators are chosen based on a review of previous studies and data availability [8], [9]. Moreover, socio-economic indicators are necessary to incorporate into a risk map to understand a community's socioeconomic vulnerability, but these indicators depend on local conditions [10]. Please note that in this study “indicator” is called as “criteria” to be consistent with the Spatial Multi-Criteria Decision Analysis (SMCDA) Method.

Geographical Information Systems (GIS) are frequently used in various studies to interpret, analyse, and convert spatial data into spatially defined layers to produce decision criteria maps [11], [12]. Maps can convert qualitative raw data such as personal opinions, observations, and documents into a more practical format that would otherwise not easily be analysed or visualised by a statistical software [13]. Numerical operation using different GIS maps are not straight forward as they represents different themes such as soil map, water level (in meter), chloride concentration (in mg/L). These maps contain different units and cannot be readily merged into one map. Feloni et al. (2020) proposed normalisation (for regular/classical SMCDA technique) and reclassification (to perform machine learning approach in SMCDA) as two methods for standardising criteria maps.

Nowadays, machine learning (ML) techniques are being integrated with the processing capabilities of GIS and field datasets, such as historical hazard inventory and geo-environmental factors [7]. Machine learning approaches can yield more accurate hazard assessments, especially in data-scarce areas [15]. ML techniques determine the susceptibility of each hazard based on the dependent variables (i.e., the locations of hazards) and a set of practical criteria (i.e., the independent variables) [16], [17]. In remote sensing (RS) applications, random forest (RF) is widely used for image classification due to its high precision level compared to other ML methods. The RF model is specifically designed for ML classification and provides appropriate speed and well-organized parameterization for the process [9]. Random forest classifier resamples the dataset with substitution. It randomly alters the predictor sets over different tree induction developments to perform classification using a combination of numerous decision trees grown on a bootstrap sample [18].

The integration of normalised social, economic, and environmental criteria maps can be achieved through multi-criteria decision-making (MCDM) methods, such as the Analytical Hierarchy Process

(AHP) [16]. AHP is one of the most widely used MCDM approaches for assessing hazard vulnerability [11]. This method structures decision-making into a hierarchical framework, which consists of multiple levels, typically including the overall goal at the top, followed by criteria and sub-criteria. By organising complex problems into a hierarchy, AHP helps decision-makers systematically evaluate various factors affecting vulnerability. Once the hierarchy is established, AHP employs pairwise comparison to assess the relative importance of each criterion. This involves constructing a pairwise comparison matrix, where two criteria are evaluated at a time to determine their relative significance in achieving the overall goal [21]. The assignment of importance values relies on expert judgment rather than historical data, providing flexibility in decision-making. This subjectivity can introduce errors and limit reproducibility, making the approach less transferable to other locations or new situations [1]. However, when dealing with a large dataset and numerous criteria, selecting the most relevant factors can be challenging, potentially impacting the accuracy of the decision-making process [10].

Hazard Risk Mapping Tools, which consider exposure and vulnerability, have emerged as crucial instruments in evaluating, visualizing, and mitigating potential threats in risk management and disaster preparedness. These tools use advanced technologies and methodologies to systematically map and analyse various hazards within a defined geographic region. They provide critical insights into the distribution, intensity, and potential impact of hazards, making them an essential resource for decision-makers, planners, and emergency responders.

5.2. Scopes

In Task 3.5, TVS has developed a web-based decision support tool for creating multi-hazard risk maps. At first, a structured methodology has been developed to facilitate hazard and vulnerability mapping. Subsequently, a multi-hazard risk map can be derived (as explained in the methodology section) by combining hazard and vulnerability maps. This decision support tool employs an Spatial Multi-Criteria Decision Analysis (SMCDA) approach to effectively analyse, prioritize, and rank vulnerability on a spatial scale. To further enhance the tool, the SMCDA approach is seamlessly incorporated into a web-based GIS environment. The web-based tool will be integrated with the C2IMPRESS decision support platform (T4.7) {work in progress under T4.7, WP4}. Additionally, a dedicated map server has been developed by SAMPAS to visualize maps and enable further data manipulation such as preparing hazard maps for presentation, combining hazard map with other regional features etc.

The tool has been tested for the Mondego River catchment in Portugal, using data obtained from different sources such as COPENICUS, USGS and CHIRPS Database [27]. The results presented in this report demonstrate different steps and corresponding methods of the tool. The CSA specific validation and demonstration of this tool, along with the presentation of results, fall within the scope of WP6. Hence, this tool will be made available to the CSAs for developing their own multi-hazard risk maps. The draft version has been already presented to the CSA partners.

5.3. Outcomes

The major outcomes of Task 3.5 are:

- A structured, step by step, method for multi-hazard risk mapping as a decision support tool.
- A selected list of representative criteria for each hazard type for risk (hazard and vulnerability) mapping to aid the end user to proceed with the analysis.
- A web-based multi-criteria analysis tool using the structured method
- A map server which allows data visualization and manipulation

5.4. Methodology

The overall aim of this task is to develop a structured but generalised methodology that can be used for risk mapping for any type of hazard. The procedure should be robust, encompassing a wide range of possibilities to ensure comprehensive hazard assessment. It can effectively determine hazards across different scenarios and locations by integrating multiple criteria such as flood susceptibility, land use, population density, and infrastructure vulnerability. This enhances the reliability of hazard assessments across varying environmental conditions and geographic regions. Keeping the complexity of multi-hazard and the dependency of risk analysis on data type, TVS has developed a structured but flexible methodology for risk mapping. The following sub-sections will provide description of each step of the analysis tool.

To determine the multi-hazard risk maps of a particular area, individual risks must first be assessed. A risk map consists of both **a hazard map** and **a vulnerability map**. The Analytical Hierarchy Process (AHP) and machine learning (ML) approaches are used to develop the hazard map, while only the AHP method is applied for vulnerability mapping due to its effectiveness in incorporating expert judgment and weighting multiple socio-economic and infrastructural factors. Figure 6 shows the developed methodology under the scope of T3.5.

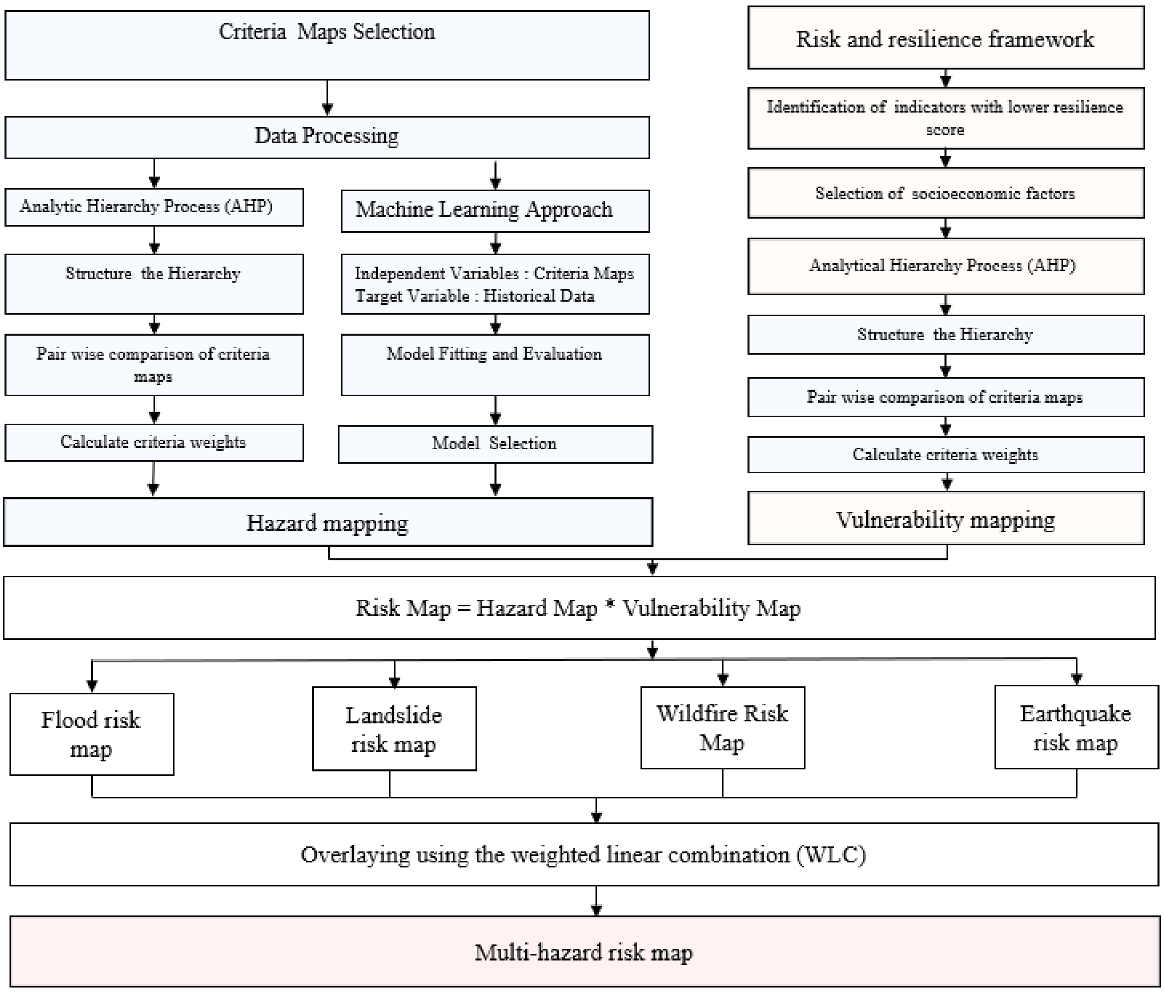


Figure 6: The methodology of multi-hazard risk assessment.

5.4.1. Hazard Mapping using Analytical Hierarchy Process

The following section provides a brief overview of the different steps of hazard mapping according to the Figure 6.

5.4.1.1. Criteria Selection

The first step in creating a hazard map is identifying the criteria that influence a hazard 9 such as flood, landslide, wildfire, etc) based on previous studies, simulation model outputs, and data availability. The likelihood of a hazard occurring in a particular location depends on factors related to the study area's meteorological, geomorphological, and geo-environmental characteristics. Some criteria are common across all hazard types, while others are specific to certain hazards. For instance, elevation [8], land use/cover [24], slope angle [23], curvature [13], and slope aspect [3] influence multiple hazards, including floods, landslides, wildfires, and earthquakes. Conversely, lithology and distance to faults are critical factors specifically relevant to landslides and earthquakes [7], [13].

We have performed intensive literature review and selected representative criteria for Flood, Wildfire, Landslide, and earthquake hazard. A complete set of vulnerability criteria is also prepared. Appendix A provides the list of criteria considered for vulnerability assessment, including socio-economic indicators, infrastructure conditions, and environmental exposure.

5.4.1.2. Data Processing

Data processing is one of the primary yet essential steps in the analysis. Often, data are collected from various sources, including national and EU-level datasets, covering a wide geographical area. Therefore, it is crucial to analyse data specific to the area of interest. Since the SMCDA utilises a GIS system (e.g., raster calculation), all maps should have the same extent, pixel size, and geographical projection. User-uploaded files, which may have different pixel sizes and geographical projections, are converted to a standardized pixel size and projection system. The pixel size is determined by the user, and for calculation purposes, all files are transformed into the WGS 1984 coordinate system. This ensures compatibility for raster calculations in any GIS environment. To facilitate this process, we have developed Python codes that enables data analysis regardless of the original data extent and coverage.

Initially, all spatial data with variable spatial extent are converted into raster format. After identifying/selecting the criteria, spatial data are transformed into decision criteria maps and clipped to match the extent of the desired study area. The criteria maps are then clipped using the study area's shapefile or boundary limits and resampled to the required pixel size.

5.4.1.3. Constraint Mapping

Constraint mapping facilitates identify and exclude areas that should not be considered in the risk map within the study area to ensure accurate hazard assessment and informed decision-making. For example, in a hilly region prone to flooding, certain steep slopes may naturally drain water quickly and not contribute significantly to flood inundation risk at that particular area. Including such areas in the risk map could lead to misleading assessments and unnecessary allocation of resources for flood mitigation. Additionally, settlements/infrastructure located on elevated terrain might be mistakenly classified as high-risk areas if the mapping does not account for topographical constraints, leading to conflicts in land-use planning and disaster preparedness efforts. Thus, constraint mapping allows users to avoid conflicts in decision-making. In this process, a value of 0 is assigned to areas that should be excluded from risk mapping, while a value of 1 is assigned to the remaining areas considered for further analysis. Separate constraint maps are created for each criterion and then overlaid to generate a single map based on Boolean logic. Although optional, this step can enhance the decision-making process. From a computational perspective, excluding certain areas from the map overlay can significantly speed up the suitability estimation process.

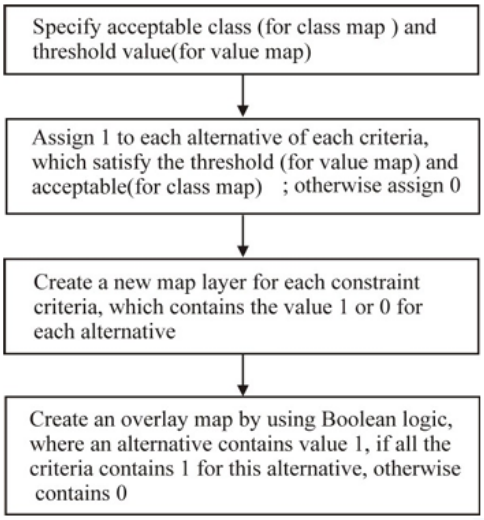


Figure 7: Flowchart for Constraint Mapping

Figure 7 outlines a Boolean-based constraint mapping process, starting with defining acceptable classes for class maps and threshold values for value maps. Each alternative is evaluated, assigning a value of 1 if it meets the criteria and 0 otherwise. A value of 1 indicates that the area should be considered for risk mapping, while 0 means the area should not be considered. These binary values are then used to create separate constraint map layers. Finally, an overlay map is generated using Boolean logic, where an alternative is assigned a value of 1 only if all criteria layers contain 1; otherwise, it is assigned 0. This method is well used in site suitability analysis and spatial decision-making.

5.4.1.4. Data Scaling

In this step, the criteria maps are converted into a standard scale through normalization or reclassification. The normalization approach involves reclassifying all the criteria maps on a scale of 0 to 1. Min-Max scaling, Box-Cox transformation, log transformation, stepwise normalization, and Z-score normalization are used for normalization in this study. The selection of the normalization method is not predetermined; instead, the user has the flexibility to choose the appropriate normalization technique for each criteria map based on data characteristics and specific analytical needs. The reclassification approach attributes values of 1, 2, 3, 4, and 5 to denote the susceptibility levels as very low, low, moderate, high, and very high, respectively.

5.4.1.5. Hierarchy Development and Weight Assignment

Hierarchy development and weight assignment are fundamental components of multi-criteria decision-making (MCDM) using the AHP method, particularly in hazard assessment, where various criteria influence the final risk evaluation. The hierarchy is structured into multiple levels (Figure 8), ensuring a systematic and logical organization of decision criteria. At the top level (level 0) is the overall goal, which defines the primary objective—such as assessing hazard vulnerability or identifying high-risk zones. The next level (level 1) represents a groups criterion. For example, surface land cover and soil type can be grouped into surface characteristics. The subsequent level (level 2) consists of criteria representing broad influencing factors, such as land use, soil type, slope, proximity to water bodies, and population density. These criteria may further be broken down into sub-criteria, refining the analysis by considering more detailed aspects. See Figure 8 for an example schematic.

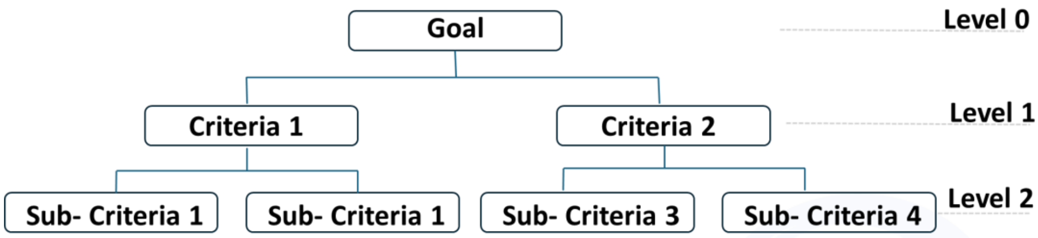


Figure 8: A schematic diagram of a 3- level hierarchy.

Once the hierarchy is established, weight assignment is performed to quantify the relative importance of each criterion. We consider that each criterion does not have same influence on a certain hazard risk. Two primary methods are commonly used in this study: direct weighting and pairwise comparison. In direct weighting, experts or stakeholders assign numerical values to criteria based on their domain knowledge and subjective judgment. This method is straightforward but may introduce bias if not carefully moderated. Alternatively, the pairwise comparison method, widely used in the Analytical Hierarchy Process (AHP), systematically compares each criterion against another to determine its relative significance [22]. This approach utilizes a predefined scale, such as Saaty's 1–9 scale, where values represent the intensity of importance between two criteria. A comparison matrix is then generated, and the eigenvector method is used to derive the final weights [23]. If the number of criteria is high, pair-wise comparison is highly recommended.

A crucial step in the pairwise comparison method is the consistency check, which ensures that the assigned weights are logically coherent and free from inconsistencies. The Consistency Ratio (CR) is calculated using the formula:

$CR=CI/RI$ and $CI=(\lambda_{max}-n)/(n-1)$

Here CI is the Consistency Index, with λ_{max} the principal eigenvalue of the pairwise comparison matrix, and n is the number of criteria. RI is the Random Index, which depends on the number of criteria and is determined from a predefined table. If the CR exceeds a predefined threshold (typically 0.1), the weight assignments need revision [22]. Once the weights are validated, they are applied to the hazard assessment model.

By systematically integrating hierarchical structuring and weighted decision-making, this approach enhances the accuracy, reliability, and objectivity of hazard risk assessment. The final output, typically a hazard map, visually represents risk-prone areas, assisting policymakers, urban planners, and emergency response teams in making informed decisions for disaster management and mitigation planning. Figure 9 summarizes the workflow described above.

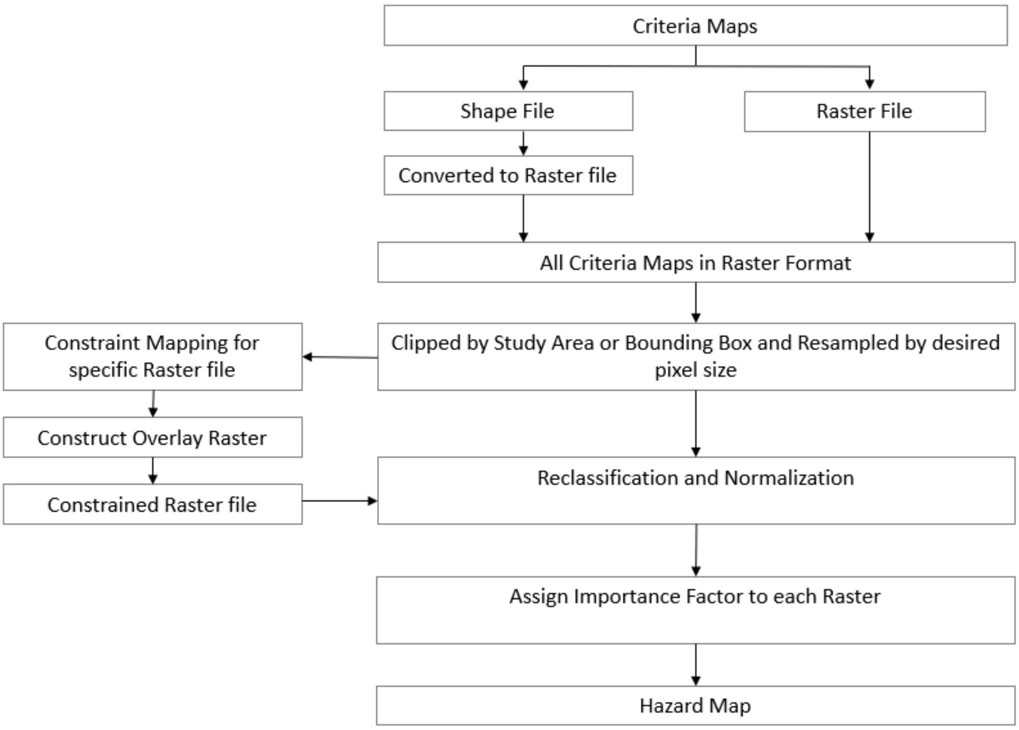


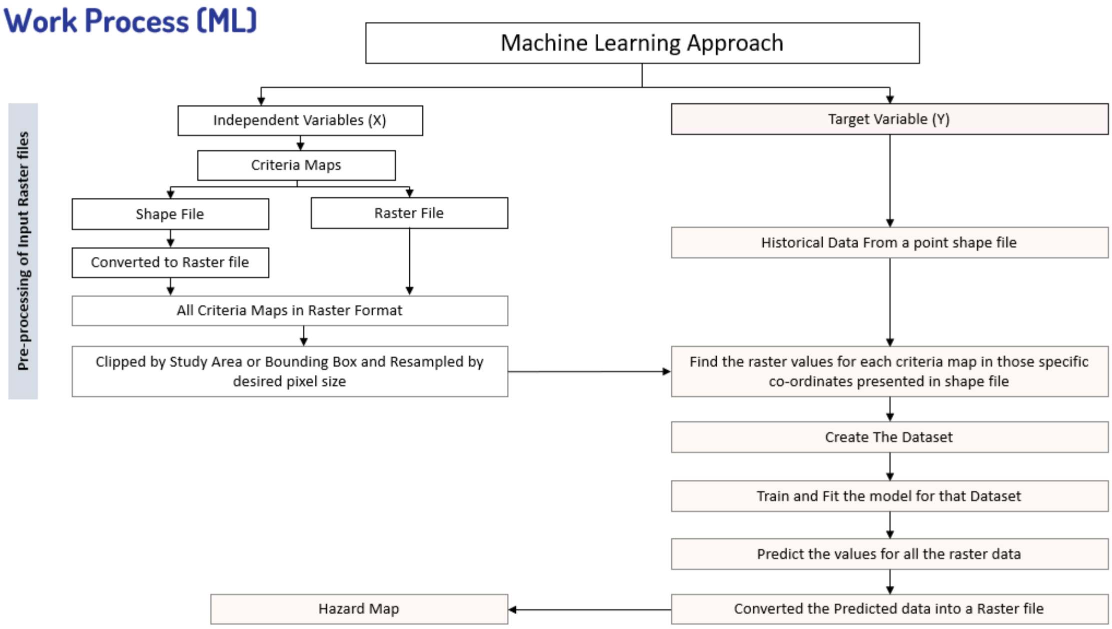
Figure 9: The methodology of Hazard Mapping (AHP)

5.4.2. Hazard Mapping using Machine Learning Method

The flowchart in Figure 10 presents a Machine Learning (ML) approach for hazard mapping, detailing each step from data preprocessing to hazard map generation. The process begins with preparing independent variables, where various hazard-related criteria maps are created (shapefiles or raster files). If the data is in shapefile format, it is first converted into raster for consistency in spatial analysis. All raster layers are then reclassified to ensure uniformity across criteria, clipped to the study area's boundaries, and resampled for spatial accuracy. This preprocessing follows the same approach as the AHP method.

In parallel, historical hazard data (observed data) stored as point shapefiles is used as the target variable to train the machine learning model. Raster values corresponding to the historical hazard points are extracted, forming a structured dataset where each point represents a past hazard occurrence along with its influencing factors. This dataset is then used to train a machine learning model, which learns the patterns and relationships between hazard occurrences and input variables, assuming that the obtained relationships can be transferred to all locations in the study area. For this purpose, Random Forest, Gradient Boosting, and AdaBoost algorithms are employed. The user has the flexibility to choose the most suitable model based on the input data and specific requirements, allowing for adaptive analysis depending on the characteristics of the dataset. Once trained, the machine learning model predicts hazard values for all spatial locations in the study area. These predictions are then transformed into a hazard map, visually representing different levels of hazard risk across the region.

The integration of GIS-based spatial data processing and machine learning enhances hazard assessment by providing a data-driven, objective, and scalable approach to identifying risk-prone areas. This method is valuable for disaster management, urban planning, and early warning systems,



ensuring proactive mitigation strategies.

Figure 10: The methodology of Hazard Mapping (Machine Learning approach)

5.4.3. Vulnerability Mapping using Analytical Hierarchy Process

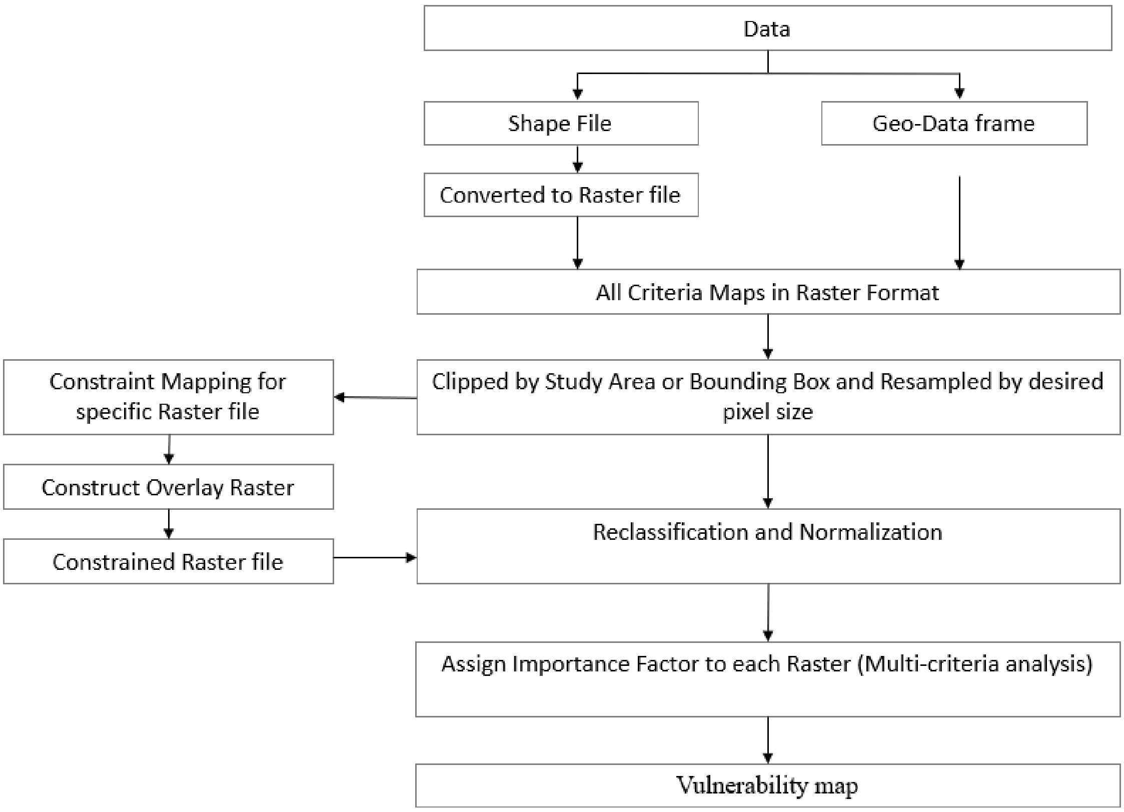
The **Risk and Resilience Framework,** developed in WP3 (T3.3), is instrumental in selecting socioeconomic factors for vulnerability mapping by evaluating the resilience scores of various community indicators. These scores reflect how well a community can withstand and recover from hazards, with lower scores indicating higher vulnerability [24]. Socioeconomic factors with low resilience scores are prioritized in the analysis, as they highlight critical weaknesses that may exacerbate disaster impacts.

For instance, in Ordu CSA, the population density received a resilience score of 7.3 out of 10, indicating relatively high resilience, whereas the health sector scored only 2.5 out of 10, signifying greater vulnerability [24]. This suggests that the availability of doctors and nurses is a more pressing concern than population density when assessing vulnerability in the region. As a result, healthcare-related indicators, such as the number of doctors and nurses per capita, should be included as key socioeconomic factors in the vulnerability mapping process.

To systematically integrate these factors, the Analytical Hierarchy Process (AHP) method, explained earlier, can be applied, mirroring the methodology used in hazard mapping. This involves data preprocessing, scaling, and weight assignment, ensuring that each factor is appropriately weighted based on its relative importance in determining vulnerability. By combining the **Risk and Resilience Framework** with AHP-based vulnerability mapping, this approach provides a comprehensive, data-driven method for identifying the most at-risk communities and informing targeted disaster preparedness and mitigation strategies [24]. Figure 11 shows the workflow for vulnerability mapping approach of this study.

The hazard mapping and vulnerability mapping methods are quite similar. The key difference is that hazard mapping incorporates two approaches—AHP and machine learning—while vulnerability mapping relies solely on the AHP method.

Figure 11: The methodology of Vulnerability Mapping



5.5. Criteria selection for hazard map

Different criteria influence different hazards, necessitating a detailed study to determine the most relevant factors for each hazard type. The selection of criteria is based on scientific literature, expert judgment, and data availability to ensure comprehensive hazard assessment. In this study, a thorough literature review has been conducted to identify specific influencing factors (i.e. criteria) for various hazards, ensuring accurate risk evaluation. A list of criteria for flood hazards, earthquakes, landslides, and wildfires are provided in the appendix section (Appendix A). Additionally, the appendix includes the criteria considered for vulnerability mapping, offering a holistic perspective on risk assessment. Depending on the availability of the information, the user can select the criteria for risk mapping.

5.6. Testing of the risk mapping method

5.6.1. Study Area

To test the methodology and demonstrate the robustness of the SMCDA techniques developed in this study, data from Portugal CSA has been used. The study area is the Mondego River Basin, located in central Portugal (Figure 12) which is the largest river basin located entirely within the country. It plays a crucial role in the region's hydrology, agriculture, and water resource management. The basin features diverse topography, including mountainous regions and floodplains, making it susceptible to hydrological hazards such as flooding and droughts. Effective vulnerability mapping in this region is essential for sustainable water management, disaster risk reduction, and land-use planning.

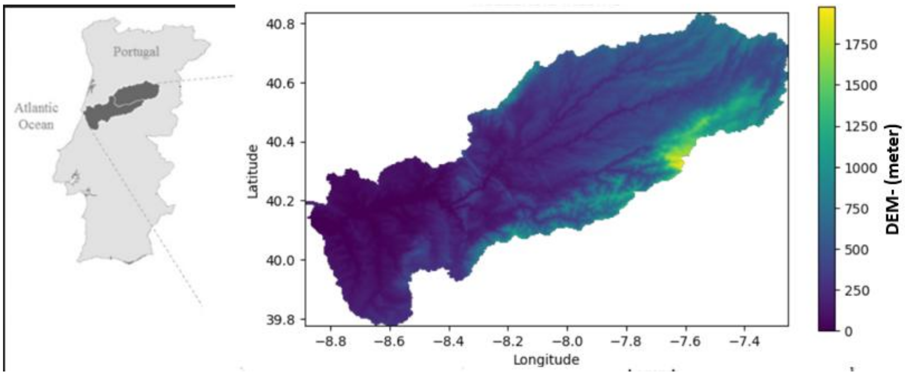


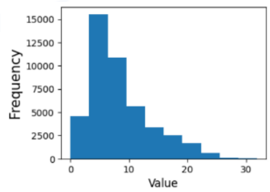
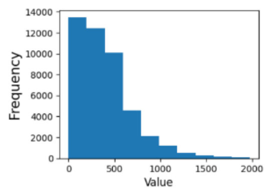
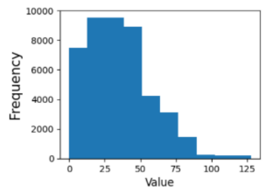
Figure 12: Study Area

5.6.2. Data collection, analysis and quality check

Based on the available data, we have selected the following criteria given in Table 1 for the PT CSA risk mapping: We have categorised two types of criteria maps. One is the value maps or continuous type and the second one is class maps or discrete type maps. Table 1 shows the continuous type of chosen factors, and Table 2 shows the discrete type for hazard mapping that influences floods in the Mondego River basin.

The data shown in Table 1 is based on the Mondego River Basin, which serves as the catchment area. The pixel size for each criteria map is 0.004, and the raster array size is 107,712 (408 × 264).

Table 1: Criteria values (continuous) and simple statistics for criteria maps in the Mondego River basin.

Factors Name	**Data Type**	**Min**	**Max**	**Average**	**Distribution**
Slope (Degree)	Continuous	0	31.8	8.38	
Elevation(meter)	Continuous	-1.17	1975	388.2	
Drainage Density(m/km^2)	Continuous	0	127	35.35	

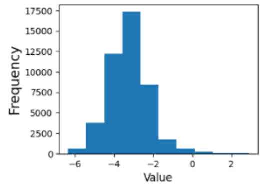
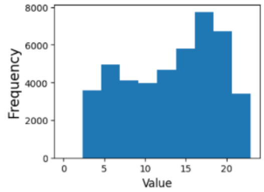
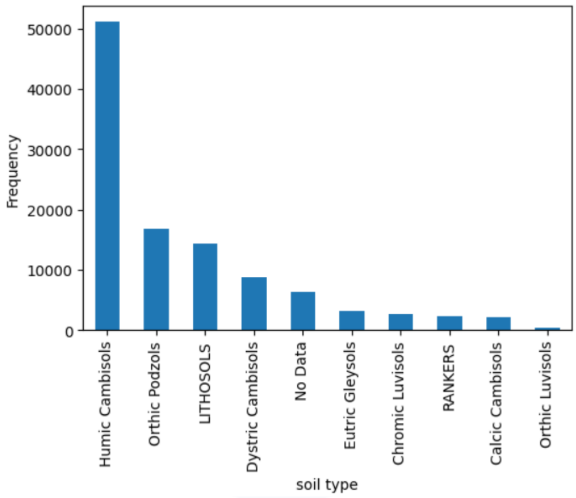
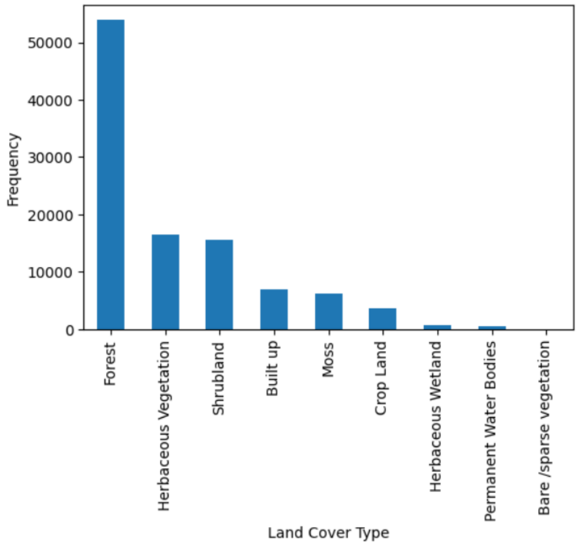
Topographic Wetness Index	Continuous	-6.33	2.89	-3.23	
Land Cover	Continuous	0	23	13.36	

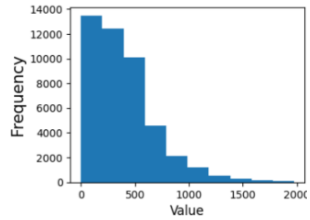
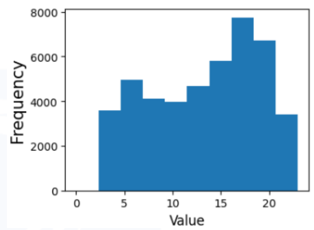
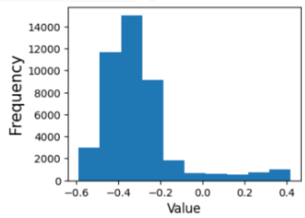
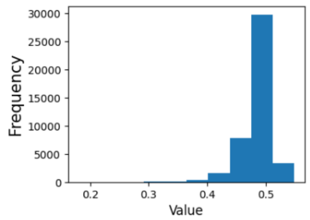
Table 2: Influencing factors (discrete) for floods in the Mondego River basin

Factor Name	**Unique Values**	**Data Distribution**
Soil Type	• Eutric Gleysols • Humic Cambisols • Dystric Cambisols • Orthic Podzols • Rankers • Lithosols • Calcic Cambisols • Chromic Luvisols	
Land Cover	• Herbaceous Vegetation • Moss • Built up • Shrubland • Herbaceous Wetland • Forest • Permanent Water Bodies	

The flood hazard map is generated using slope, precipitation, drainage density, TWI, and soil criteria maps, while the wildfire hazard map is based on elevation, TWI, land cover, and precipitation. The datasets were sourced from Copernicus, USGS, and the CHIRPS database.

For vulnerability mapping, the required data are not readily available in the PT CSA, meaning that only a single value per criterion is available for the entire catchment. To test the spatial variability of vulnerability, we developed a synthetic dataset by interpolating the available data and generating spatially distributed values based on relevant socio-economic and infrastructural patterns (Table 3).

Table 3: Synthetic Socio-economic factors for vulnerability mapping

Criteria Name	**Data Type**	**Min**	**Max**	**Average**	**Distribution**
Household Income (Euro)	Continuous	0	1974	388	
Literacy Rate (Percentage)	Continuous	0	23	13	
Emergency Management	Continuous	-.588	.41	.3	
Access to Clean Water	Continuous	.18	.54	.48	

5.7. Result

A case study assessment is conducted on the Mondego River Basin, Portugal (PT use case) following the previously described methodology, using the data listed in the Table 1, Table 2 and Table 3. Initially, criteria maps are selected to assess flood hazard and vulnerability. Data processing, scaling, constraint mapping, and weight assignment are then applied to each criterion map. The final output is a comprehensive flood risk map.

5.7.1. Criteria Map Selection

For hazard maps, the selected criteria, based on data availability and data accuracy at PT CSA, include slope, precipitation, drainage density, soil, and the Topographic Wetness Index (TWI) for the Mondego River Basin. Similarly, for vulnerability mapping, the selected criteria are synthetic household income, literacy rate, emergency management, and access to clean water, ensuring a comprehensive assessment of both hazard exposure and societal resilience.

5.7.2. Data Processing

The criteria maps, initially in raster or shapefile format (polygon or point), are first converted to raster. Categorical shapefiles are assigned unique numerical values, and all raster files are clipped to the study area, resampled to a specified pixel size, and transformed into the WGS 1984 coordinate system.

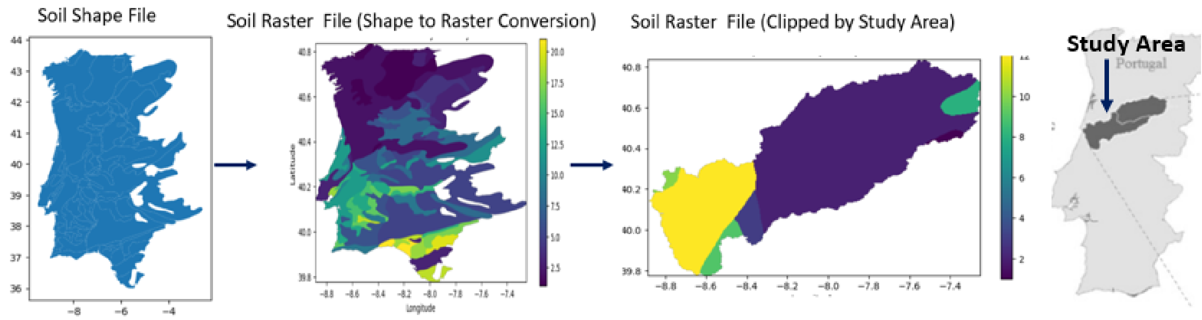
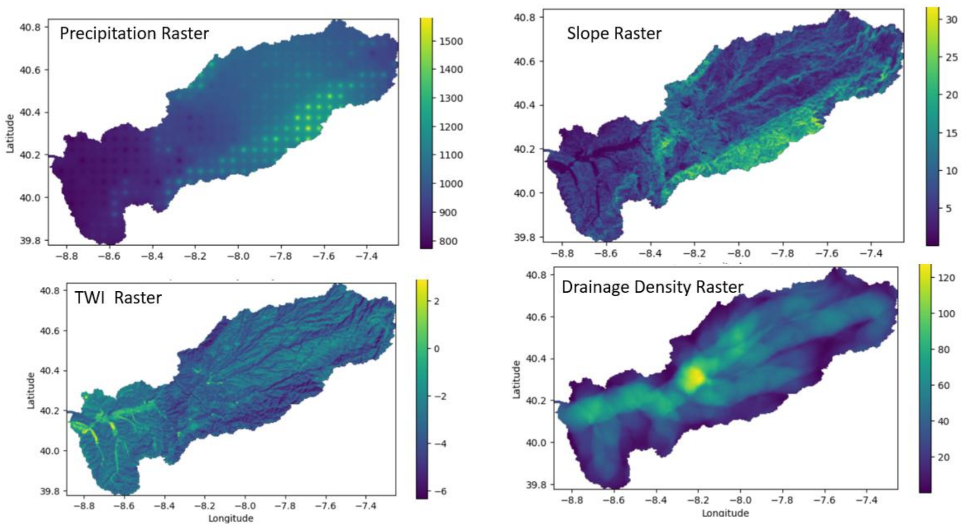


Figure 13: An example of Data Processing for Categorical Variables using soil data

The soil shapefile contains categorical values representing different soil types. Each unique soil type is assigned a numerical value (Table 4) before converting the shapefile into raster format. Figure 14 shows all the processed criteria maps.

Table 4: Example of Numerical Conversion of Categorical Values using soil map

Soil Type	Unique Value	Soil Type	Unique Value	Soil Type	Unique Value	Soil Type	Unique Value
U	1	I	6	Lv	11	Lf	16
Bh	2	WR	7	Po	12	Wd	17
Bk	3	Bd	8	Lo	13	Zg	18
Bg	4	Lc	9	Je	14	Vc	19
Be	5	Re	10	Lg	15	Vp	20
						Qc	21



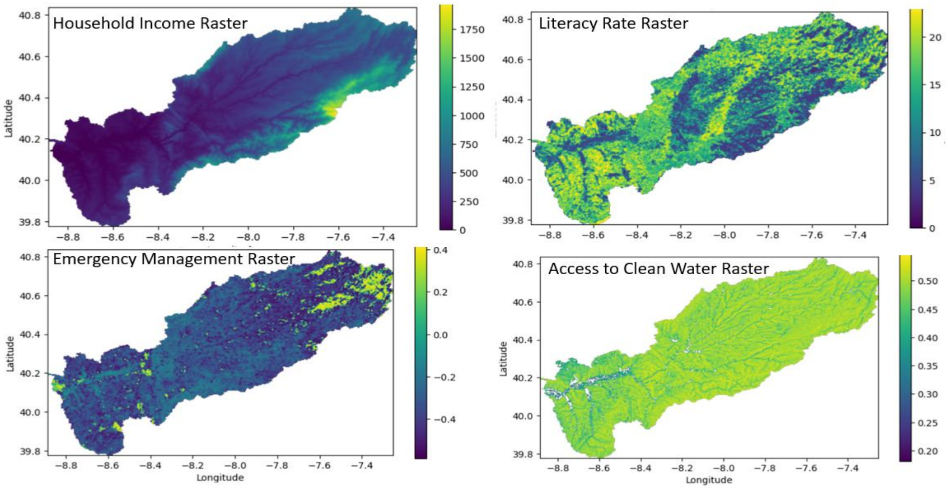


Figure 14: Data Processing for Numerical Value

5.7.3. Data Scaling

Data scaling is achieved through normalization and reclassification methods, each tailored to the specific characteristics and requirements of the hazard data. In the context of the Analytic Hierarchy Process (AHP), normalization is applied to ensure that all criteria are evaluated on a consistent scale, allowing for accurate comparisons and prioritization of factors. The choice of normalization technique varies based on the nature of the data and the specific needs of the decision-making criteria for each criteria map, as detailed in Table 5. For example, in case of slope we considered a linear normalisation (min-mas) method and reverse transformation was used. We considered that, if the slope is less the likelihood of flood water retention on the topography and flood inundation is more. Higher slope allows the water to flow to the lower slopes and are less likely to be flood than the low sleep area. It is important to note that the normalization ranges provided are for testing purposes and are informed by insights from multiple literature sources. CSA partners have the flexibility to adjust these values and conduct their own analyses using our web-based SMCDA tool.

Table 5: Criteria for Data Scaling in Maps

Criteria Map	Normalization Method	Relation with Hazard
Slope (degree)	Min-Max	Reverse
Drainage Density (m/km^2)	Box-Cox	Proportional
Precipitation (mm)	Log Transformation	Proportional
TWI	Step wise	Proportional
Soil	Min-Max	Reverse
Household Income (Euro)	Min-Max	Reverse
Literacy Rate (Percentage)	Z Score	Reverse
Emergency Management	Log Transformation	Reverse
Access to clean Water	Log Transformation	Reverse

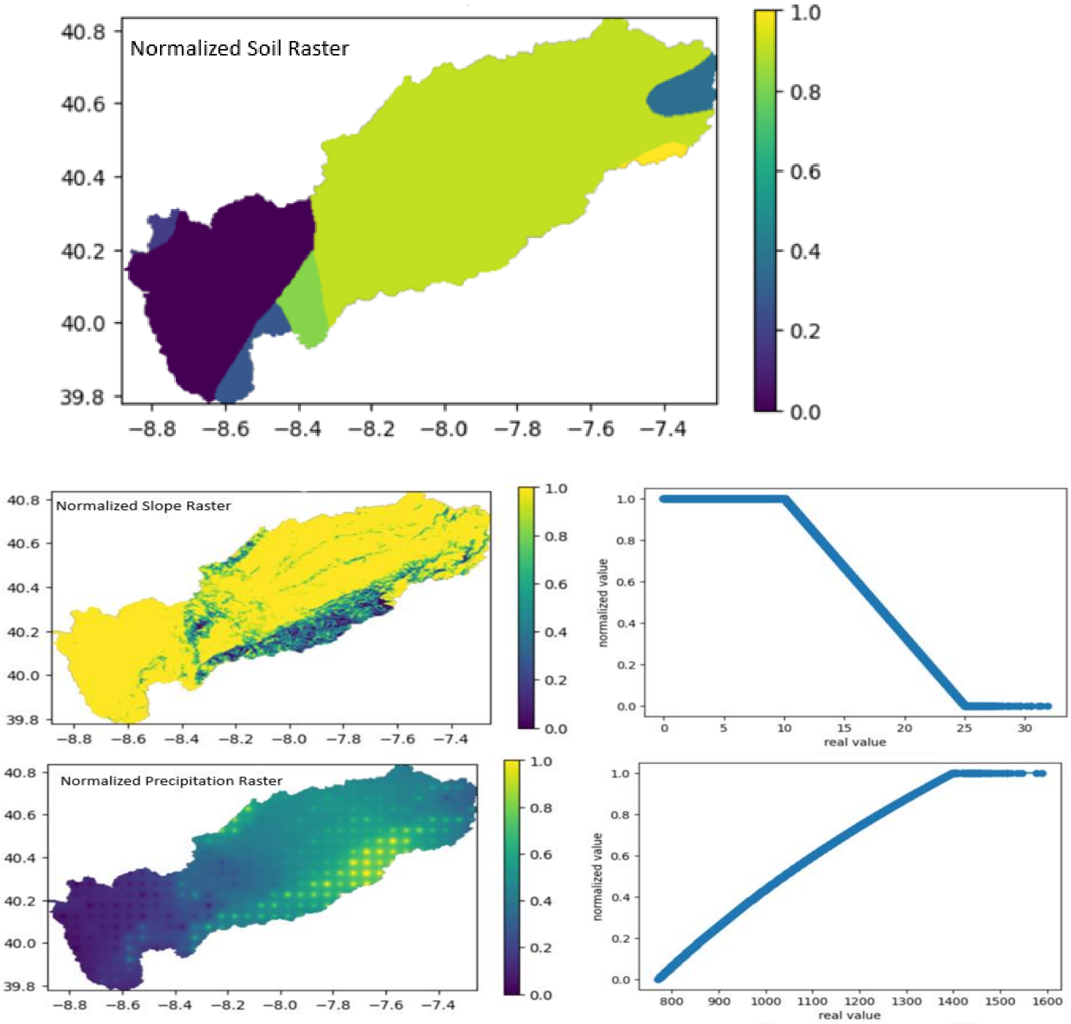
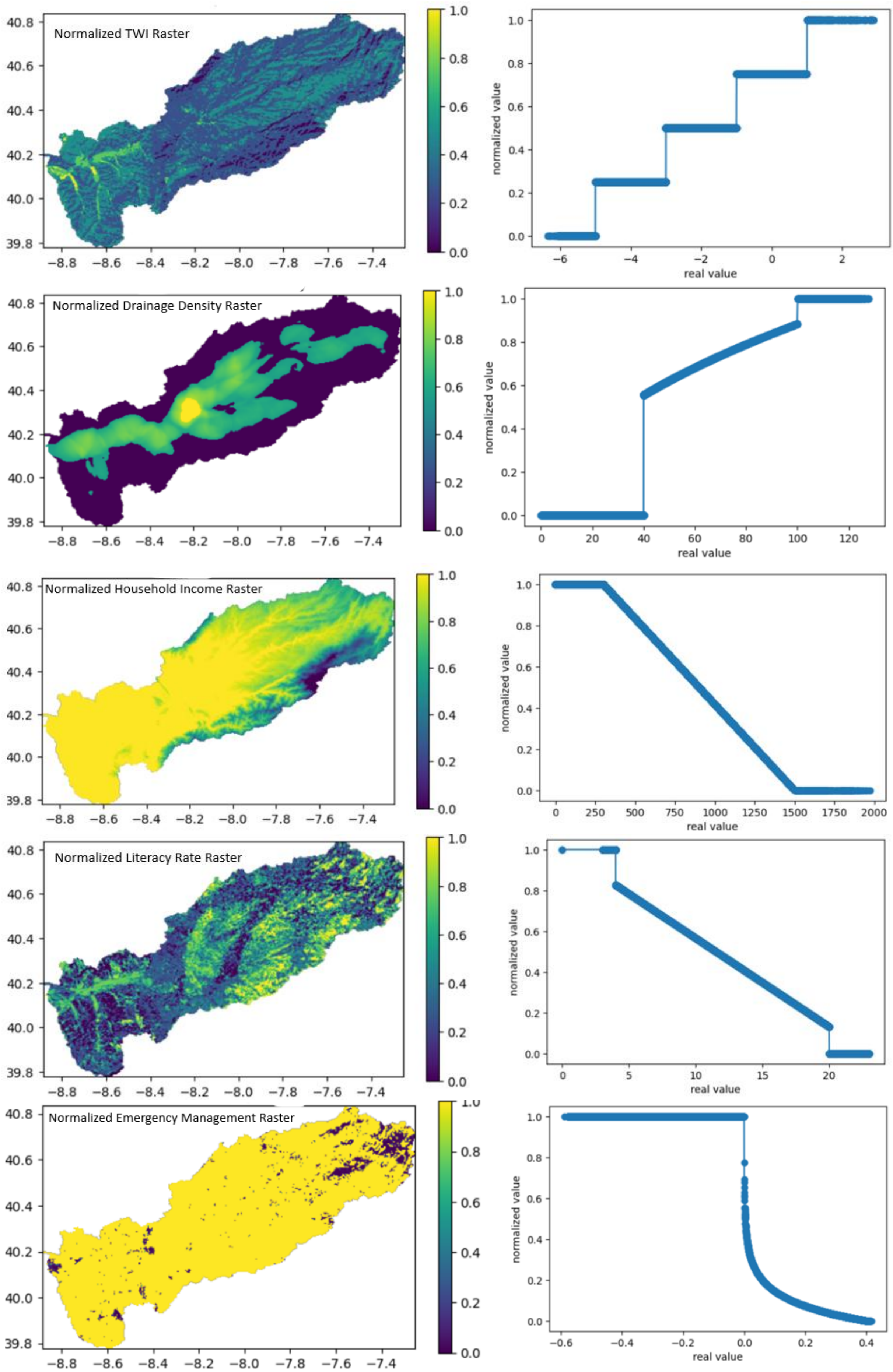


Figure 15: Data Scaling for soil (categorical value) Map


Normalized TWI Raster
Normalized Drainage Density Raster
Normalized Household Income Raster
Normalized Literacy Rate Raster
Normalized Emergency Management Raster
normalized value
real value

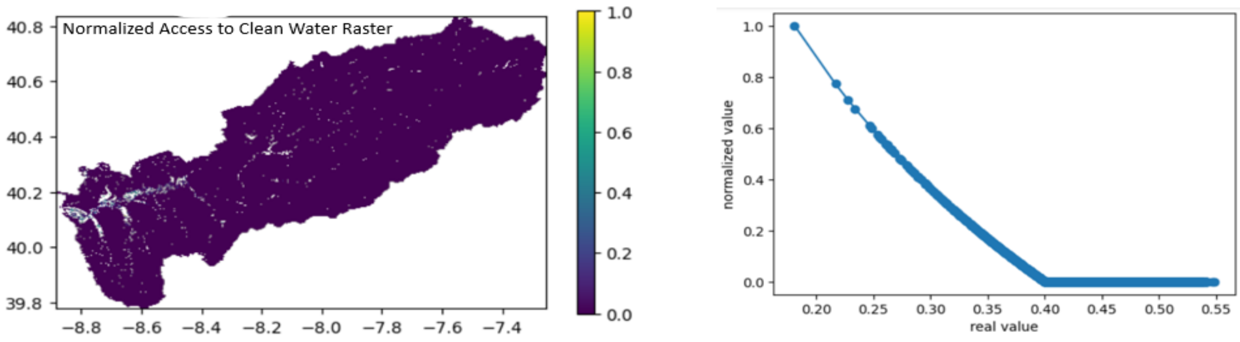


Figure 16: Data Scaling for Numerical Maps

The web-based tool allows users to define the relationship between specific criteria maps and the hazard of interest. Additionally, they can select the normalisation range and choose the appropriate normalization method to standardize the data for analysis. The digital tool is generalised and use has the freedom to define own criteria.

5.7.4. Constraint Mapping

For constraint mapping, raster maps of slope, TWI, and precipitation are used and following method is used.

Table 6: Constraint Mapping Criteria

Criteria Maps used for Constraint Mapping	Assign 1 or Retain Values
Slope (degree)	Less Than 25
TWI	Greater than -5
Precipitation (mm)	Greater than 800

These threshold values were chosen based on their significance in flood hazard assessment. Slopes less than 25 degrees are more prone to water accumulation and reduced runoff, making them more susceptible to flooding. TWI values greater than -5 indicate areas with higher soil moisture retention, which are more likely to experience surface water buildup. Precipitation levels above 800 mm highlight regions with excessive rainfall, increasing the potential for flooding. These constraints help refine the hazard map by focusing on areas with the highest flood risk.

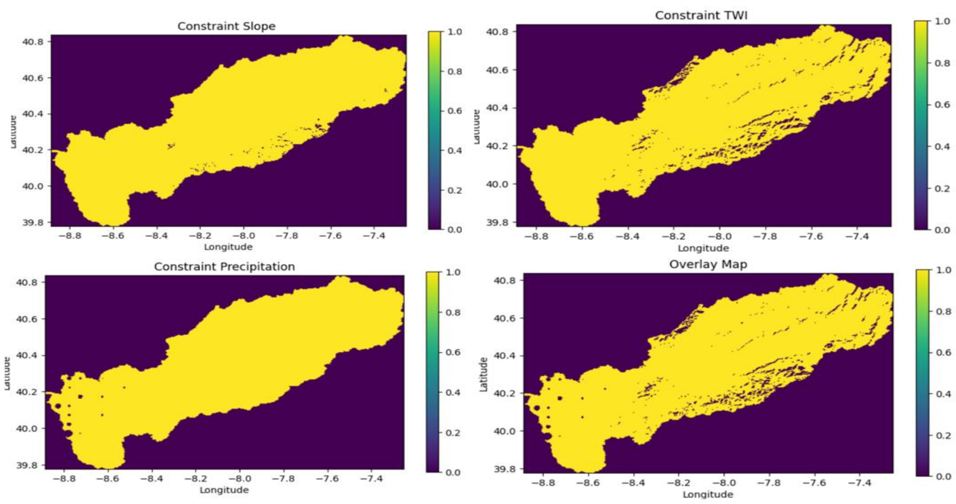


Figure 17: Overlay Map from Constraint Mapping

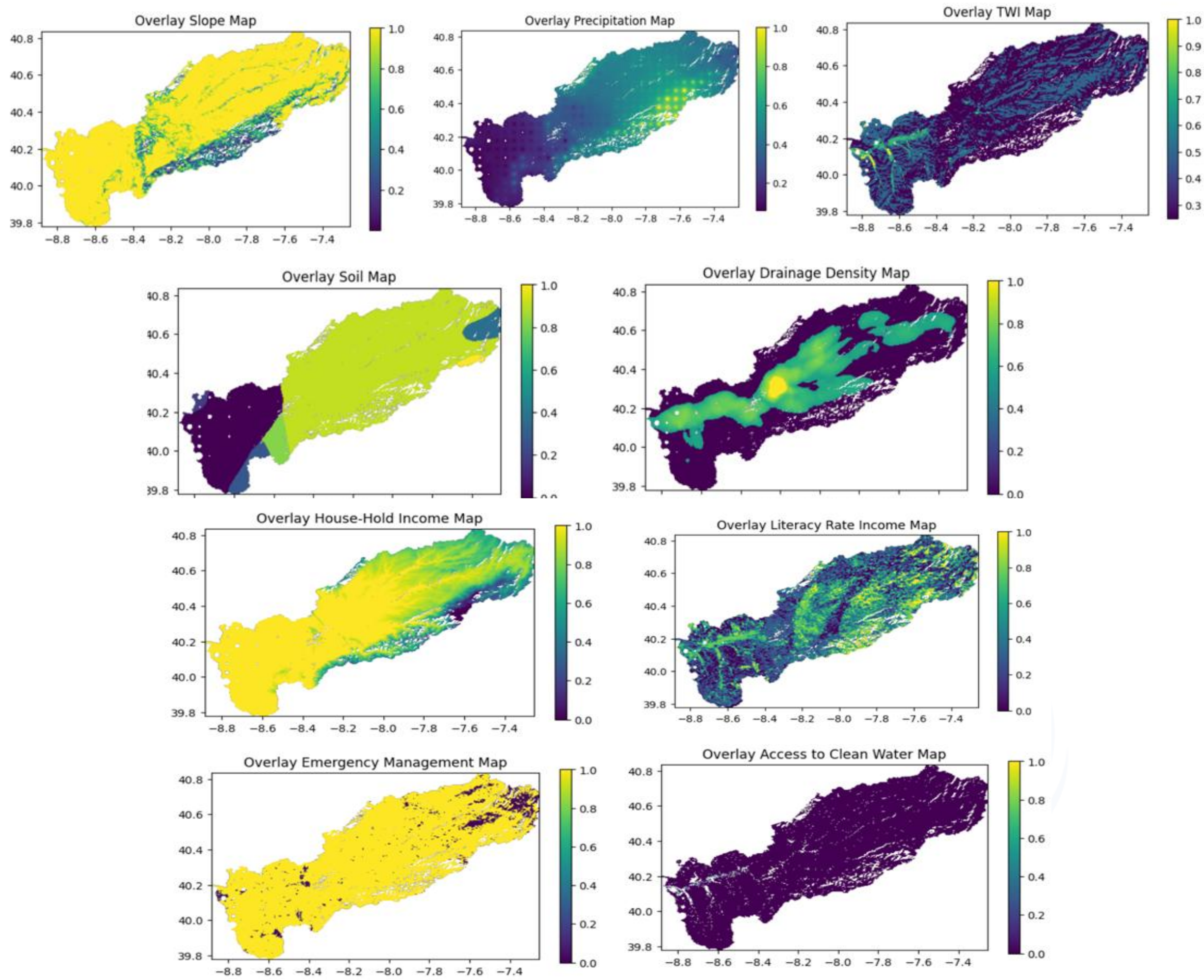


Figure 18: Modified Criteria Maps Using Constraint Overlay

Figure 17 and Figure 18, show all the criteria maps masked by the constrain overlay. The digital tool provides users with the functionality to select specific criteria maps for constraint mapping and define the portions of each criteria map that hold significant value for the hazard assessment. This allows for a more refined and customized analysis, ensuring that only the most relevant areas are considered in the mapping process.

5.7.5. Hierarchy Development and Weight Assignment

The AHP process begins by decomposing the goal into a three-level hierarchy (Figure 19). The top level represents the hazard map, the middle level contains key criteria, and the bottom level consists of detailed sub-criteria linked to the main criteria.

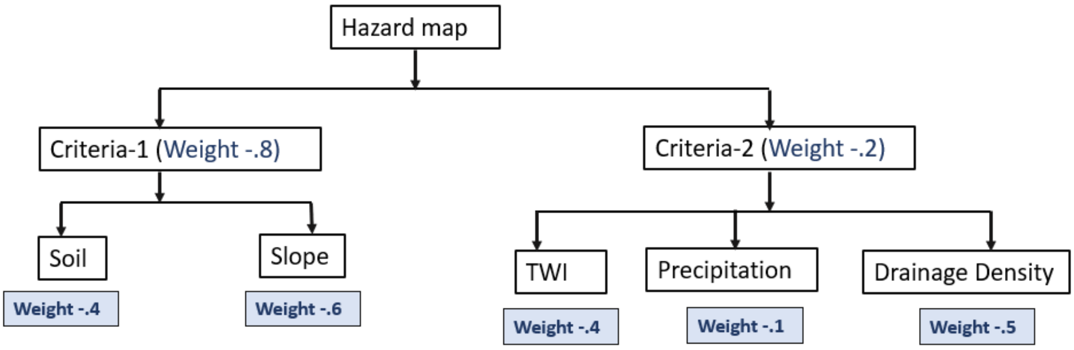


Figure 19: Hierarchy Development and Weight Assignment for Hazard Mapping

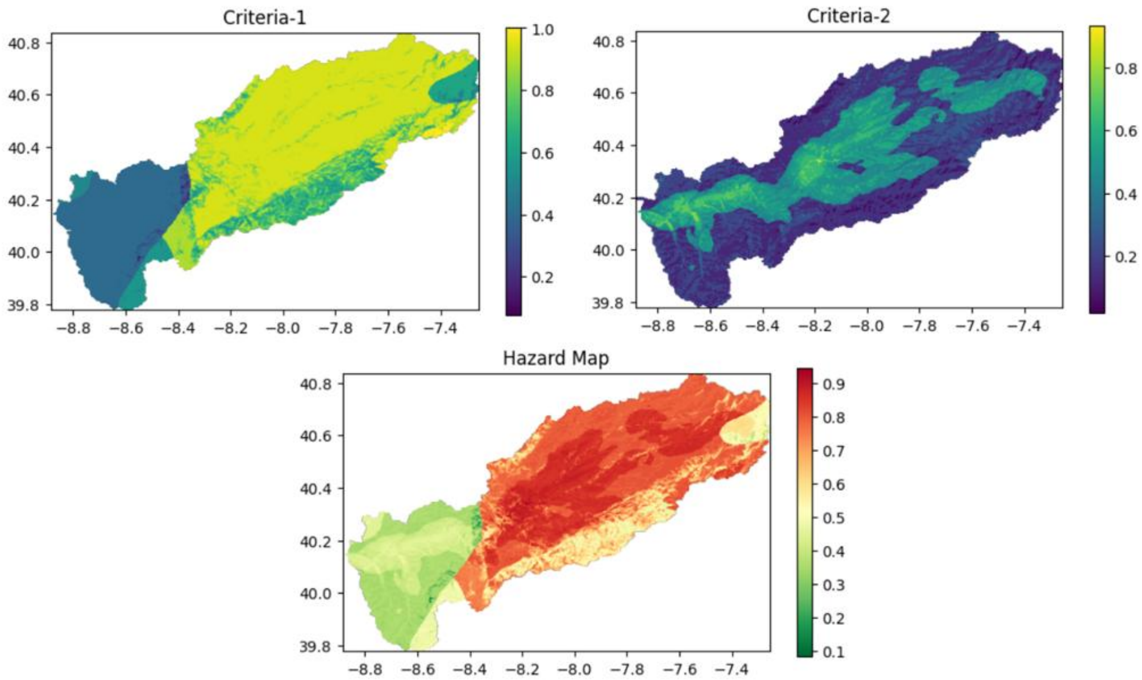


Figure 20: Hazard Map

Hazard maps can also be generated using a Machine Learning-based approach, leveraging algorithms such as Random Forest, Gradient Boosting, and AdaBoost. In this study, historical hazard data stored in a point shapefile is used as the training dataset, while a separate dummy point shapefile is created within the catchment area using ArcGIS. This dummy shapefile serves as the target variable and is used for model training. Once the models are trained, they can predict hazard levels at individual points across the study area.

In the web tool, users can upload a point shapefile representing hazard data for their specific study area. The model will then be trained based on this user-provided data, allowing for customized hazard predictions. The results obtained from the three Machine Learning algorithms are presented in Figure 21.

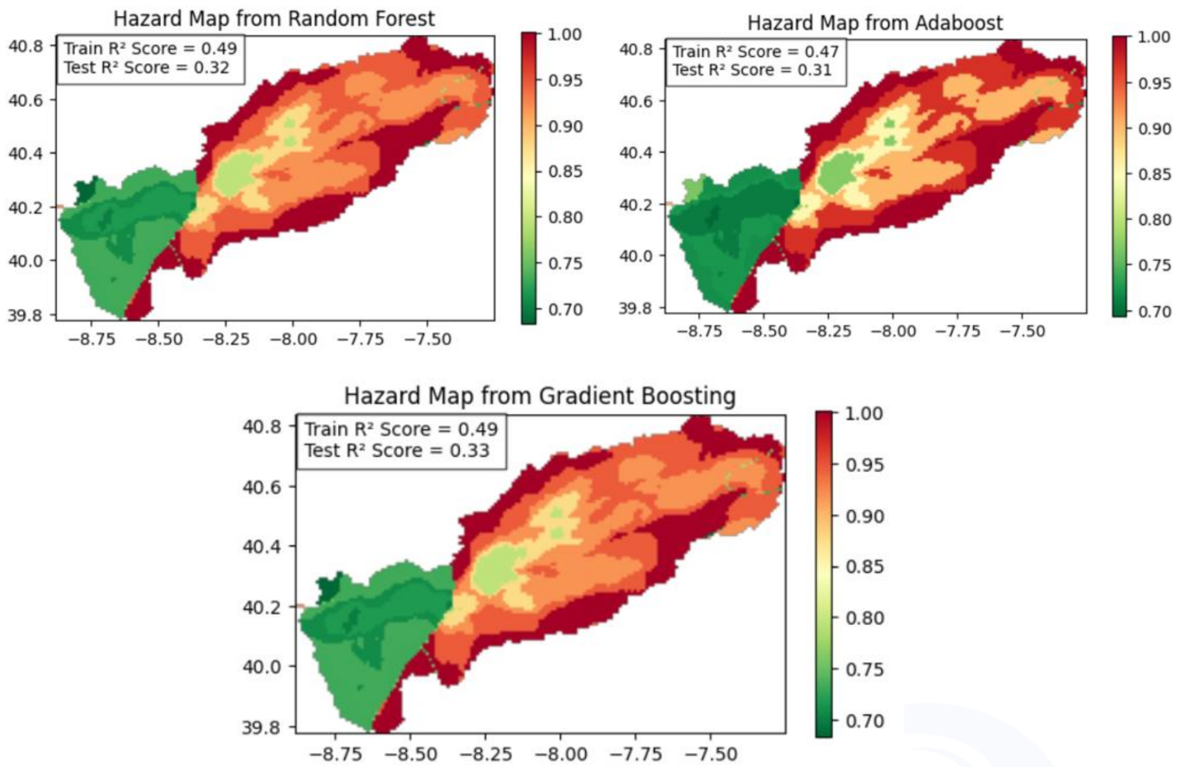


Figure 21: Hazard Map Derived from Machine Learning-Based Predictions

Vulnerability Map using AHP method: The vulnerability map is generated using the same process as the hazard map. The Analytic Hierarchy Process (AHP) is applied to derive the vulnerability mapping, ensuring a structured decision-making approach (Figure 22). For weight assignment, both direct weight assignment and pairwise comparison methods are used, following the same approach as in hazard mapping to maintain consistency and accuracy in the assessment. Figure 23 shows the combined vulnerability map.

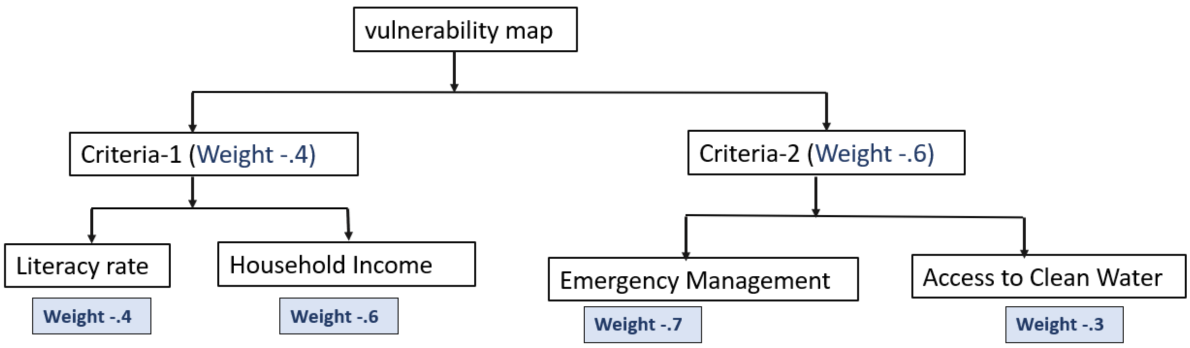


Figure 22: Hierarchy Development and Weight Assignment for Vulnerability Mapping

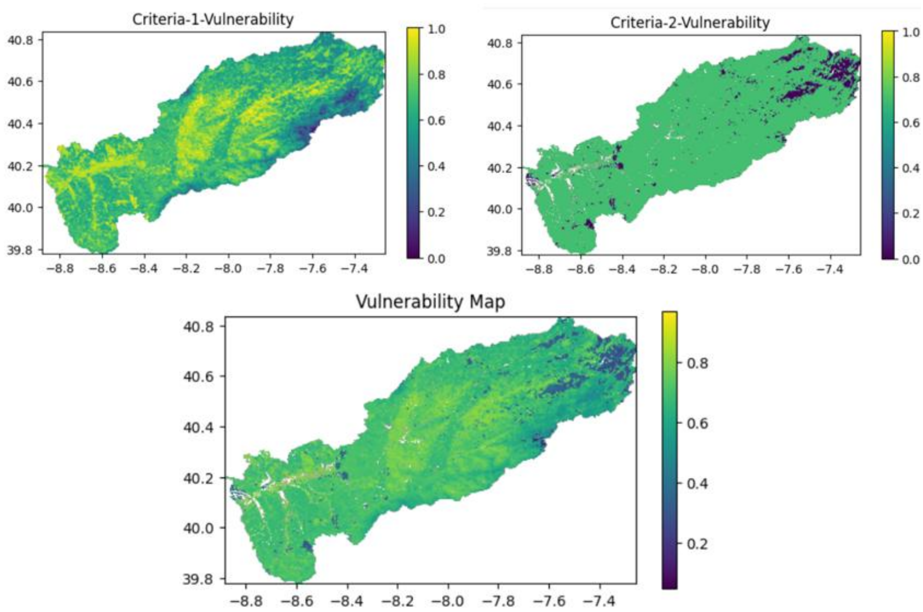


Figure 23: Vulnerability Map

The risk map is generated by multiplying the hazard map and the vulnerability map, combining both the hazard exposure and the vulnerability factors to provide a comprehensive risk assessment. This process allows for the identification of high-risk areas, where both hazard intensity and vulnerability are significant.

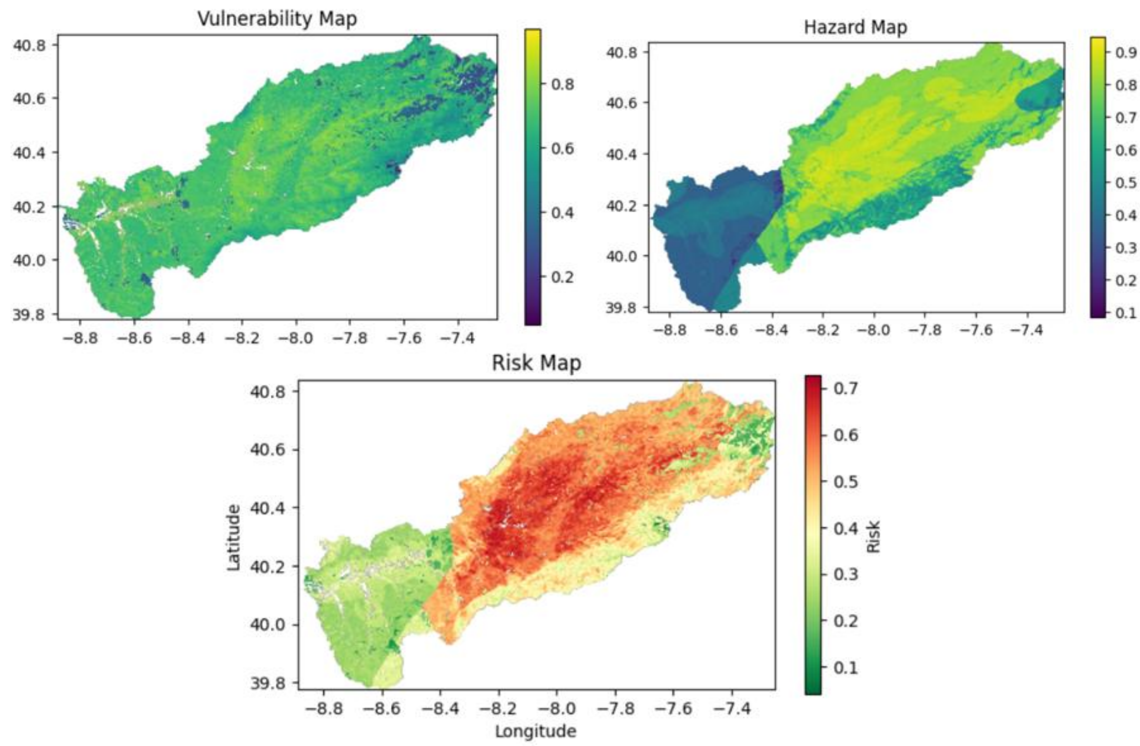


Figure 24: Risk Map

The previous result was generated without using the overlay map produced from the constraint mapping process. If constraint mapping is applied, the overlay raster files should be incorporated into the analysis (Figure 25).

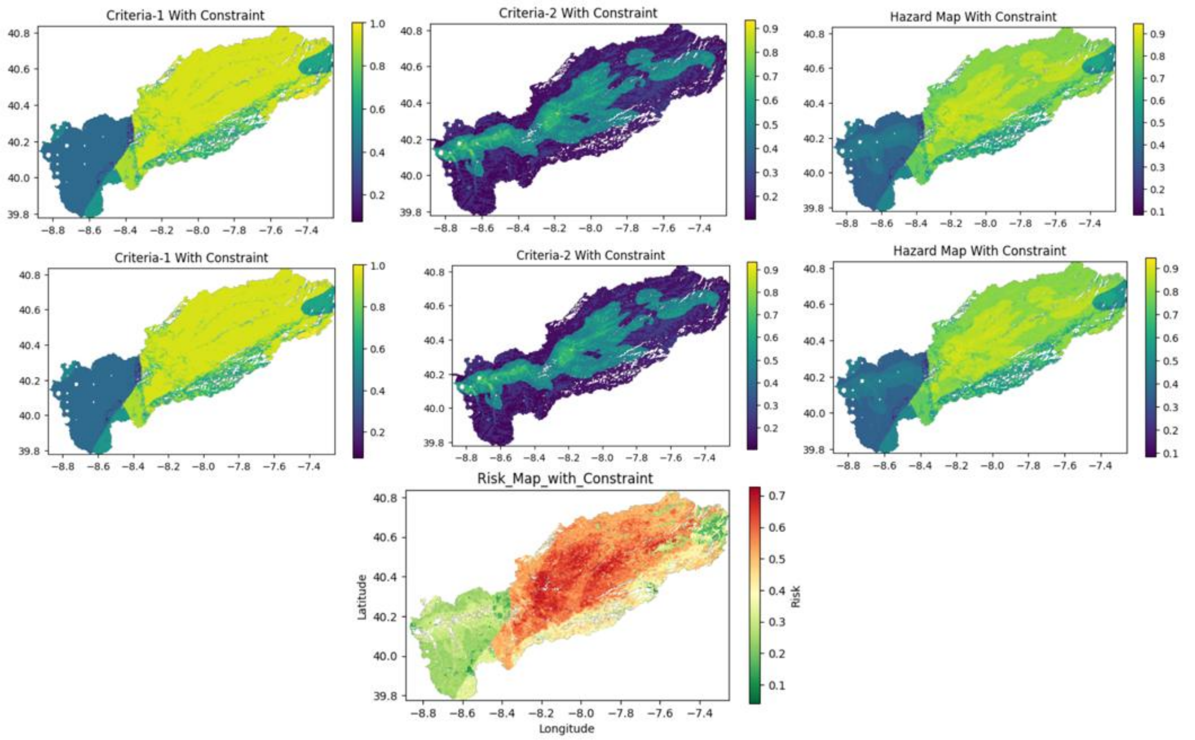


Figure 25: Risk Map (With Constraint)

Wild Fire Hazard

To demonstrate the multihazard risk mapping facility of the tool, we have performed another risk map preparation for Wilde-Fire risk using from the collected data mentioned earlier. For wildfire hazard assessment, criteria maps of elevation, land cover, precipitation, and the Topographic Wetness Index (TWI) are utilized. Meanwhile, criteria such as access to clean water, emergency management capacity, household income, and literacy rate contribute to vulnerability mapping. The process of generating the risk map follows the same methodology as flood risk assessment. See the data presentation in Flood risk mapping (Figure 22 and Figure 23).

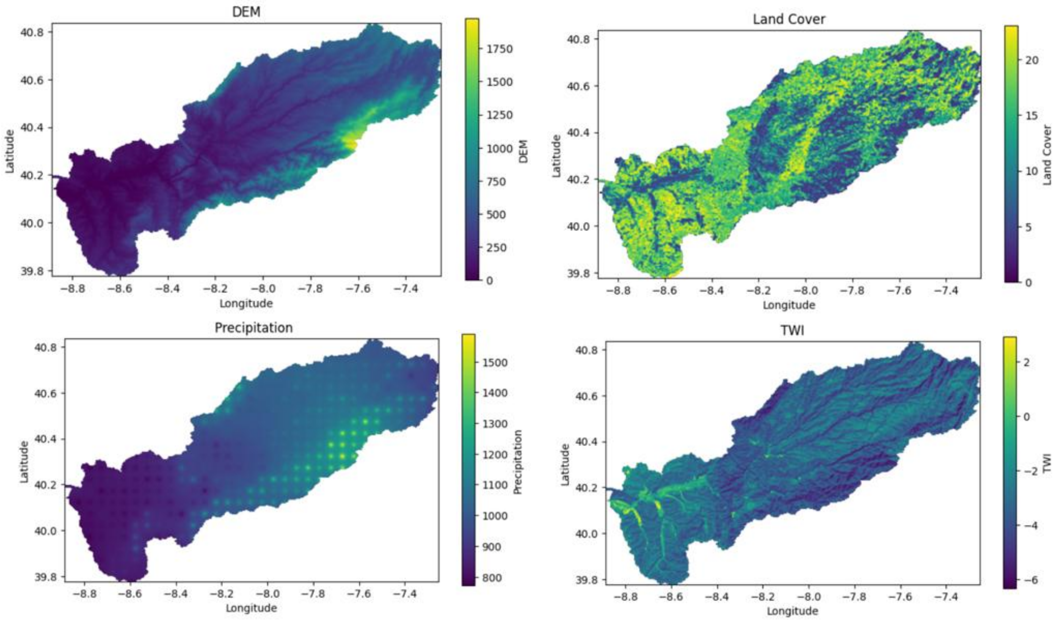


Figure 26: Criteria Maps used for Wildfire Hazard mapping

We followed the steps mentioned in the methodology section and explain during the hazard and vulnerability map for Flood preparation. Fro the brevity of the report, we have not explained these steps for Wildefire risk map preparation. Table 7 shows the normalisation methods used for Wildfire risk mapping.

Table 7: Criteria for Data Scaling in Maps (Wildfire)

Criteria Map	Normalization Method	Relation with Hazard
Land Cover	Z-Score	Proportional
Elevation	Min-Max	Reverse
Precipitation (mm)	Log Transformation	Reverse
TWI	Stepwise	Reverse
Household Income (Euro)	Min-Max	Reverse
Literacy Rate (Percentage)	Z Score	Reverse
Emergency Management	Log Transformation	Reverse
Access to clean Water	Log Transformation	Reverse

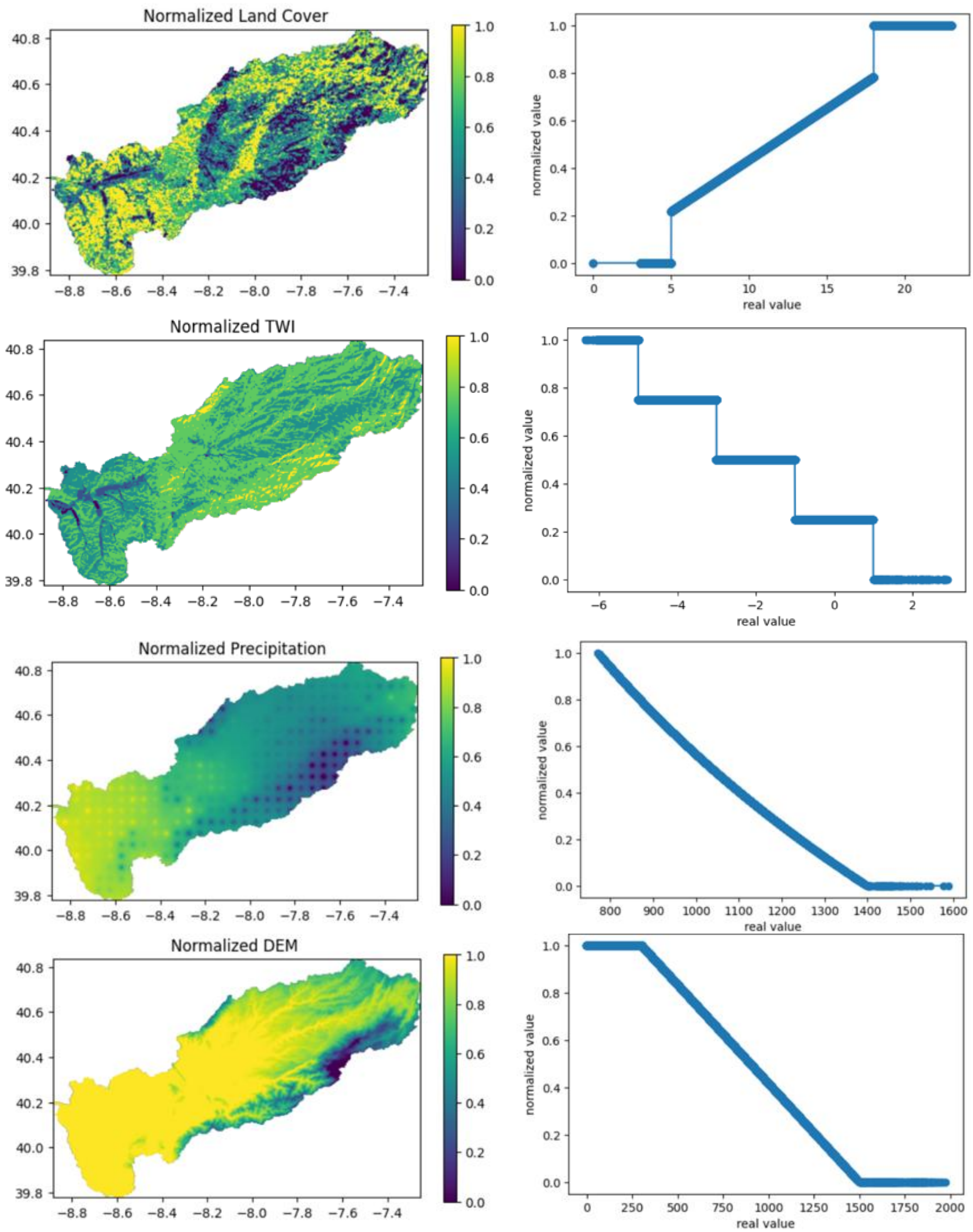


Figure 27: Data Scaling for Numerical Maps (Wild-fire)

Data scaling for vulnerability maps follows the same process as that of flood mapping.

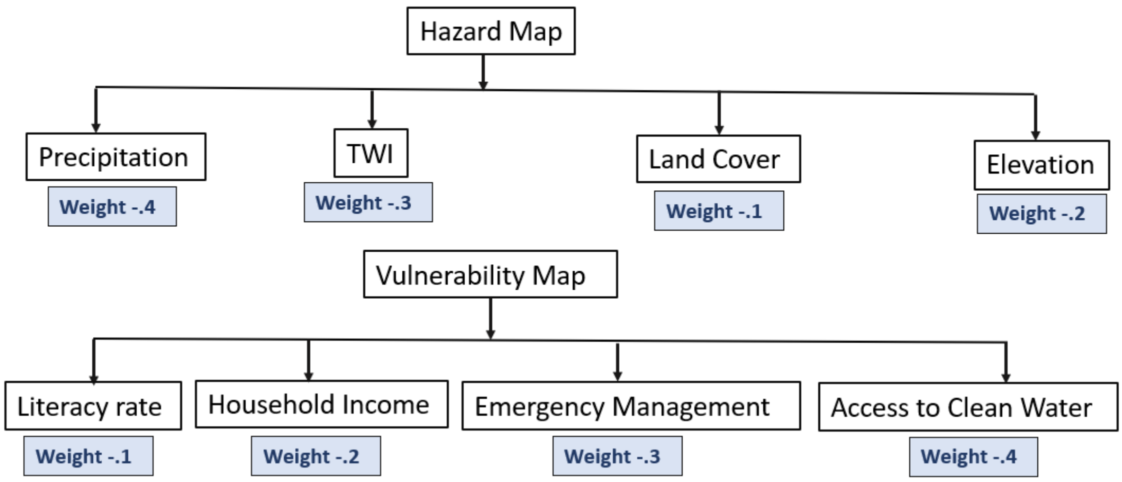


Figure 28: Hierarchy Development and Weight Assignment for Wildfire

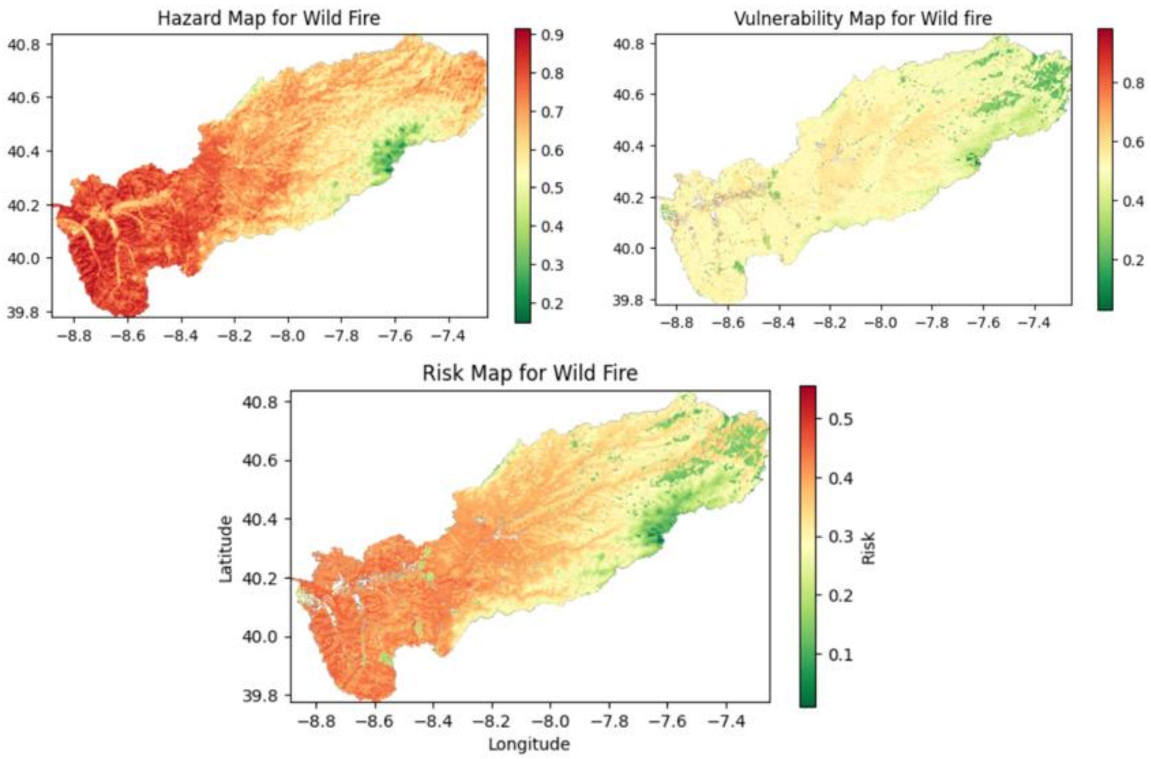


Figure 29: Risk Map for Wildfire

One can develop multiple hazard risk maps for different types of hazards. After creating more than one risk map, we generated a multi-hazard risk map using a weighted linear combination. Assigning weights to different hazards is necessary to complete the multi-hazard risk mapping process. The weight depends on the decision makers knowledge and history of these hazards in the study area. For the testing purpose we have used 0.6 for flooding and 0.4 for wildfire risk (Figure 30). Figure 31 shows the overlayed multihazard map of the study area.

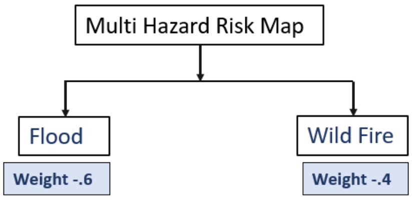


Figure 30: Weight Assignment for Multi-hazard Risk Mapping

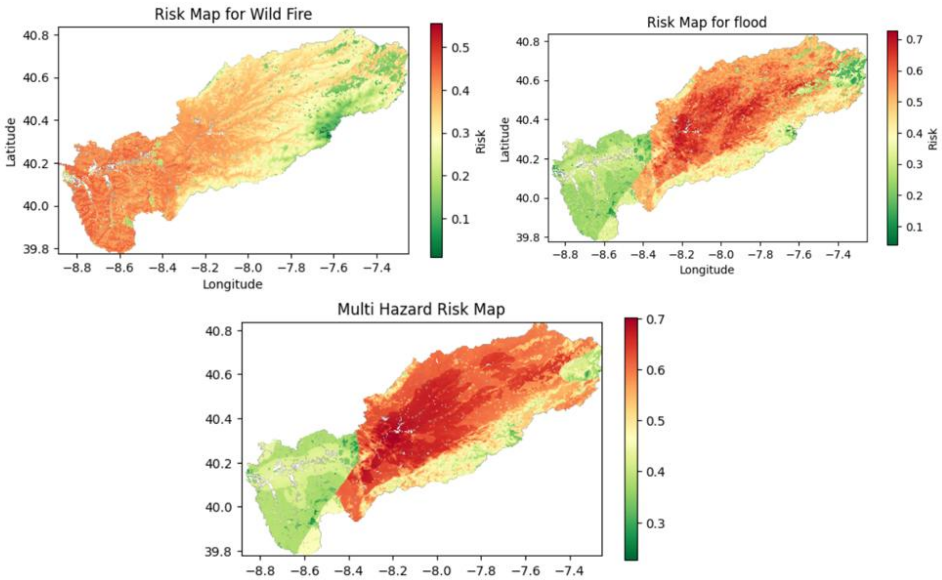


Figure 31:Multi-hazard Risk Map

5.8. Web-based Tool Development

The web-based Spatial Multi-Criteria Decision Analysis (SMCDA) tool development leverages Vue 2 and Nuxt.js for the frontend, providing a structured framework for rendering and managing geospatial data. It integrates OpenLayers to visualize GeoJSON and enable interactive geospatial functionalities. The frontend connects to a NestJS-based backend, which handles API endpoints, data management, and business logic.

As Q-GIS only desktop based application, we have not considered Q-GIS for the web-based tool. Rather we choose open sources codes so that in future it could be more developed and other novel features can be added by the partners and external members as well.

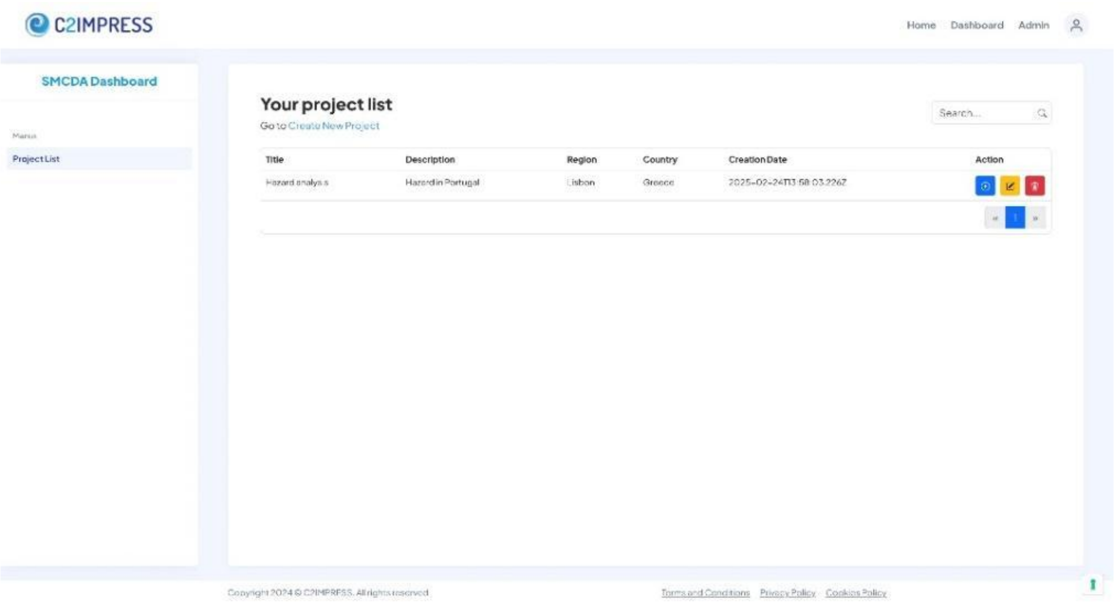
For geospatial data processing, a Python-based transformation service extracts shapefiles and generates raster files using libraries such as GDAL, Rasterio, and GeoPandas. Communication between NestJS and Python is managed using RabbitMQ, ensuring efficient, asynchronous, message-based data processing. MongoDB serves as the primary database, offering flexible storage for unstructured geospatial datasets.

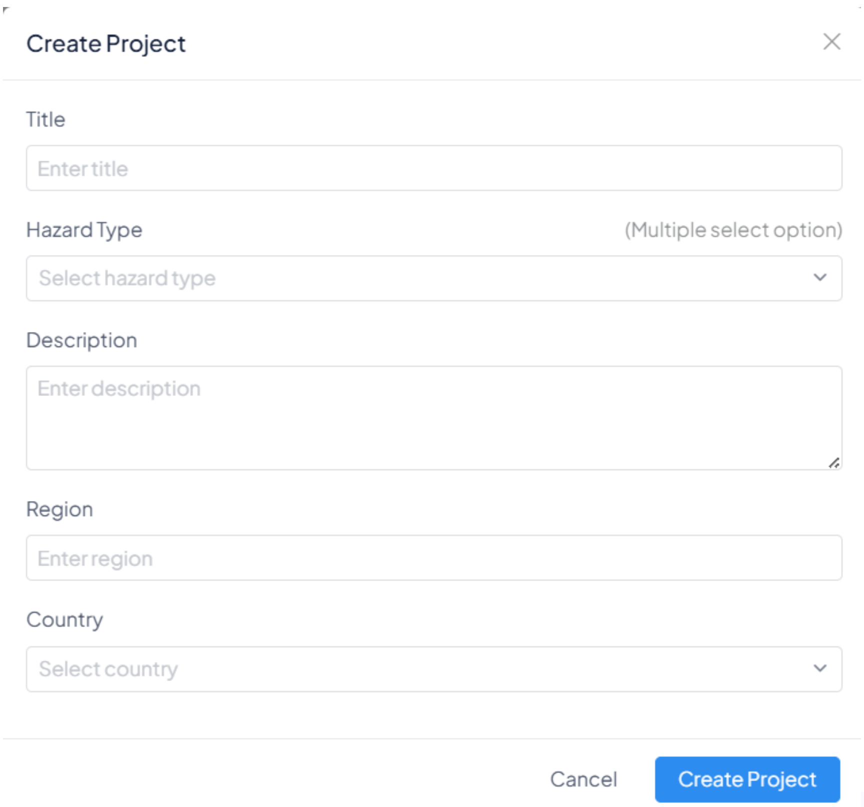
This architecture enables spatial analysis, optimized data processing, and efficient geospatial rendering. The combination of Nuxt.js, NestJS, and Python ensures seamless performance and scalability for large-scale mapping applications. OpenLayers enhances dynamic visualization, providing users with an interactive experience.

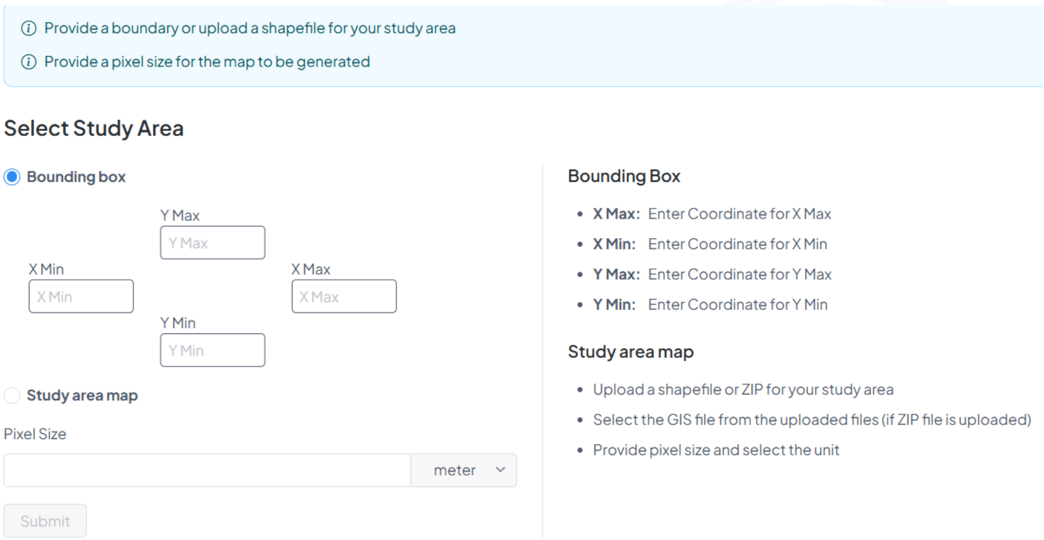
By leveraging RabbitMQ, the system ensures modular and scalable communication between services. This solution effectively processes and renders geospatial data, offering a robust and structured approach to geospatial application development.

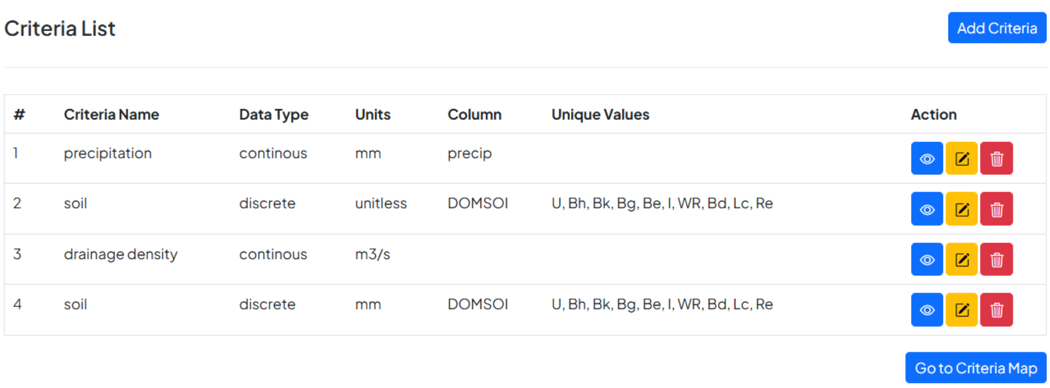
The SMCDA tool includes features for shapefile-to-raster conversion, clipping by study area or bounding box, and constraint mapping using specific criteria maps to create overlays. Users have the flexibility to define the raster pixel size. If a user uploads files with different coordinate systems, the tool automatically converts them to the WGS 1984 coordinate system using geospatial libraries, allowing seamless integration of datasets with varying coordinate systems.

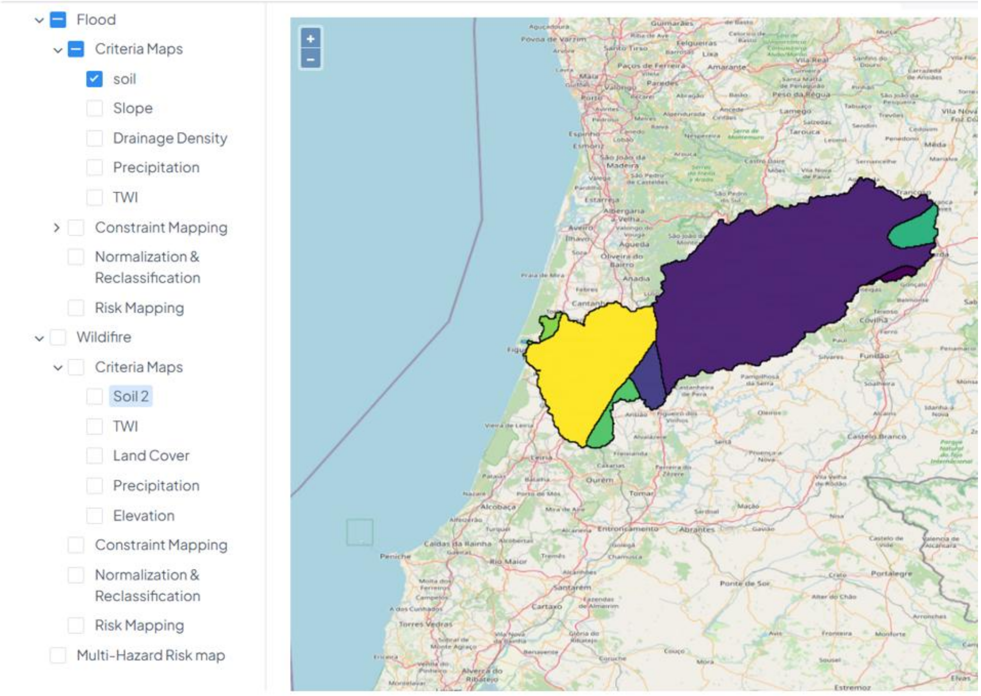
The user interface of the SMCDA (Spatial Multi-Criteria Decision Analysis) project is designed for seamless interaction with spatial data. It features an interactive map, layered visualizations, and customizable filters, enabling users to analyse multiple decision criteria effectively. The structured layout ensures easy navigation with clearly labelled menus, responsive controls, and an organized dashboard. Users can toggle between different data layers, adjust parameters, and visualize results in real time, enhancing the decision-making process. The interface allows users to perform clipping, constraint mapping, and reclassification, leading to the generation of the final risk map, which serves as the core output of the analysis.

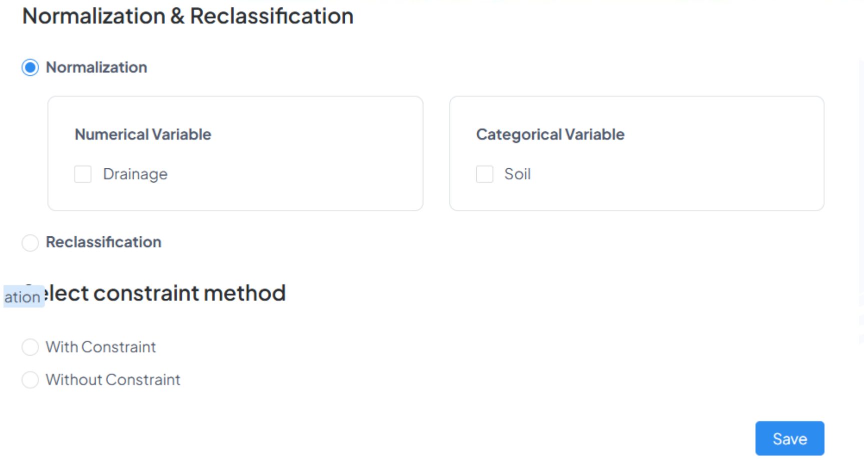


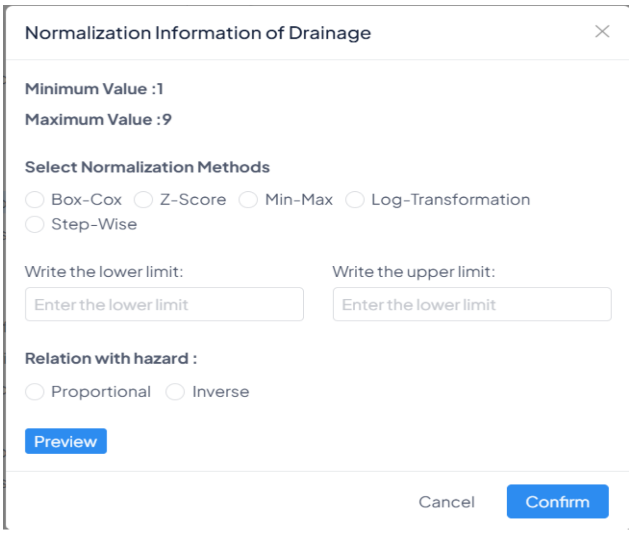

Create Project
Title
Enter title
Hazard Type
(Multiple select option)
Select hazard type
Description
Enter description
Region
Enter region
Country
Select country
Cancel
Create Project

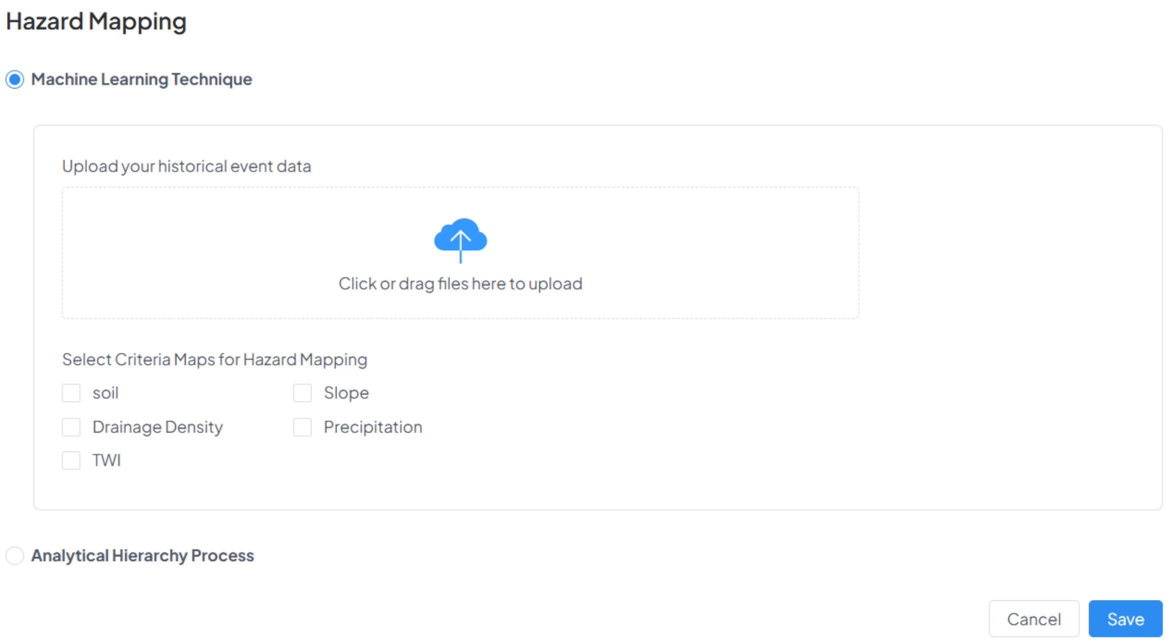

Provide a boundary or upload a shapefile for your study area
Provide a pixel size for the map to be generated
Select Study Area
Bounding box
Y Max
Y Max
X Min
X Min
X Max
X Max
Y Min
Y Min
Study area map
Pixel Size
meter
Submit
Bounding Box
X Max: Enter Coordinate for X Max
X Min: Enter Coordinate for X Min
Y Max: Enter Coordinate for Y Max
Y Min: Enter Coordinate for Y Min
Study area map
Upload a shapefile or ZIP for your study area
Select the GIS file from the uploaded files (if ZIP file is uploaded)
Provide pixel size and select the unit


Criteria List
Add Criteria
Criteria Name Data Type Units Column Unique Values Action
1 precipitation continous mm precip
2 soil discrete unitless DOMSOI U, Bh, Bk, Bg, Be, I, WR, Bd, Lc, Re
3 drainage density continous m3/s
4 soil discrete mm DOMSOI U, Bh, Bk, Bg, Be, I, WR, Bd, Lc, Re
Go to Criteria Map


Flood
Criteria Maps
soil
Slope
Drainage Density
Precipitation
TWI
Constraint Mapping
Normalization & Reclassification
Risk Mapping
Wildfire
Criteria Maps
Soil 2
TWI
Land Cover
Precipitation
Elevation
Constraint Mapping
Normalization & Reclassification
Risk Mapping
Multi-Hazard Risk map


Normalization & Reclassification
Normalization
Numerical Variable
Drainage
Categorical Variable
Soil
Reclassification
ation :lect constraint method
With Constraint
Without Constraint
Save


Normalization Information of Drainage
Minimum Value :1
Maximum Value :9
Select Normalization Methods
Box-Cox
Z-Score
Min-Max
Log-Transformation
Step-Wise
Write the lower limit:
Enter the lower limit
Write the upper limit:
Enter the lower limit
Relation with hazard :
Proportional
Inverse
Preview
Cancel
Confirm


Hazard Mapping
Machine Learning Technique
Upload your historical event data
Click or drag files here to upload
Select Criteria Maps for Hazard Mapping
soil
Slope
Drainage Density
Precipitation
TWI
Analytical Hierarchy Process
Cancel
Save

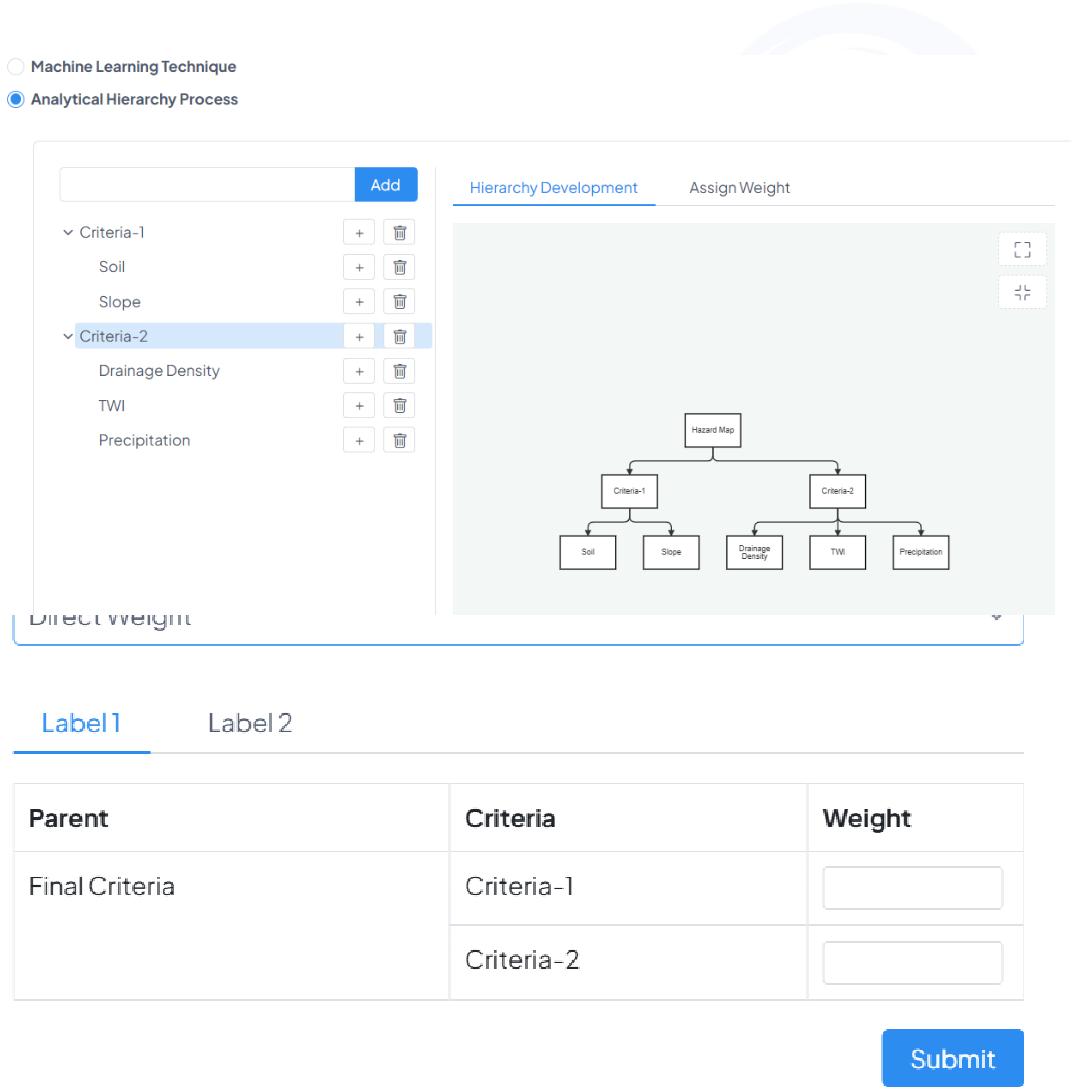

Machine Learning Technique
Analytical Hierarchy Process
Add
Criteria-1
Soil
Slope
Criteria-2
Drainage Density
TWI
Precipitation
Hierarchy Development
Assign Weight
Label 1
Label 2
Parent
Criteria
Weight
Final Criteria
Criteria-1
Criteria-2
Submit

Figure 32: User Interface of SMCDA

The detail user interface and its integration is the scope of T4.7. The detail description will be provided in D4.4.

5.9. Map Server for Integrated Risk and Resilience Analysis

As part of Task T3.5, the Map Server has been developed to support the C2IMPRESS Decision Support System (DSS), providing an integrated, interactive, and robust spatial hazard, vulnerability, and risk mapping tool. It is designed to enhance decision-making processes by enabling the visualization and modification of geospatial data derived from the Spatial Multicriteria Decision Analysis (SMCDA) tool.

Key Functionalities and Features

Visualization of Spatial Data

The Map Server will support multiple geospatial data formats, including raster data, shapefiles, and GeoJSON files.

It will allow users to visualize geospatial outputs generated by the SMCDA tool and other microservices within the DSS.

The tool will ensure that spatial data is rendered in a user-friendly format, enabling intuitive interaction with complex datasets.

Seamless Integration with the DSS Platform

- The Map Server will be fully integrated into the C2IMPRESS DSS to ensure smooth and cohesive user experience.
- The DSS will leverage the Map Server to present geospatial outputs dynamically, supporting risk and resilience assessments across various decision-making scenarios.
- Users will be able to access and visualize geospatial outputs without requiring authentication, ensuring easy and open access to spatial insights.

Interactive Data Modification and Analysis

- The tool will provide functionalities for layer-based visualization, enabling users to overlay multiple spatial datasets for enhanced comparative analysis.
- Users will be able to interact with, modify, and analyse spatial data to support reporting and decision-making.
- Customizable visualization options will allow for the creation of tailored maps that can be exported for reports and other analytical purposes.

Embedding via iFrame for DSS Accessibility

- The visualization component will be designed to be embedded into the Task 4.7 DSS platform using iFrame technology.
- This will allow DSS users to access and interact with spatial data within the main C2IMPRESS DSS interface without requiring separate applications or installations.

The integration and technical implementation details of the Map Server, including its architecture, data flow, and interaction with the Decision Support System (DSS), will be further elaborated in Deliverable D4.4 – Decision support platform – report and demonstration v2 due M34.

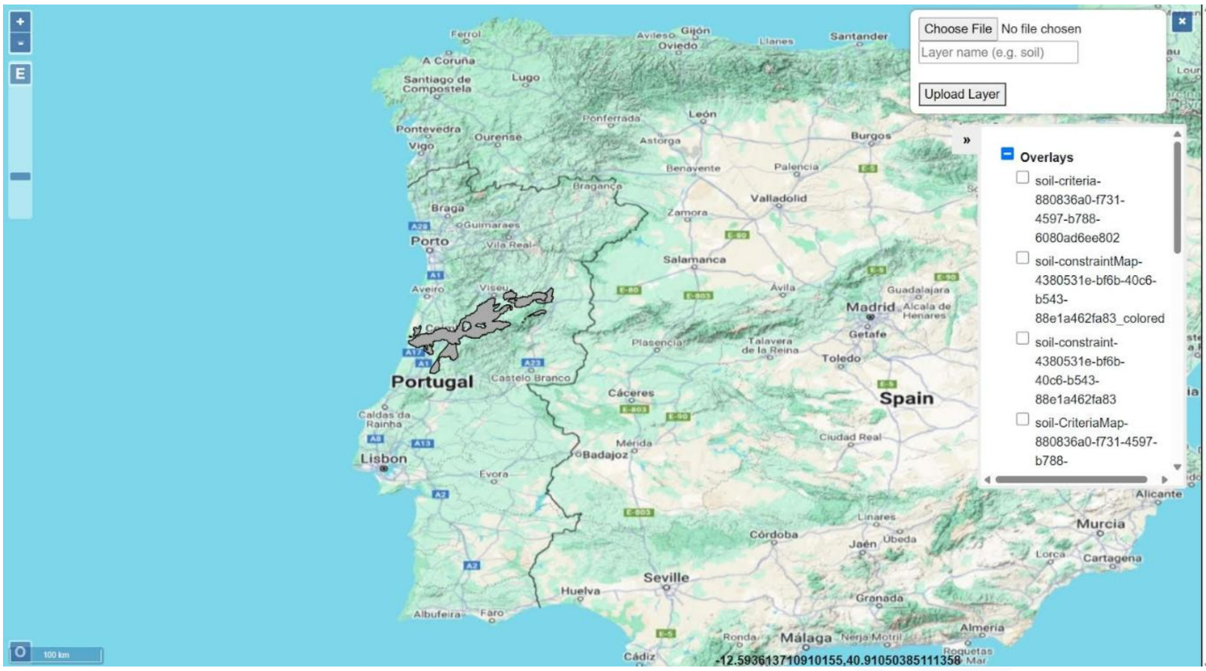


Figure 33: Map Server for Integrated Risk and Resilience Analysis

6. Conclusion and future outlook

This deliverable presents a structured methodology of risk mapping as a decision support tool. This methodology compiles the State-of-the art techniques and provide innovation by developing a structured method for risk mapping including several overlay method and normalisation techniques. The methodology is rigorously tested using the data obtained from PT CSA. After testing the methodology, a web-based tool has been developed to allow the tool to be used around the EU and other countries. The web-based tool provides the flexibility to the user to select their own criteria, include data, choose normalisation method, and overlay techniques. By changing or selecting the methods, the decision-makers can develop different risk maps under different scenarios. For example, for each IPCC scenario, one risk map can be developed. Hence, one can analyse the potential risks under each scenario.

The data pre and processing is done by using python language which is being integrated to the front end of the tool by API. Now the tool is being integrated to the C2IMPRESS Decisions Support System (WP4, T3.5). Once the tool in integrated, the tool will be handed to each CSA and a training will be given on the use of the tool. After that each CSA will be able to perform the risk mapping using their own risk map that will be further used in decision making. The map server will be also integrated in the DSS that will allow to visualise the performed risk maps and manipulate/edit the maps for visualisation or presentation.

The tool is so robust that it can be used for any kind of problems related spatial criteria decision making. Such as it can be used for site selection of open space, site selection for any nature-based solutions, etc. The web-based tool needs no modification for other objectives. Another advantage is more overlay and normalisation methods can be added to the tool by TVS or who has the access to the codes. The tool is open access and everyone can use it.

7. References

[1] R. Khatakho *et al.*, “Multi-Hazard Risk Assessment of Kathmandu Valley, Nepal,” *Sustainability*, vol. 13, no. 10, p. 5369, May 2021, doi: 10.3390/su13105369.

[2] C. Luu, J. Von Meding, and S. Kanjanabootra, “Assessing flood hazard using flood marks and analytic hierarchy process approach: a case study for the 2013 flood event in Quang Nam, Vietnam,” *Nat. Hazards*, vol. 90, no. 3, pp. 1031–1050, Feb. 2018, doi: 10.1007/s11069-017-3083-0.

[3] H. R. Pourghasemi *et al.*, “Assessing and mapping multi-hazard risk susceptibility using a machine learning technique,” *Sci. Rep.*, vol. 10, no. 1, p. 3203, Feb. 2020, doi: 10.1038/s41598-020-60191-3.

[4] B. T. Pham *et al.*, “Flood risk assessment using deep learning integrated with multi-criteria decision analysis,” *Knowl.-Based Syst.*, vol. 219, p. 106899, May 2021, doi: 10.1016/j.knosys.2021.106899.

[5] K. Ullah and J. Zhang, “GIS-based flood hazard mapping using relative frequency ratio method: A case study of Panjkora River Basin, eastern Hindu Kush, Pakistan,” *PLOS ONE*, vol. 15, no. 3, p. e0229153, Mar. 2020, doi: 10.1371/journal.pone.0229153.

[6] J. Vojteková and M. Vojtek, “Assessment of landslide susceptibility at a local spatial scale applying the multi-criteria analysis and GIS: a case study from Slovakia,” *Geomat. Nat. Hazards Risk*, vol. 11, no. 1, pp. 131–148, Jan. 2020, doi: 10.1080/19475705.2020.1713233.

[7] A. M. Youssef and H. R. Pourghasemi, “Landslide susceptibility mapping using machine learning algorithms and comparison of their performance at Abha Basin, Asir Region, Saudi Arabia,” *Geosci. Front.*, vol. 12, no. 2, pp. 639–655, Mar. 2021, doi: 10.1016/j.gsf.2020.05.010.

[8] M. Azarafza, M. Azarafza, H. Akgün, P. M. Atkinson, and R. Derakhshani, “Deep learning-based landslide susceptibility mapping,” *Sci. Rep.*, vol. 11, no. 1, p. 24112, Dec. 2021, doi: 10.1038/s41598-021-03585-1.

[9] H. Farhadi and M. Najafzadeh, “Flood Risk Mapping by Remote Sensing Data and Random Forest Technique,” *Water*, vol. 13, no. 21, p. 3115, Nov. 2021, doi: 10.3390/w13213115.

[10] B. T. Pham *et al.*, “Flood risk assessment using hybrid artificial intelligence models integrated with multi-criteria decision analysis in Quang Nam Province, Vietnam,” *J. Hydrol.*, vol. 592, p. 125815, Jan. 2021, doi: 10.1016/j.jhydrol.2020.125815.

[11] E. Feloni, I. Mousadis, and E. Baltas, “Flood vulnerability assessment using a GIS-based multi-criteria approach—The case of Attica region,” *J. Flood Risk Manag.*, vol. 13, no. S1, p. e12563, Jan. 2020, doi: 10.1111/jfr3.12563.

[12] A. Tiwari, M. Shoab, and A. Dixit, “GIS-based forest fire susceptibility modeling in Pauri Garhwal, India: a comparative assessment of frequency ratio, analytic hierarchy process and fuzzy modeling techniques,” *Nat. Hazards*, vol. 105, no. 2, pp. 1189–1230, Jan. 2021, doi: 10.1007/s11069-020-04351-8.

[13] R. Jena *et al.*, “Integrated model for earthquake risk assessment using neural network and analytic hierarchy process: Aceh province, Indonesia,” *Geosci. Front.*, vol. 11, no. 2, pp. 613–634, Mar. 2020, doi: 10.1016/j.gsf.2019.07.006.

[14] S. A. Ali *et al.*, “GIS-based comparative assessment of flood susceptibility mapping using hybrid multi-criteria decision-making approach, naïve Bayes tree, bivariate statistics and logistic regression: A case of Topľa basin, Slovakia,” *Ecol. Indic.*, vol. 117, p. 106620, Oct. 2020, doi: 10.1016/j.ecolind.2020.106620.

[15] X. Lei *et al.*, “Urban flood modeling using deep-learning approaches in Seoul, South Korea,” *J. Hydrol.*, vol. 601, p. 126684, Oct. 2021, doi: 10.1016/j.jhydrol.2021.126684.

[16] M. Tonini, M. D’Andrea, G. Biondi, S. Degli Esposti, A. Trucchia, and P. Fiorucci, “A Machine Learning-Based Approach for Wildfire Susceptibility Mapping. The Case Study of the Liguria Region in Italy,” *Geosciences*, vol. 10, no. 3, p. 105, Mar. 2020, doi: 10.3390/geosciences10030105.

[17] S. Yousefi, H. R. Pourghasemi, S. N. Emami, S. Pouyan, S. Eskandari, and J. P. Tiefenbacher, “A machine learning framework for multi-hazards modeling and mapping in a mountainous area,” *Sci. Rep.*, vol. 10, no. 1, p. 12144, Jul. 2020, doi: 10.1038/s41598-020-69233-2.

[18] Q. B. Pham *et al.*, “A comparison among fuzzy multi-criteria decision making, bivariate, multivariate and machine learning models in landslide susceptibility mapping,” *Geomat. Nat. Hazards Risk*, vol. 12, no. 1, pp. 1741–1777, Jan. 2021, doi: 10.1080/19475705.2021.1944330.

[19] C. Luu and J. Von Meding, “A Flood Risk Assessment of Quang Nam, Vietnam Using Spatial Multicriteria Decision Analysis,” *Water*, vol. 10, no. 4, p. 461, Apr. 2018, doi: 10.3390/w10040461.

[20] F. Radwan, A. A. Alazba, and A. Mossad, “Flood risk assessment and mapping using AHP in arid and semiarid regions,” *Acta Geophys.*, vol. 67, no. 1, pp. 215–229, Feb. 2019, doi: 10.1007/s11600-018-0233-z.

[21] D. Rincón, U. Khan, and C. Armenakis, “Flood Risk Mapping Using GIS and Multi-Criteria Analysis: A Greater Toronto Area Case Study,” *Geosciences*, vol. 8, no. 8, p. 275, Jul. 2018, doi: 10.3390/geosciences8080275.

[22] Z. T. Mohammed, L. Y. Hussein, and M. H. Abood, “Potential Flood Hazard Mapping Based on GIS and Analytical Hierarchy Process,” *Journal of Water Management Modeling*, vol. 12, no. 7, paper C528, 2024, doi: 10.14796/JWMM.C528.

[23] Y. K. Wondim, “Flood Hazard and Risk Assessment Using GIS and Remote Sensing in Lower Awash Sub-basin, Ethiopia,” *Journal of Environment and Earth Science*, vol. 6, no. 9, pp. 69–80, 2016

[24] C2IMPRESS, D3.3 – Report on (a) the risk framework, (b) resilience framework and (c) the support tool for operationalization v2*, WP3: Multi-hazard Risk Exposure and Resilience Framework*, Jan. 2024.

[25] E. G. Carayannis, T. D. Barth, and D. F. J. Campbell, “The Quintuple Helix innovation model: global warming as a challenge and driver for innovation,” *Journal of Innovation and Entrepreneurship*, vol. 1, no. 1, p. 2, Aug. 2012, doi: 10.1186/2192-5372-1-2.

[26] H. Ross, “Transmission of knowledge and social learning for disaster risk reduction and building resilience: A Delphi study,” *Sustainable Development,* 2023, doi: 10.1002/sd.2685. Available: https://onlinelibrary.wiley.com/doi/10.1002/sd.2685.

[27] Copernicus Data: https://dataspace.copernicus.eu,

CHIRPS Data: https://www.chc.ucsb.edu/data/chirps,

USGS Data: https://earthexplorer.usgs.gov

A. Appendices

Appendix A: List of criteria for each hazard type and vulnerability

Table A.1: Selected Criteria for Earthquake Hazard

Criteria Maps for Earthquake Hazard	Description
Elevation	Elevation can be a factor in earthquake risk, but its impact varies greatly depending on the underlying geology and tectonic setting. For example, some mountainous regions may be less prone to seismic activity than certain types of low-lying areas, such as sedimentary floodplains
Lithology	Unconsolidated sedimentary deposits can amplify ground shaking during earthquakes, while lithology can influence the formation and behavior of faults, which in turn can contribute to seismic activity
Distance to faults	Earthquake waves reduce their intensity when travelling through the ground, therefore earthquake magnitude is lower with increasing distance from the fault.
Land Use / Land Cover (LULC)	The presence of built- area creates the favourable environment for fire, flood, and earthquake hazard mostly due to exposure and the underlying vulnerabilities of constructed facilities
Slope angle	The relationship between slope and earthquake hazard is significant, as steeper slopes can be more susceptible to landslides and other mass movement phenomena during seismic events. Areas with considerable slopes may experience increased ground shaking and destabilization, leading to a higher risk of geological hazards such as landslides, particularly in regions with loose or unconsolidated materials. Understanding this relationship is essential for assessing seismic risk and implementing effective land-use planning and mitigation strategies.
Epicentre density	Spatial epicentre density identifies zones of earthquake clustering, indicating areas prone to seismic activity. By analysing epicentre density, one can focus on epicentres of major earthquakes, riftogenesis attractor structures, and primary fracture zones.
Epicentre distance	With increasing distance from the epicentre, the probability of earthquake occurrence decreases
Magnitude-Frequency Distribution (MFD)	MFD describes the relative proportion of earthquake magnitudes.
Peak Ground Acceleration (PGA) density	PGA density provides ground acceleration information that is derived from information on to the lithology, earthquake magnitude, and distance from the epicentre.
Amplification factor	This is an important factor, as Seismic waves travel faster through hard rocks than through softer rocks and sediments. Therefore, the softer and thicker the soil, the greater the shaking or amplification of waves produced by an earthquake.
Fault density	Fault density is an important factor because earthquakes are predominantly triggered by movement along faults, where rocks slip past one another. The higher the density the higher the likelihood of earthquakes occurrences.

Table A.2: Selected Criteria for Flood Hazard

Criteria Maps for Flood Hazard	Description
Slope	Steeper slopes increase runoff, reducing infiltration and increasing flood risk in connected areas with low gradient.
Aspect	Determines the direction of slope, affecting sun exposure and vegetation cover/density and moisture retention.
Elevation	Lower elevations are more prone to flooding due to water accumulation.
Distance to Streams	Areas closer to streams are at higher risk of flooding during heavy rainfall.
Drainage Density	Higher drainage density (number of tributary rivers) channels rainfall more quickly and reduces the lag time between rainfall and discharge peak indicating increasing flood susceptibility.
Flow Accumulation	Maps areas where water converges in a landscape, increasing flood potential.
Topographic Roughness Index (TRI)	Quantifies the roughness or variability of the terrain, influencing water flow and flood dynamics.
Topographic Wetness Index (TWI)	TWI quantifies terrain driven variation in soil moisture and therefore indicates areas of potential water retention, impacting flood risks.
Stream Power Index (SPI)	Assesses the erosive power of water flow, influencing flood intensity.
Sediment Transportation Index (STI)	Evaluates sediment transport potential, affecting river stability and flood impact.
Normalized Difference Vegetation Index (NDVI)	Quantifies vegetation greenness, thereby inferring vegetation density and plant health, which affects water absorption and retention and partially controls floods .
Profile Curvature	Influences water flow direction and accumulation, impacting flood risk.
Precipitation	Higher rainfall intensity increases surface runoff, leading to greater flood risks.
Soil Type	Different soil types have distinct infiltration rates, modulating flood potential.
Land Cover	Urbanization and deforestation decrease water infiltration, evapo-transpiration and increase surface runoff.

Figure A.3: Selected Criteria for Landslide Hazard

Criteria Maps for Landslide Hazard	Description
Elevation/Slope	Elevation does not directly contribute to the formation of landslides but affects , weathering, wind action, and precipitations that influence slope instability. Higher slope of prone to lanslide.
Lithology	Geological formations have an important role in the occurrence or absence of landslides due to the diversity of characteristics such as the resistance and penetrability and stability of rocks and soils.
Distance to faults	The presence of structural discontinuities, which are tectonic breaks including faults, folds, fractures, joints, and shear zones, play a role in weakening the rock masses (decreasing the rock strength) and facilitating landslide. Also, landslides

	are more likely to happen when an earthquake creates movement along the fault line.
Normalized Difference Vegetation Index (NDVI)	NDVI allows inferring slope stabilization through the quantification of vegetation greenness, which indicates vegetation density and plant health. Low vegetation coverage can create conducive conditions for erosion and landslide occurrence, whereas high coverage plays an important role in immobilizing large volumes of water and increasing the shear resistance and soil cohesion of the lithological mass. In general, the value NDVI ranged from -1 to 1; the high the value the denser the vegetation cover. Quantifies vegetation greenness, thereby inferring vegetation density and plant health,
Land Use / Land Cover (LULC)	Influences the susceptibility of rainfall-triggered landslides, by directly affecting soil mechanical behaviour and moisture. For example vegetation can protect soil from erosion and improve slope stability, whereas deforestation, road or building construction, on hillslopes often reduce slope stability.
Distance to streams	Proximity to the stream can be negatively correlated with the stability of slopes because of potential slope erosion due to saturation of the lower part of the material and undercutting of river banks caused by flowing water
Distance to roads	Distance from road is negatively correlated with landslide as proximity to road may increase susceptibility of landslide hazard due to possible inadequate design of drainage systems and mechanical destabilisation by undercutting and overloading
Slope aspect	It affects hydrological processes such as evapotranspiration and weathering, the amount of rainfall, wind and heat exposure. This results in alteration of pore water pressure of slope material. Slope aspect classes are highly susceptible to landslide whereas the flat and northwest facing classes are lower susceptibility to the landslide.
Slope angle	Steeper slopes are more prone to landslides as the shear force proportionately increases (the force of gravity stays the same and the normal force decreases)
Profile curvature	Plan curvature has a direct impact on the convergence and dispersion of surface runoffs. Surface waters on concave slopes have higher carving ratios than on convex slopes, but nevertheless, both curvatures are more susceptible to landslide than flat curvature,.
Soil	Soil characteristics and properties significantly influence its ability to bear loads. In particular, clay-rich soils can exhibit sensitive behaviors that affect stability. The sensitivity of clay is heavily influenced by its water content; as the water content increases, so does the sensitivity of the clay. This heightened sensitivity can lead to an increased vulnerability to landslides during seismic events or heavy rainfall.
Precipitation	Rainfall is a major triggering parameter for landslides that causes infiltration of water into the soil and also increasing pore-water pressure and soil saturation.

Table A.4: Selected Criteria for Wildfire Hazard

Criteria Maps for Wildfire Hazard	Description
Elevation	Elevation is a critical physiographic criterion that governs fire behaviour by affecting the volume and schedule of rainfall and exposure to the prevailing wind and vegetation density at high altitudes. Wildfires are more probable at lower elevations.
Normalized Difference Vegetation Index (NDVI)	NDVI quantifies vegetation greenness (related to the plant's photosynthetic activity), is useful in understanding vegetation density and assessing changes in plant health, which is closely related to soil water availability. It helps identifying vegetation cover that has the potential to become wildfire fuel and presents an insight into possible fire hazard.
Topographic Wetness Index (TWI)	TWI quantifies terrain driven variation in soil moisture Thus, TWI defines the spatial distribution of soil moisture and directly impacts the development of scenarios for forest fires.
Land Use / Land Cover (LULC)	The built-up area creates a favourable environment for fire, flood, and earthquake hazards primarily due to exposure and the underlying vulnerabilities of constructed facilities.
Distance to streams	The distance from streams plays a crucial role in determining the impact, scope, and severity of wildfires by influencing moisture availability, vegetation density, and fire spread dynamics. Areas closer to streams tend to have higher soil moisture levels and more lush vegetation, which can slow down fire ignition and spread. In contrast, regions farther from water sources often experience drier conditions, making them more susceptible to intense and widespread wildfires. Additionally, streams can act as natural firebreaks, limiting the fire's expansion and reducing its overall severity.
Distance to roads	Good access and the proximity of the road network from the settlements reduce losses due to fire hazards, as roads facilitate access for fire brigades to affected areas .
Slope aspect	The aspect of an area influences fire behaviour directly through the amount of solar radiation and moisture availability and indirectly through changes in vegetation composition and density. Hence fuels are usually drier and less dense on northern and western slopes
Slope angle	Fire spreads faster uphill ,as the uphill vegetation, is pre-heated allowing it to ignite more rapidly. Conversely it spreads slower downhill .
Temperature	Temperature has a direct relation to wildfires. High temperatures increase forest fire risk by making fuels highly susceptible to fire, mainly due to dryness. making it more vulnerable to ignition. Increasing temperature directly impacts the destructive nature, coverage, and frequency of wildfires.
Precipitation	Rainfall has an inverse relation to wildfires. Little/no rain increases the risk of wildfires by reducing the moisture content of the fuels and making them susceptible to fire, whereas high precipitation has the opposite effect.
Wind Speed	Stronger wind provides fresh oxygen feeding an existing fire.. high wind speed also lowers the degree of surface moisture, which causes fuel drying. High-speed and powerful winds head toward the rapid expansion of a fire cover. High wind speed in the summer period enhances the frequency of wildfires.

frequency of lightning	The frequency of lightning is directly related to wildfire hazard, as areas experiencing frequent lightning strikes are at greater risk of ignition, especially in dry conditions. Such lightning-induced fires can rapidly spread, significantly increasing the potential for extensive wildfire outbreaks.

Table A.5: Selected Criteria for Vulnerability Mapping

Factor Name	Description	Data Type
Number of Disabled People	The number of disabled people indicates vulnerability, as individuals with disabilities face greater challenges in mobility, evacuation, and accessing resources during hazards.	Numerical and Zone wise.
Under and over-aged people	The proportion of underage (youth) and overage (elderly) individuals reflects vulnerability, as these groups may have a higher dependency on others and face greater risks during hazards due to limited mobility or health concerns.	Numerical and Zone wise.
Communication Capacities	Communication capacities refer to the ability of individuals, organizations, or systems to effectively exchange information, which is crucial for mitigating vulnerabilities and enhancing resilience during crises	Zone wise Ranking
Internet Access	Internet access is a critical factor in reducing vulnerabilities by enabling access to information, resources, and communication during emergencies and crises	The number of people connected to the Internet or zone wise ranking
Literacy rate	Literacy rate is a key indicator of a population's educational level, influencing economic opportunities, social equity, and resilience to vulnerabilities.	Zone wise Percentage or ranking
Emergency Management	Emergency management is the coordinated effort to prepare for, respond to, and recover from disasters, reducing vulnerabilities and enhancing community resilience.	Zone wise ranking
Emergency Services Capacities	Emergency services capacities refer to the ability of systems and organizations to effectively respond to crises, minimizing vulnerabilities and protecting lives and property.	Zone wise ranking
Early Warning System	An early warning system reduces vulnerabilities by providing timely alerts and information to mitigate the impact of impending hazards or disasters.	Zone wise Ranking

Access to clean water and public sewage	Access to clean water and public sewage is essential for reducing vulnerabilities by preventing waterborne diseases and ensuring public health and sanitation.	Zone wise Ranking
Household Income	Household income is a critical factor for indicating vulnerability, as lower income levels can limit access to resources, services, and opportunities for resilience during crises.	Zone wise average household income or ranking