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Enhancing Risk Analysis toward a Landscape Digital Twin Framework: A Multi-Hazard Approach in the Context of a Socio-Economic Perspective

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Abstract: In the last decades, climate and environmental changes have highlighted the fragility and vulnerability of the landscape, especially in mountain areas where the effects are most severe. This study promotes the methodological setup of a landscape digital twin to establish a multi-disciplinary and multi-scalar hazard overview according to a matrix framework implementable over time and space. The original contribution to the research addresses a holistic vision that combines meaningfully qualitative with quantitative approaches within a multi-hazard framework from the socio-economic perspective. This contribution presents road network risk analysis by exploiting flooding and landslide scenarios. The critical road segments or nodes most vulnerable or impacted by network performance and accessibility can be identified with minimal preprocessing from credible open-source sources. Service maps are used to show the spatial distribution of risk scores for different typologies of points of interest and hazards. Origin-destination matrix graphs display changes in travel time between facilities under various scenarios. Using a risk scores formula to generate risk maps has made it possible to effectively represent the interconnectedness among natural hazards, infrastructure, and socio-economic factors, fostering more resilient decision-making processes. The method's applicability is tested through a case study in northern Italy's Piedmont Region.

Keywords: landscape digital twin; GIS; natural hazards; road; floods; landslide; risk analysis; open-source data; risk maps; socio-economic approach

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1. Introduction

1.1. Background and Motivation

Nowadays, the Alpine space is facing significant challenges: the need for increasing digital and ecological transition is compounded by ageing and emigration trends. Re-populating mountain areas in a sustainable and digital key [1] requires a wide-ranging multidisciplinary and multi-scalar strategy to produce tangible impacts on the territory. This need is even more pronounced concerning climate and environmental changes. Indeed, mountains are very sensitive and more vulnerable to the effects of such modifications, with clearly visible and amplified responses affecting their morphology.

Global warming has decreased the extent of snow- and ice-covered areas, resulting in the darker soil's reduced ability to absorb solar radiation and warmth. Permafrost, ice segregation, and a higher frequency of extreme precipitation events have been argued to be responsible for increased slope-failure events over the last decades [2]. At the same time, the danger of flooding phenomena [3] is mainly attributable to anthropogenic causes, such as buildings in high-risk areas, urbanization, and often uncontrolled cementing, as well as deficiencies in cleaning riverbeds and surrounding areas, which have reduced the flood containment capacity, increasing the risk of flooding. The human settlements established in the valleys and the infrastructures are thus directly or indirectly threatened occasionally [4]. Since road transportation networks are essential for the mobility and accessibility of people and goods to critical facilities and services [5–7] and for the regions' economic and social development, assessing the impact of hazards on these factors is crucial for enhancing the region's resilience and reducing the risk of hazards.

While studies have always been oriented toward the built and historical heritage for preservation, management, and maintenance purposes, understanding the landscape is crucial today more than ever. An in-depth knowledge of the territory and monitoring of its transformations is urgently needed. Specifically, it is necessary to have a scalable multi-hazard framework that can integrate diverse data types while considering their contextual information and address the gap in understanding the socio-economic effects of natural hazards. Such a framework can help to identify the most vulnerable areas and populations, evaluate the potential impacts and risks of different scenarios, and support the decision-making process for disaster preparedness and mitigation.

The methodological setting of a digital twin (DT) [8] constitutes the paradigm around which to hinge any potential theoretical and practical developments. This research front is supported by the European Commission, which first targeted this flagship initiative through the Destination Earth (DestinE) project [9], which aims to develop a highly accurate digital model of the Earth on a global scale to guarantee a sustainable future. The European Space Agency is also moving in this direction through a new representation of the Earth System based on integrating earth observation data, inter-connected numerical simulations, and artificial intelligence [10]. The mountain digital twin is a digital model of the mountain that is created through the acquisition of all available data to have a snapshot of the complexity of the territory. The spatial representation based on the oro-geographical model is enriched in real time by the data collected in the field, which are used to create simulations, reasoning, and predictive scenarios. Therefore, the idea of DT focuses on the possible content and levels of knowledge to be handled for land planning and management.

This study promotes a matrix view of hazards affecting the land by promoting methods and tools to relate specialized data and simulations of each domain to each other with geospatial databases. Specifically, a framework relating the transportation network with floods and landslides is presented. The method is validated through a real-world case study. The potential for creating these intersections of data, tools, and methodologies emerges immediately, corroborating the approach and opening up new segments of specific experimentation.

1.2. Literature Review

Natural hazards are extreme events that threaten human lives, livelihoods, and environments [11]. They can cause direct impacts resulting from the physical contact of people and assets with the hazard agent, such as deaths, injuries, damages, and losses, as well as indirect effects that disrupt the normal functioning of society and the economy due to hazardous events, such as displacement, unemployment, poverty, and social unrest [12]. According to the United Nations Office for Disaster Risk Reduction (UNDRR), natural hazards affected more than 4.2 billion people and caused over USD 2.9 trillion in economic losses between 2000 and 2019 [13]. Moreover, natural hazards are expected to increase in frequency and intensity due to climate change, population growth, urbanization, and environmental degradation [14].

One of the significant challenges in disaster risk management is understanding and assessing the socio-economic effects of natural hazards, which are often complex, dynamic, and context specific [15]. They can be influenced by factors such as populations' exposure, vulnerability, coping capacity, recovery potential, and adaptation strategies [6]. The effects can also vary depending on the events' type, magnitude, frequency, and duration, as well as the combination of natural hazards [16]. Short-term results occur immediately or shortly after the hazard event, such as rescue operations, emergency relief, and temporary shelter [17]. Long-term effects persist for months or years after the hazard event, such as reconstruction, recovery, and adaptation [18]. Socio-economic impacts can significantly affect human societies' well-being, development, and sustainability. For instance, natural hazards can reduce income and consumption, increase inequality and poverty rates, disrupt education and health services, degrade natural resources and ecosystems, and undermine social cohesion and trust [19,20].

Therefore, understanding and assessing the socio-economic effects of natural hazards is essential for designing and implementing adequate disaster risk management policies and strategies. Most studies have focused on single-hazard events, overlooking the possibility and reality of multi-hazard events [21]. Multi-hazard events are situations where two or more natural hazards occur simultaneously or sequentially in the same area, causing compounded or cascading effects [22]. For example, earthquakes can trigger landslides and tsunamis, and floods can cause mudflows and power outages. Only a multidisciplinary approach can capture the complexity, diversity, and dynamism of human-hazard interactions. It also requires a comprehensive data collection and analysis system integrating different sources and data types at different spatial and temporal scales [23].

A multi-hazard process considers the interactions and interdependencies among multiple dangers and their impacts on human societies. It provides a more realistic and comprehensive picture of different areas and populations' potential risks and vulnerabilities [23–25]. Different methodologies for multi-hazard risk analysis assessment can be categorized into qualitative, quantitative, and semi-quantitative approaches to assess the socio-economic effects of multi-hazard events [23,26]. Qualitative methods rely on descriptive and narrative techniques, drawing insights from expert opinions, stakeholder analysis, and scenario analysis. While they capture the complexity and diversity of multi-hazard situations, they may suffer from subjectivity and lack of empirical data [26]. On the other hand, quantitative methods utilize mathematical and statistical techniques with numerical data, models, and simulations to provide objective and consistent results. However, data availability, quality, and model assumptions can challenge these methods [26]. Semi-quantitative methodologies bridge the gap by combining qualitative and quantitative elements, balancing complexity and simplicity. They use scoring, ranking, weighting, and mapping techniques to transform qualitative information into quantitative values and vice versa [27]. Two main types can be distinguished among the quantitative methodology: multi-layer single-hazard and multi-hazard risk assessment approaches [26]. The former assesses each hazard separately and overlays or aggregates the results [27]. At the same time, the latter considers interactions and interdependencies among hazards, providing a more comprehensive understanding but demanding more data and complexity. The increasing complexity of multi-hazard events necessitates methodologies that effectively combine qualitative and quantitative approaches and their socio-economic impacts.

One of the aspects that can enhance the understanding and assessment of the socio-economic effects of natural hazards is the use of visualization tools that can display the multi-hazard scenarios and their impacts clearly and intuitively. Visualization tools can help communicate complex and uncertain information to stakeholders, such as decision-makers, planners, and the public, and facilitate their participation and collaboration in disaster risk management. Moreover, visualization tools can support analyzing and evaluating disaster risk management options and their trade-offs, such as mitigation, preparedness, response, and recovery measures [28]. However, most of the existing visualization tools for natural hazards are limited to two-dimensional (2D) maps or charts that cannot capture the spatial and temporal dynamics of multi-hazard events and their effects on the built environment. Therefore, there is a need for more advanced visualization tools that can leverage the three-dimensional (3D) spatial data embedded in building information models (BIMs) and city information models (CIMs) to create realistic and interactive representations of multi-hazard scenarios and their impacts on individual buildings and urban areas.

From the literature analysis, the existing knowledge gap intended to be covered through this paper is detectable. This research paper emphasizes adopting a multi-hazard approach to capture a more realistic and comprehensive understanding of the socio-economic impacts. Additionally, the methodology employed in this study is designed to be scalable, meaning it can be applied to other study areas, enhancing the generalizability and practicality of the findings.

1.3. Significance of the Study

This study contributes to the existing literature on disaster risk management by providing a novel approach to assess the socio-economic effects of natural hazards using a scalable multi-hazard framework.

The general objectives are as follows:

- To define and operationalize risk analysis indicators that capture the socio-economic effects of natural hazards.
- The definition and operationalization of risk analysis indicators can reflect the socio-economic effects of natural hazards on people's lives.
- To present the risk analysis outcomes in terms of qualitative (risk maps) and quantitative (origin–destination matrix graphs) outputs.
- To perform and compare risk analysis with several categories of points of interest (POIs) under different scenarios.
- To calculate risk scores based on a robust formula that considers the type of point of interest, the type of hazard, and the land cover classification.
- To propose a scalable methodology that can integrate multiple data sources and types for multi-hazard analysis.

Expressly, the scope of this research paper is limited to the following:

- The focus on road network accessibility as a risk indicator.
- The road network analysis according to different types of points of interest (health facilities, public facilities, town centers, and tourism facilities) under different scenarios (basic, disrupted).
- The consideration of two types of natural hazards: landslides and floods.
- The use of publicly available credible data sources such as government portals.
- The application of open-source tools such as the quantum geographic information system (QGIS).

The integrated approach has been validated through a real-world case study in the Piedmont region of Italy. As the Orco Valley has experienced severe flood and landslide events, flood and landslide hazard maps from existing sources or models have been used to create disrupted scenarios for the road network in the valley.

2. Materials and Methods

As anticipated in the previous section, the specific objective is to create a scalable method that generates risk maps by integrating different data domains to perform a road network risk analysis, within a multi-hazard framework, specifically in the context of a socio-economic perspective. The research framework described in Figure 1 consists of the following main steps: (i) the selection of a case study for the experimentation; (ii) the definition of the input data; (iii) the risk analysis performed both within qualitative and quantitative research; (iv) the outcomes achieved; and (v) the scalability of the system according to a landscape digital twin vision. The methodological approach is described in this section, while the practical application to the case study is described in the results.

2.1. Case Study Area

The methodology was tested by taking the Orco Valley on the Graian Alps in the metropolitan area of Turin (Italy) as a reference case study. The valley, located in the central part of the Gran Paradiso Massif, is carved by the Orco River, and it is characterized by a landscape typical of glacial valleys where the shaping action of glaciers over millennia is evident and a slow process of deep-seated gravitational slope deformation is undergoing. Its orography is very interesting as it includes several mountains and alpine passes [29]; it is rich in lakes, as well as some natural alpine other artificial reservoirs, as several hydroelectric power plants are situated there. The precipitation rate is pre-alpine, and the average annual rainy days register from the Ceresole Reale station varies from 90 to 110. On the Orco basin, average annual precipitations are about 1224 mm/year, and yearly rainy days are 96 with an intensity of 12.8 mm/day [30]. The maximum snow level recorded at Rosone was about 2 m in 1995, while the average in around 0.35 m. The Orco Valley runs mainly in a west–east direction and is particularly narrow, especially in the central part, where some villages in winter do not see the sun for many days. The five main centers are Ceresole Reale, Noasca, Locana, Sparone, and Pont Canavese, with about 5620 inhabitants [31], as shown in Figure 2. The valley has acquired an excellent vocation for tourism, mainly related to the presence of the Gran Paradiso National Park, and is renowned for its many climbing routes. Agriculture and forestry are the main economic activities as well. Two main lithological complexes can be found in this area. In the lower valley from Cuorgnè up to Locana, it is possible to find calcites, rocks easily subject to erosion, which are also in the high altitudes at the northwestern margins of the Gran Paradiso massif. The second complex that starts north of Locana and extends to French territory consists of glandular and meta-granitoid orthogneisses, also called the "occhiadine" gneiss complex, and is derived from metasomatic granitization at the damage of volcanic rocks [30,32]. In the last two centuries, the Orco basin has been repeatedly struck by significant flood events that have seriously affected the hillslopes and along the hydrographic network, causing damage to infrastructure and occasionally fatalities [30,33]. Also, deposits of the Piantonetto flow, the Orco's left tributary, and flooding on the alluvial spectrum dragged debris into the hydroelectric power plants in the area. The increase in human activity along the valley floor and the lack of room for flood expansion have forced people to occupy high-hazard zones such as alluvial fans, intravalley plains, and river corridors. The most severe damage in the lowland sector occurs at river crossings and roads, on riverside bank protections, and on existing buildings. There is also significant destruction of vegetation, shrubs, and trees. However, the primary damage observed is attributable to a highly complex landslide, historically known as the "Rosone landslide", belonging to an extensive deep-seated gravitational deformation that was reactivated following intense rainfall, leading to rock falls and soil slips, which reached the highway, damaging it in several places. Figure 3 maps the damage recorded for flooding, landslides, and riverbank erosion. As it is possible to observe from the infographic, unstable areas represent most of the territory, with the punctual presence of areas marked by high hydrogeological risk in correspondence with the villages of Noasca, Rosone, and Sparone. The only National Road No. 460 from Turin to Ceresole Reale is located at the toe of the slope. In 2017, the territory was affected by a large fire that developed mainly in the Locana area due to the prolonged drought.

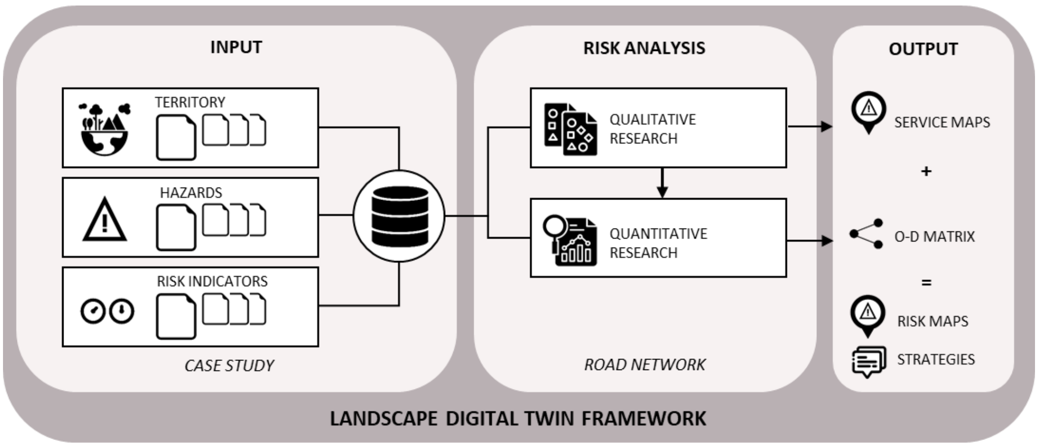

Figure 1. Research framework.

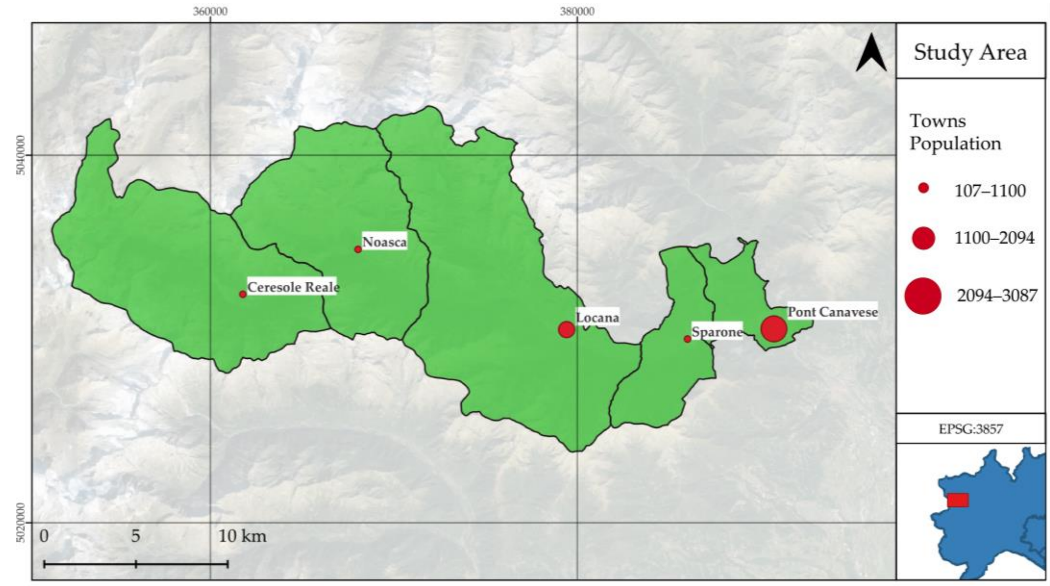

Figure 2. Location of the study area and distribution in the five municipalities.

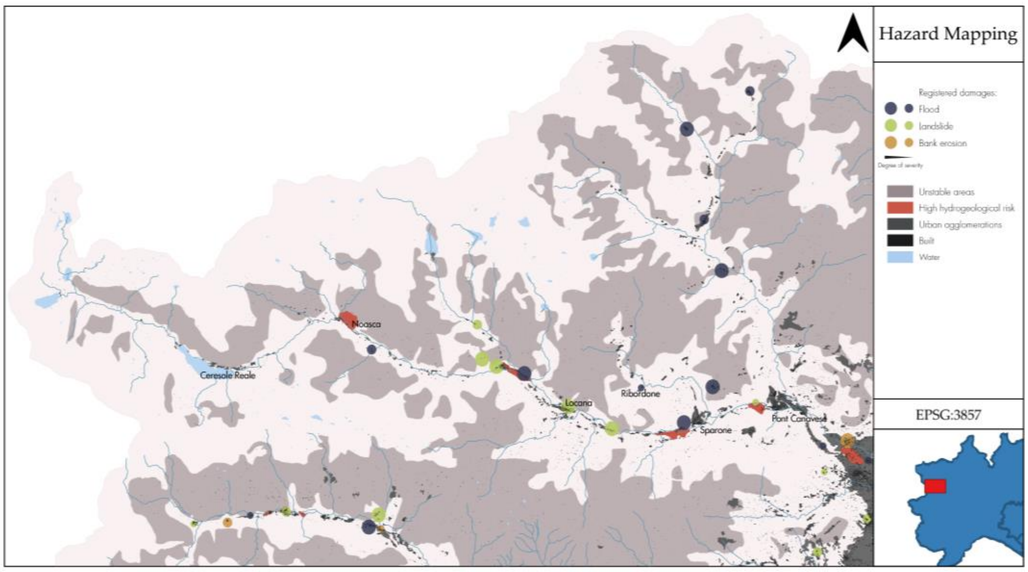

Figure 3. Hydrogeological and landslide hazard mapping in the Orco Valley.

2.2. Input

The starting point to carry out any land investigation is always data availability. In the case of specific projects, these are collected from the state of the art and, if necessary, integrated on an ad hoc basis with punctual surveys and monitoring activities. This research promotes a streamlined method for risk assessment through minimal data preprocessing. Therefore, it is essential to refer to credible and publicly available data sources to achieve this goal. These thus prove to be a valuable shared reference, facilitating the integration of diverse information layers managed by specialists in each domain. For this study, three main categories of data can be identified: (i) those referring to the territory and its graphical representation, (ii) hazard maps, (iii) and risk indicators.

- Territory

The concept of territory is essential in multi-hazard risk analysis, as it refers to the area under examination, including its physical, social, economic, and environmental aspects. To conduct meaningful research, data related to the territory is crucial, and this involves gathering and integrating meaningful information from various sources such as satellite imagery, elevation models, land cover maps, road networks, and census data.

A significant part of data acquisition is identifying and selecting critical points of interest within the territory. These POIs represent essential facilities that play a vital role in the well-being and resilience of the population and infrastructure in terms of socio-economic development. This study chooses the commune level as the territorial scale for the multi-hazard risk analysis. A commune is an administrative division corresponding to a municipality or town in Italy. This scale helps capture the spatial variability and socio-economic factors affecting vulnerability and exposure to natural hazards in the case study area. Reliable data sources are available at this level from official government portals, including emergency points providing healthcare and emergency services, public ones supporting social and economic development, and tourism points contributing to economic activity and cultural identity. Figure 4 provides an infographic of tourist points of interest, such as panoramic routes, heritage enhancement points, trial networks, sanctuaries, and mines.

Analyzing these POIs at the chosen territorial scale allows for a comprehensive and realistic assessment of vulnerability and exposure to natural hazards in the case study area. Integrating data acquisition with specific territorial characteristics enhances the accuracy and effectiveness of the multi-hazard risk analysis.

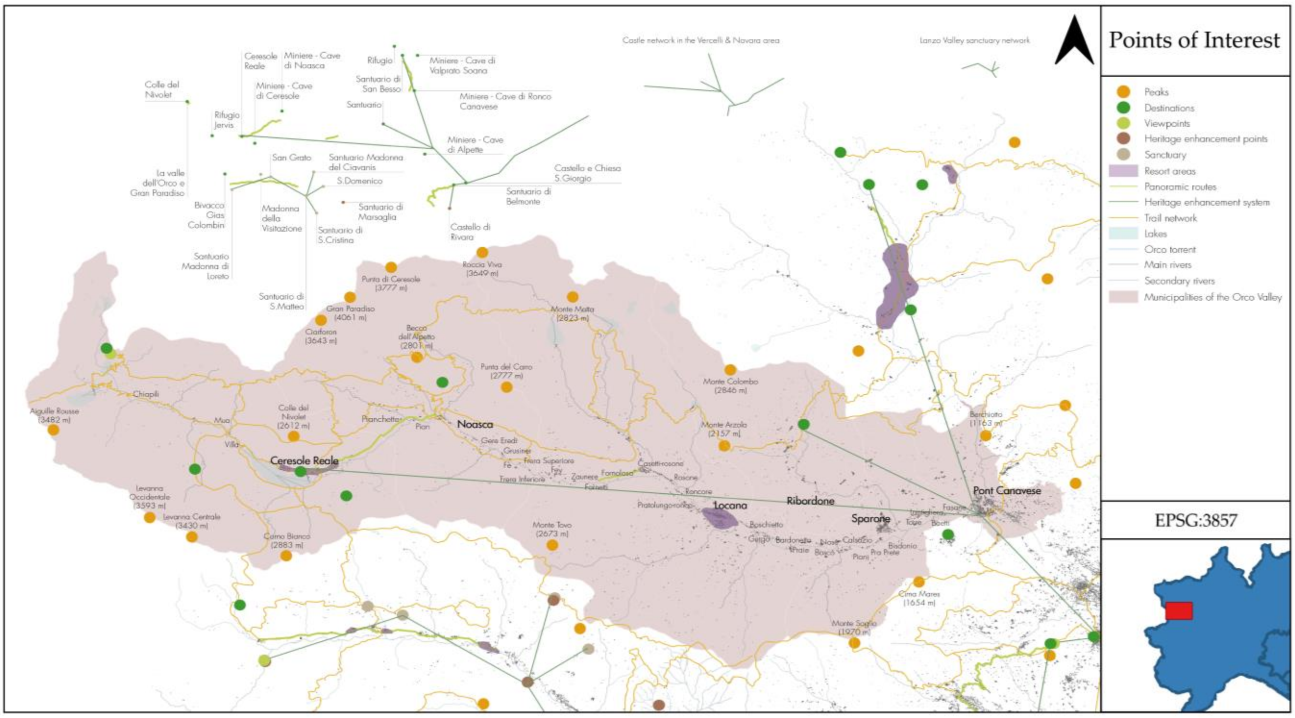

Figure 4. Tourist and points of interest facilities located in the Orco Valley.

- Hazard

Natural hazards are inherent events or phenomena that arise from natural processes and can potentially cause harm or damage to people, property, infrastructure, or the environment. These hazards can be categorized into several types, including geological, hydrological, meteorological, climatological, or biological hazards. Each type exhibits distinct characteristics, causes, triggers, frequency, intensity, duration, and impacts. Consequently, evaluating the risk associated with natural hazards is vital for understanding the likelihood and severity of their occurrence and their potential repercussions on socio-economic functions and activities within a specific area.

The Orco Valley is exposed to numerous natural hazards, particularly landslides and floods. These hazards threaten the road network and socio-economic activities in the valley.

Landslides predominantly occur due to rainfall, snowmelt, or seismic events, forming rockfalls, debris flows, or slides. Meanwhile, floods are primarily caused by heavy or prolonged rain, snowmelt, or glacial lake outbursts (GLOFs), leading to riverine or flash floods. Figure 5 provides an overview of the hazard maps depicting the distribution of potential hazards within the study area. As the case study description mentioned, the Orco Valley was also subject to forest fires. However, this kind of hazard was not covered in this study as the focus was evaluating interlinked risks. The probability of having a fire is almost zero if flooding or landslides occur.

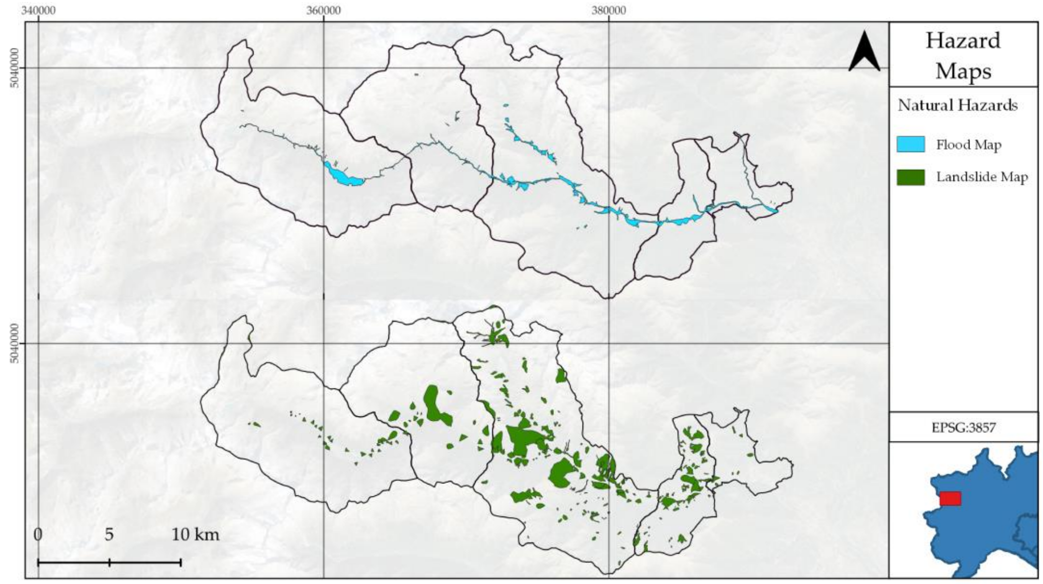

Figure 5. Hazard maps of the case study area.

- Risk indicators

Risk indicators are variables or parameters that gauge the level of natural hazard risk in a specific area. These indicators are derived from various sources, including historical records, statistical models, simulation models, expert opinions, or surveys. Employing risk indicators is crucial in risk analysis as they aid in comprehending the probability and severity of natural hazards, along with their potential impact on socio-economic functions and activities in the region.

In this study, the primary focus for multi-hazard risk analysis is road network accessibility, defined as the capacity to reach a destination using the road network in the area under examination. This indicator directly reflects the socio-economic functions and activities reliant on the road network within the case study region. Natural hazards such as landslides and floods can adversely affect road segments or nodes, impacting road network accessibility. By employing this indicator at the commune level as the territorial scale for multi-hazard risk analysis, the study offers a comprehensive and realistic assessment of the vulnerability and exposure of the population and infrastructure to natural hazards within the case study area. Figure 6 shows the road network for the case study.

In sum, the data sources and types used for this study are summarized in Table 1. The data were processed and integrated using QGIS, as shown in Figure 7.

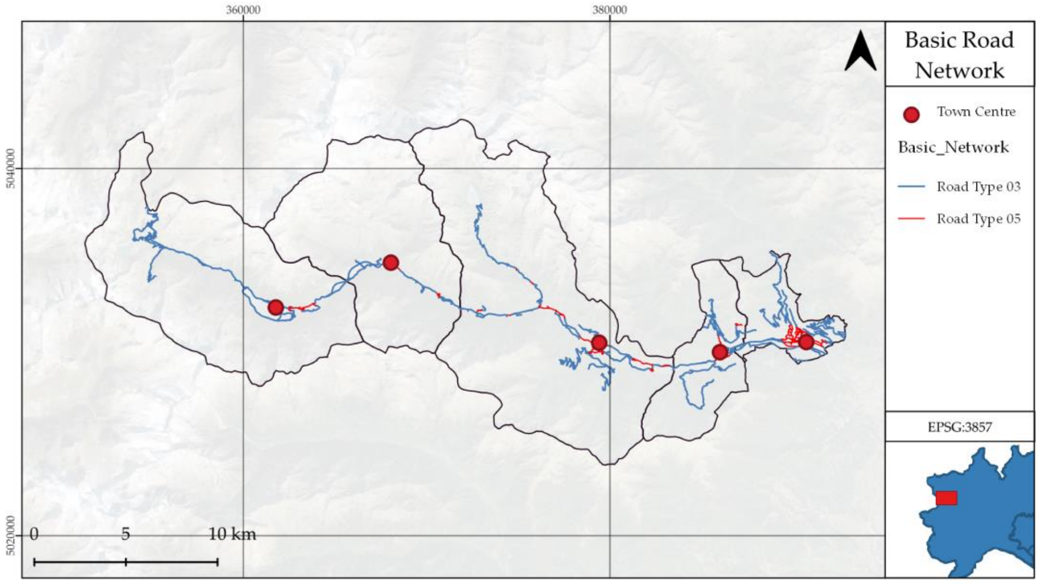

Figure 6. Road network for the given case study.

Table 1. Data sources and types used for this study.

Type	Source	Format	Details
Population	Piedmont Statistical Database	Tabular	Population statistics by commune [31]
Road network	ACI—Speed limit data	Vector	Road network map with speed limits by road type [34,35]
Commune boundaries	ISTAT—Administrative boundary data	Tabular	Commune boundary polygons with codes [36]
Hazard maps	ISPRA Open data—Hazard data	Raster	Hazard maps for landslides and floods [37]
Points of interest (POIs)	National Geoportal—Public and private school dataset; Piedmont Geoportal—Healthcare building data; Piemonte Open Data Portal—Additional data sources; OpenStreetMap—QuickOSM	Vector	Points of interest for health facilities, public facilities, town centers, and tourism facilities [38–41]
Land use and land cover (LULC)	Copernicus Land Monitoring Service—CORINE Land Cover (CLC)	Raster	Land use and land cover map [42]
Monetary values	Literature review	Tabular	Monetary values for different types of assets [43,44]

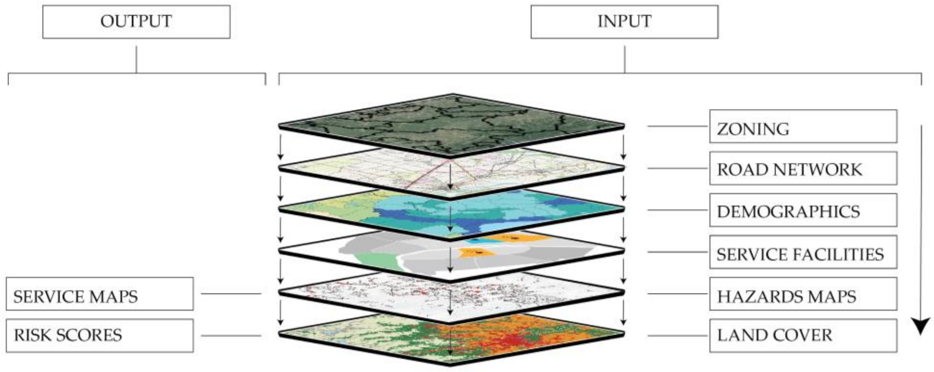

Figure 7. Data layers inputted after integration.

2.3. *Risk Analysis*

The study assesses natural hazards' potential impacts on human societies and assets in the Orco Valley. This process, commonly known as risk analysis, involves estimating the consequences of hazardous events. Through risk analysis, vulnerable areas and populations can be identified, various scenarios and uncertainties can be evaluated, and decision making for disaster risk management can be supported. The methods and approaches used for risk analysis vary depending on factors such as the type and scale of the hazard, data availability and quality, and the purpose and scope of the investigation. The study adopts a multi-hazard approach that integrates both qualitative and quantitative methods to assess the socio-economic effects of natural hazards on the road network and POIs in the Orco Valley. By combining these approaches, a comprehensive understanding of the risks posed by various hazards can be achieved, enabling more effective disaster risk management strategies.

2.3.1. Road Network Analysis

Road network analysis (RNA) is a method to assess the accessibility and connectivity of road networks under different scenarios [45]. It can provide useful information on the potential impacts of natural hazards on road infrastructure and the socio-economic activities that depend on it. RNA can also help identify critical road segments or nodes vulnerable or exposed to natural hazards. Network modeling and network analysis are the two main steps. The first involves creating a graph representation of the road network using nodes (intersections or terminals) and links (road segments). The second consists of applying different algorithms or methods to measure various network attributes or performance indexes such as travel time, travel distance, travel cost, accessibility, connectivity, reliability, redundancy, etc.

In this study, RNA was performed using QGIS 3.28.9 Firenze [46] and QNEAT3 1.0.5 plugin [47], open-source spatial, and network analysis tools. QGIS is a geographic information system software that allows users to create, edit, visualize, analyze, and publish geospatial data. QNEAT3 is a QGIS plugin that provides a set of algorithms and tools for network analysis within QGIS. QNEAT3 can generate different types of outputs from RNA, such as service maps used as qualitative research and origin–destination (O-D) matrices used as quantitative research.

2.3.2. Qualitative Research

Qualitative research is a method that aims to describe and interpret the characteristics, patterns, and relationships of natural hazards and their impacts using non-numerical data such as texts, images, maps, or diagrams [48]. Qualitative research can provide a rich and contextual understanding of the phenomena under study and capture the diversity and complexity of human–hazard interactions. Qualitative research can also complement quantitative research by providing additional insights or explanations that may not be captured by numerical data alone.

This study utilized qualitative research to generate service maps of the POIs under different scenarios of natural hazards. Service maps are polygons that show the reachable areas within a given travel cost from a POI. They can illustrate the spatial distribution and extent of accessibility and connectivity of road networks under different conditions. Service maps can also help identify the areas most affected by natural hazards regarding reduced or disrupted service provision.

Service maps were used as input for calculating the exposure of a POI to a hazardous event in the risk score formula. Exposure is the degree to which people, property, infrastructure, or the environment are susceptible to harm or damage from natural hazards [40]. Exposure can be measured by indicators such as population density, asset value, land use type, or critical facility type [41]. In this study, exposure is measured by the service area of a POI under different scenarios of natural hazards.

2.3.3. Quantitative Research

Quantitative research is a method that utilizes numerical data such as statistics, graphs, tables, or equations to measure and quantify the characteristics, patterns, and relationships of natural hazards and their impacts [48]. It offers a precise and objective understanding of the phenomena under study and allows for testing hypotheses or models based on empirical evidence. Additionally, quantitative research can complement qualitative research by providing numerical support or validation for findings from non-numerical data such as service maps.

This study utilized quantitative research to generate origin–destination matrices of the POIs under different scenarios of natural hazards. O-D matrices are tables that show the travel cost between each pair of POIs in a road network. They can illustrate the numerical distribution and extent of accessibility and connectivity of road networks under different conditions. O-D matrices can also help identify the POIs most affected by natural hazards in terms of increased or decreased travel costs.

O-D matrices were used as input for calculating the vulnerability of a POI to a hazardous event in the risk formula. Vulnerability is the degree to which people, property, infrastructure, or the environment will likely experience harm or damage from natural hazards [40]. Vulnerability can be measured by physical fragility, functional dependency, adaptive capacity, or coping strategies [41]. In this study, vulnerability is measured by the change in travel cost between POIs under different scenarios of natural hazards.

2.4. Outputs

The output of the multi-hazard risk analysis is a set of risk scores and risk maps for the POIs in the Orco Valley under different scenarios of natural hazards. The risk scores and risk maps are derived from integrating the qualitative and quantitative approaches using the service maps and the O-D matrices, as well as other variables based on literature as inputs.

The risk score formula is a method to estimate the potential impact of natural hazards on a POI based on a combination of factors that influence risk. It can provide a simple and intuitive way to compare and rank different POIs according to their level of risk exposure. From the risk score, it is then possible to identify priority areas or actions for disaster risk reduction or mitigation.

In this study, a dynamic formula was employed, considering the POI type, hazard type, land use/land cover (LULC) classification, and other economic indicators. The formula is as follows:

$$R = P \times E \times V \times C \times L \times O$$

where

- R is the normalized risk score for a POI in a scenario.

- P is the probability of occurrence of a hazardous event derived from the literature review [43,44], which can either increase or decrease the risk depending on how likely the hazard is to happen.
- E is the exposure level for a POI in a scenario, measured by the service area from the qualitative analysis, representing the hazard's potential impact on the POI.
- V is the vulnerability level for a POI in a scenario, measured by the change in travel cost from the quantitative analysis, which represents how much the hazard affects the accessibility and connectivity of the POI.
- C is the consequence level for a POI in a scenario, derived from the literature review [43,44], which can either increase or decrease the risk depending on how important and valuable the POI is.
- L is the effect of the land use/land cover (LULC) on the service area, derived from data availability [42–44], which can either increase or decrease the risk depending on how the LULC influences the service area of the POI.
- O is another economic indicator derived from data availability, which can either increase or decrease the risk depending on how they affect the economic or social aspects of the POI.

The values P, C, and L are derived from literature on a scale of 0 to 2, with higher values indicating higher risk. The risk score formula was applied to each type of POI using qualitative and quantitative analysis, resulting in risk maps. Then, these risk maps are normalized between 0 and 1 to obtain the risk scores.

Table 2 provides the values for the consequence level for different points of interest. They are based on how important and valuable they are for providing essential services and functions to people and society. For example, a health facility that provides medical care and emergency response would have a high consequence value. In contrast, a tourism facility that offers recreational and cultural services would have a low consequence value.

Table 2. Range of values taken for the consequence level for a POI in a scenario.

Point of Interest	Consequence (C)
Health facility	1.6–2.0
Public facility	1.4–1.6
Town center	1.2–1.4
Tourism facility	1–1.4

Table 3 provides the effect values taken for different land use/land cover types. They are based on how they influence the service area of the POIs. For example, urban land use/land cover type would positively affect the service area, providing more infrastructure and facilities for people and services. In contrast, snow land use/land cover type would hurt the service area, reducing mobility and accessibility for people and services.

Table 3. Values taken for the land cover type.

Land Use/Land Cover Type	LULC (L)
Water	1
Forest	0.8
Urban	1.4
Rock	1
Snow	0.6

Table 4 provides the probability values of occurrence for landslides and flood hazards, which are based on how likely they are to happen in a given period. For example, a landslide with a return period of 10 years would have a low probability value, as it is less likely to occur than a landslide with a return period of 100 years, which would have a high probability value.

Table 4. Value for the probability of occurrence of a hazardous event.

Hazard Type	Return Period (years)	Probability (P)
Landslide	10	0.5
Landslide	50	1
Landslide	100	1.5
Flood	10	0.6
Flood	50	1.1
Flood	100	1.4

One of the advantages of using this risk score formula is that it can be updated dynamically using live data from IoT devices, Earth observation satellites, or other sources. This procedure can help to capture the changes and uncertainties in the natural hazard environment and the human system. For example, IoT devices such as wearable medical devices or intelligent sensors can provide real-time data on the status and location of POIs. Earth observation satellites can provide near-real-time hazard intensity and extent data, such as flood maps or landslide detection. Other sources can provide updated economic or social indicator data, such as market prices or population statistics. By integrating these data sources into the risk score formula, we can obtain more accurate and timely estimates of the risk exposure and impact of natural hazards on the POIs.

3. Results

The study assessed road network conditions and vulnerability by comparing RNA results under different scenarios: basic (no hazard), disrupted due to floods, and landslides. Service maps and O-D matrix graphs for each POI were used to explore the socio-economic perspective of multi-hazard risk analysis. Risk maps showed the spatial distribution of risk scores for each POI and hazard under various scenarios. The impact of these maps is limited to the extent of the road network, particularly in the valley area, where the road network is relatively constrained. This limitation arises as the indicator for the analysis is based on the road network's extent. However, despite this constraint, the insights provided by these maps are valuable for evaluating the road network and POIs' resilience and recovery in the face of natural hazards, influenced by factors such as POI location, hazard intensity, alternative routes, and mitigation strategies.

3.1. Quantitative Analysis: Service Maps

- Hazard Emergency Health Services Facilities

Figure 8 shows that the health facilities are exposed to varying levels of service depending on their location and the type of hazard. The service maps indicate that the health facilities in Ceresole Reale, situated at the end of a road prone to flood, face challenges during hazardous events. Establishing additional health facilities in Noasca and Ceresole Reale, especially in mountainous regions, is essential to ensure continuous access to medical services. The risk maps also suggest that the health facilities may need to coordinate and cooperate in providing medical services and assistance to the affected population in case of a natural hazard event.

- Public Facilities

Figure 9 shows that public facilities are exposed to varying levels of service depending on their location and the type of hazard. The service maps indicate that public facilities in Noasca, including the town hall and post office, are highly exposed to floods and landslides. It is crucial to consider alternative routes and implement appropriate mitigation and response strategies to enhance their resilience and recovery during hazardous events. Coordination and cooperation among public facilities may also be necessary to ensure the continuity of essential services and maintain public order during natural hazard events.

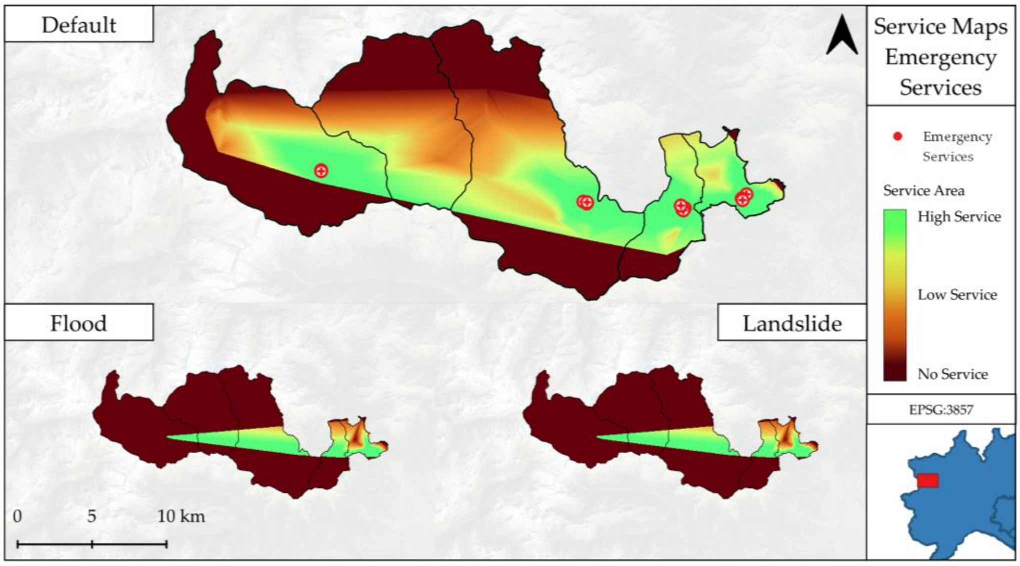

Figure 8. Service maps for emergency health facilities under different scenarios.

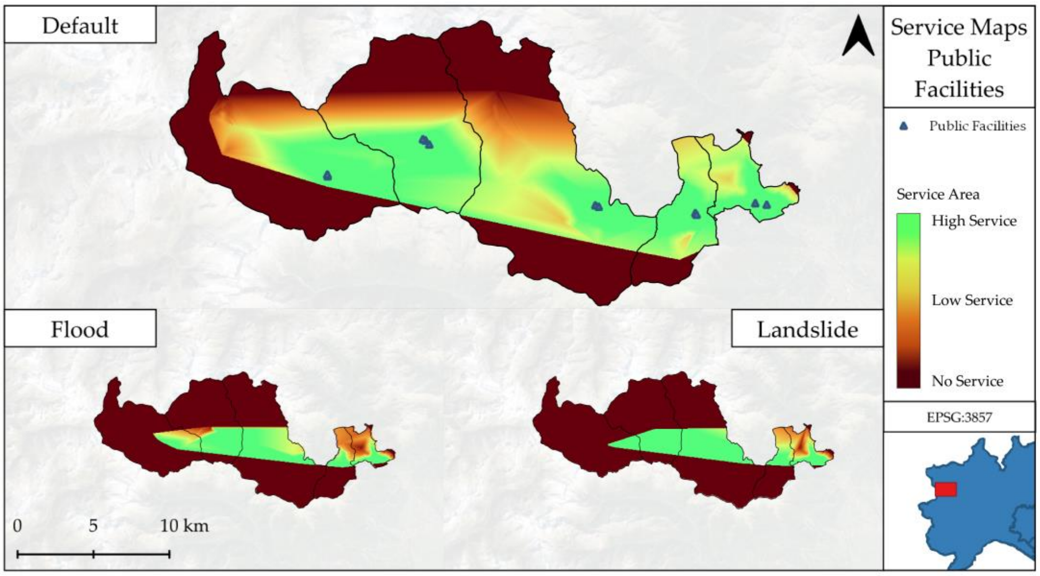

Figure 9. Service maps for public facilities under different scenarios.

- Critical infrastructures

Figure 10 shows that also critical infrastructure is exposed to varying levels of service area depending on its location and the type of hazard. The hydroelectric power plant in Rosone serves as a vital energy source for the downhill of Turin metropolitan areas, Italy, producing around 99 MWh of energy. The figure shows that the power plant is highly prone to landslide hazards suggesting an intervention to increase resilience.

- Town Centers for Public Activity and Mobility

Figure 11 shows the service maps for town centers under different scenarios. The figure shows that the town centers are exposed to varying levels of risk depending on their location and the type of hazard. The service maps reveal that in the event of landslides and floods, the accessibility of all five town centers, especially Ceresole Reale and Noasca, becomes limited. It is crucial to consider alternative routes, implement appropriate mitigation and response strategies, and promote coordination among town centers to support economic activity and mobility in the valley to enhance their resilience and recovery during hazardous events.

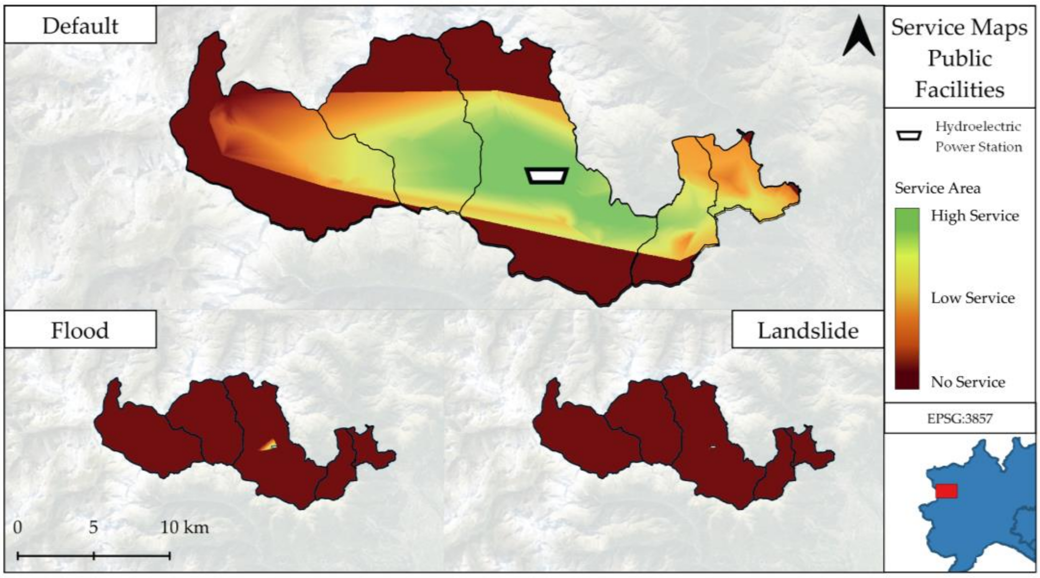

Figure 10. Service maps for critical infrastructures under different scenarios.

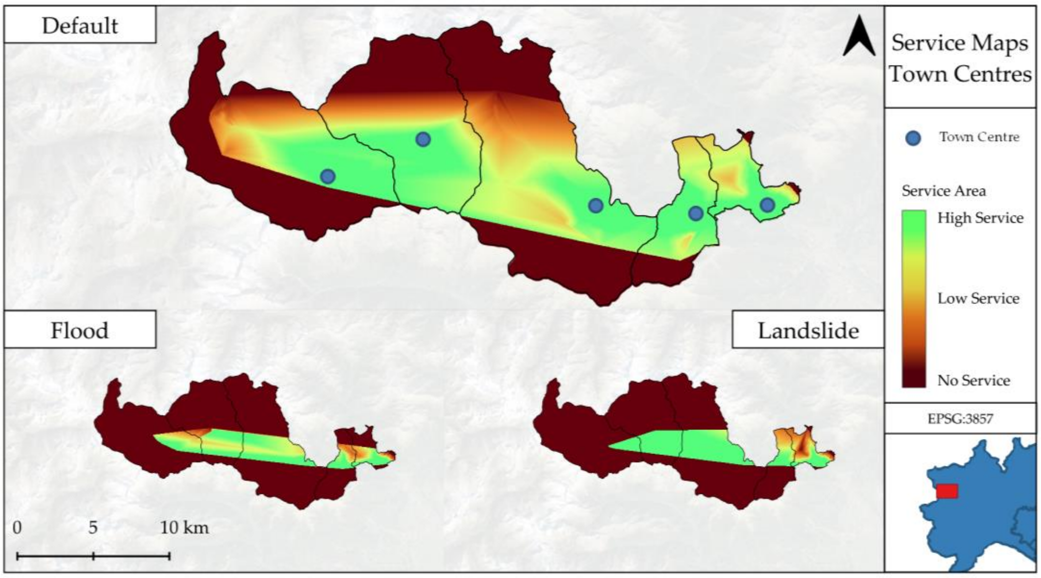

Figure 11. Service maps for town centers under different scenarios.

- Tourism Facilities

Figure 12 highlights the crucial role of a specific point in constraining tourism facilities during natural hazards. This significance becomes more pronounced within Figure 12b, where service maps depict various scenarios. Although many facilities have weather hazards with minimal disruption, the focus shifts to the accessibility of the Critical Point located at SS2460 road near Madonna delle Grazie al Gurgo Church in Locana—an urgent concern. This critical point, visible as the Google Earth snapshot in Figure 12a, is susceptible to landslides and floods, rendering it impassable during such events. Consequently, a decline in tourism occurs, especially among urban residents exploring uphill areas such as Locana, Noasca, and Ceresole Reale. Addressing this challenge requires establishing an alternate route to enhance resilience and ensure uninterrupted access to these regions. Additional measures such as flood protection and the development of evacuation plans around this critical point further contribute to risk mitigation and overall resilience improvement within the tourism sector across the picturesque Orco Valley.

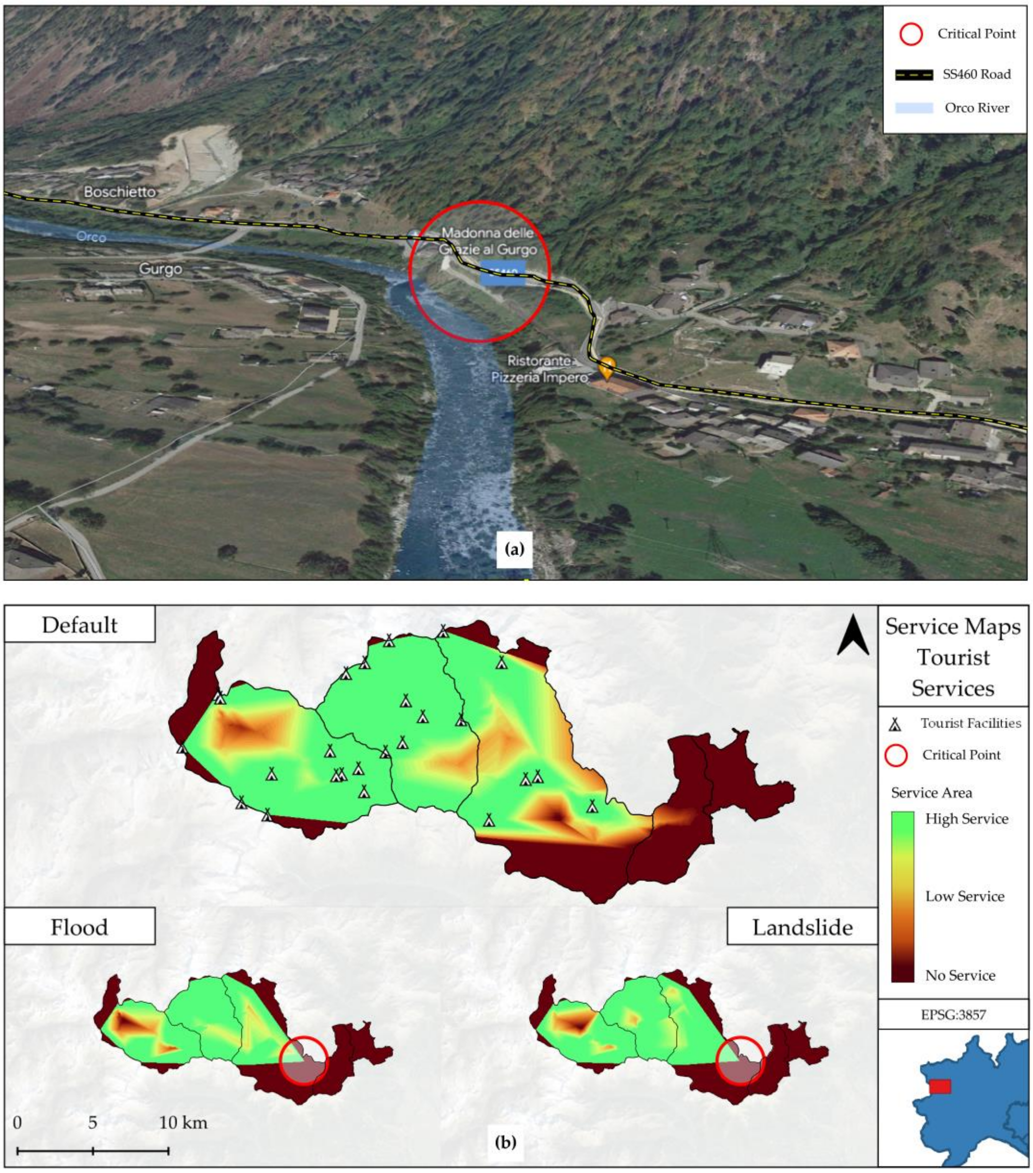

Figure 12. (**a**) Google Earth Snapshot of the critical point. (**b**) Service maps for tourism facilities under different scenarios.

3.2. Quantitative Analysis: O-D Matrix Graphs

To comprehensively analyze risks, separate O-D matrix evaluations were conducted for flood and landslide hazards, resulting in 12 distinct assessments for the risk score formula. Figure 13 provides a concise summary depicting the accessibility of POIs after natural hazards compared to the baseline scenario. The results reveal that after the hazards, accessible emergency services reduced to 36 for floods and 33 for landslides, down from 90 in the basic scenario. Similarly, public services decreased from 45 to 25 for floods and 25 for landslides. Tourism facilities decreased to 79 for floods and 72 for landslides, from 120.

3.3. Risk Maps and Risk Scores

The risk score analysis was performed using the risk scores formula for each type of POI and hazard under different scenarios. The risk scores are values that measure the potential impact of natural hazards on a POI based on a general formula that considers the type of POI, the type of hazard, and the LULC classification.

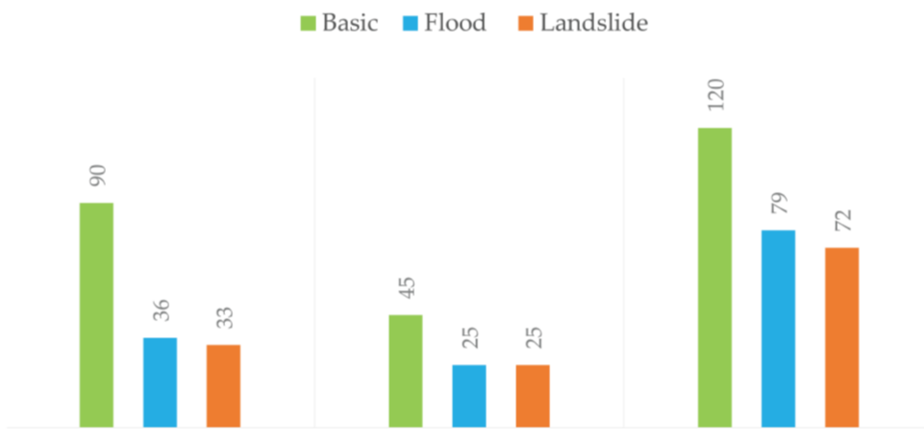

Figure 13. O-D matrix graphs for health facilities under different scenarios.

Figure 14 shows an example of a land cover classification map for the Orco Valley, which is used to update the risk maps according to the land cover as stated in previous chapters. Figure 15 presents the risk maps based on risk scores for emergency services, town centers, public facilities, tourism facilities, and the hydroelectric power plant system.

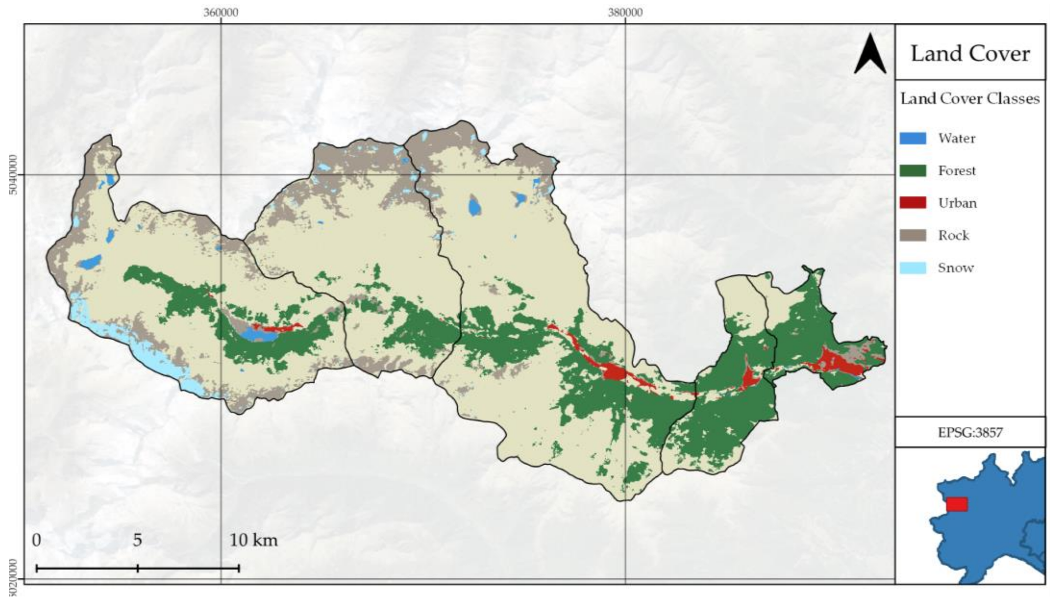

Figure 14. Land cover classification map for the Orco Valley.

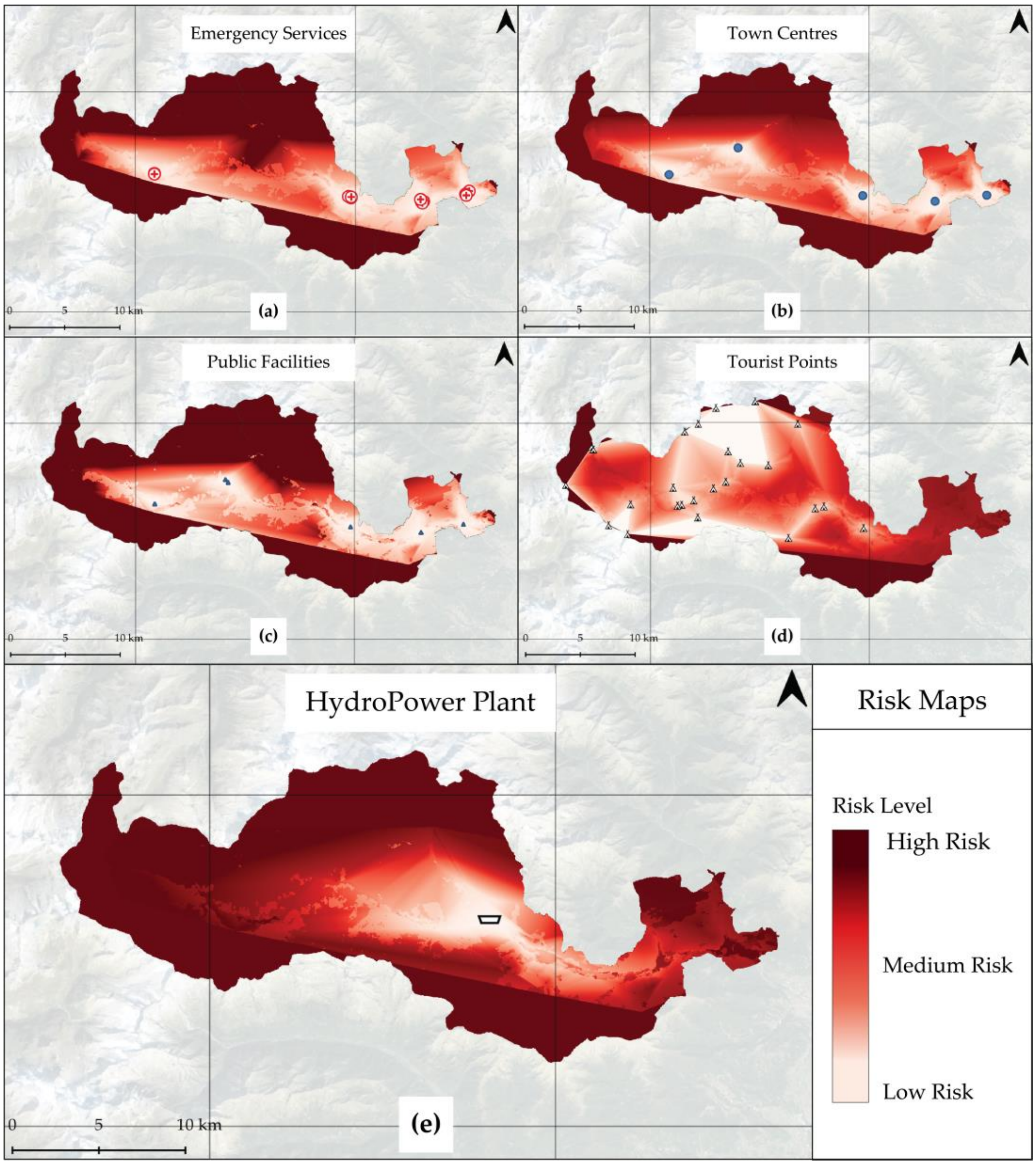

Figure 15. Risk maps based on risk scores. (**a**) emergency services; (**b**) town centers; (**c**) public facilities; (**d**) tourism facilities; (**e**) hydroelectric power plant system.

4. Discussion

This research presents an all-encompassing analysis of multi-hazard risks to enhance informed decision making and preparedness in Italy's Orco Valley. By utilizing advanced risk mapping techniques and origin–destination (O-D) matrix graphs, the study identifies areas of vulnerability, critical road segments, and communities at risk. The approach assesses vulnerabilities across various flood and landslide scenarios, using qualitative and quantitative methodologies to consider their socioeconomic implications.

The outcomes of this investigation align closely with existing literature that underscores the necessity to capture the intricate and diverse interactions between socio-economic factors and multi-hazard risk assessment. A prior study advocates for a comprehensive data collection and analysis framework, integrating various data sources across spatial and temporal scales for multi-hazard risk assessment [25]. The findings of this study also reinforce the prevailing literature, emphasizing the significance of recognizing interrelationships and interdependencies among multiple hazards and their ramifications on societies [23–25]. Furthermore, another study recommends applying approaches encompassing scoring, ranking, weighting, and mapping to comprehend the socioeconomic factors and comprehensively understand the area [27]. Notably, the results of this study demonstrate the effectiveness of the risk-scoring formula as a tool that combines qualitative insights with quantitative values, striking a balance between complexity and simplicity [26,27].

Nonetheless, the study's limitations are primarily tied to the availability, quality, and underlying assumptions of the data and models used. While credible open-source data sources were employed, potential gaps, inaccuracies, and delays in data could impact the outcomes. Challenges in integrating data with varying spatial resolutions and formats further complicate the analysis. However, diligent data selection can help alleviate these limitations.

Conversely, the study's implications hold significant value for both theoretical advancements and practical implementations. The adaptable approach provides valuable insights for decision-makers, stakeholders, and communities, aiding in risk assessment, prioritization of interventions, as well as promoting collaboration across sectors during natural hazard events.

4.1. Scalability: Landscape Digital Twin Model

The methodology employed in this study is designed to be scalable, meaning it can be applied to other study areas with different data sources and types of natural hazards. Due to the heterogeneous data environment and multidisciplinary nature that characterizes the landscape, the definition of a digital twin provides the guiding principle for future work. The landscape digital twin (LDT) model can monitor, analyze, and simulate the interactions; provide feedback between natural and human systems; and support the sustainable development and management of natural resources.

Accordingly, some researchers have presented architectures and frameworks [49] to address the data integration and management challenges. The LDT architecture involves five main layers: physical, data storage, integration, application, and visualization. Figure 16 presents the LDT model architecture for multi-hazard risk analysis.

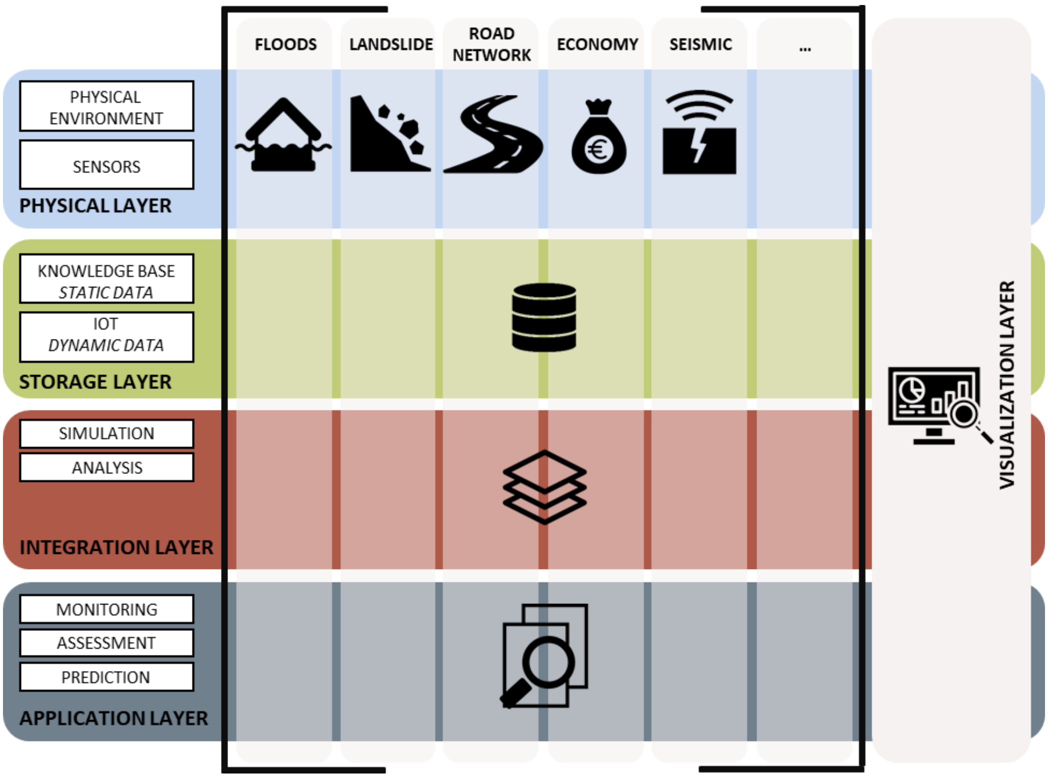

Figure 16. Landscape digital twin architecture for multi-hazard risk analysis.

The visualization of different layers stockpiled on top of each other offers a simultaneous overview of existing data categories. In this way, the data are exposed and queried according to differentiated levels of processing.

The physical layer represents the physical environment and includes sensors collecting information by monitoring variables of interest: for example, rain gauges or systems to detect the evolution of a landslide. Sensor data are transferred to a dedicated database in the data storage layer via protocols such as HTTP.

The data storage layer identifies two primary data sources environment: static data for the landscape knowledge base and dynamic data from IoT devices. The GIS handles physical territory mapping. However, building information model (BIM) representations of significant buildings/infrastructure can enrich the understanding of the dynamics of the territory.

The integration layer involves processing and harmonizing data from different sources. It performs simulation, monitoring, and prediction tasks using other models and algorithms. For example, hydrological and geological models can simulate flood and landslide hazards under different rainfall scenarios, climate change, land use change, etc. Network analysis algorithms can assess the impact of risks on road network performance and resilience under different scenarios of hazard occurrence or network recovery.

The application layer provides services using integrated data access through the query mediator. It includes a variety of applications, such as real-time monitoring, hazard assessment, risk assessment, impact assessment, scenario analysis, etc.

The visualization layer uses GIS-based tools to present and communicate data analysis results using different formats, such as interactive maps, charts, tables, and dashboards, that can help the users to understand the risk and impact of hazards and to explore different mitigation and adaptation strategies.

The overall system is conceived as a matrix implementable over time and space where the rows are the different layers, while the columns are the domains related to risk assessment. Flood, landslide, and road network domains are considered in this study. It can enrich the same results by supplementing the data with real-time information related to precipitation or snow events [50]. This dynamic landscape representation enhances the assessment of socio-economic aspects.

4.2. Sustainability: GIS-BIM Approach

This study mainly uses a GIS environment to manage the multi-hazard risk analysis. However, it only represents the first stage of the DLT vision setting. The BIM approach is an essential component to be integrated into the model. The study of landscapes, as well as of cities, cannot today prescind from the combined use of GIS-BIM to study the resilience of a system and evaluate strategic actions to face the digital and ecological challenges. BIM can help plan, design, operate, maintain, and decommission the environment in the best possible sustainable way. Sustainability practices using BIM create a healthy built environment and answer social, environmental, and economic concerns in a balanced way. The spatial three-dimensionality feature represents a powerful way to study the territory more effectively and truthfully. With the sustainability dimension of BIM (6D), the built and natural environmental performance can be effectively displayed, and additional methods and tools can be used to link hazard maps with the digital graphical representation of the territory. Figure 17 shows the risk maps from GIS methodology with Infraworks [51] 3D visualization at Locana. It is clear how the size of the damage and its severity can be inferred in more detail.

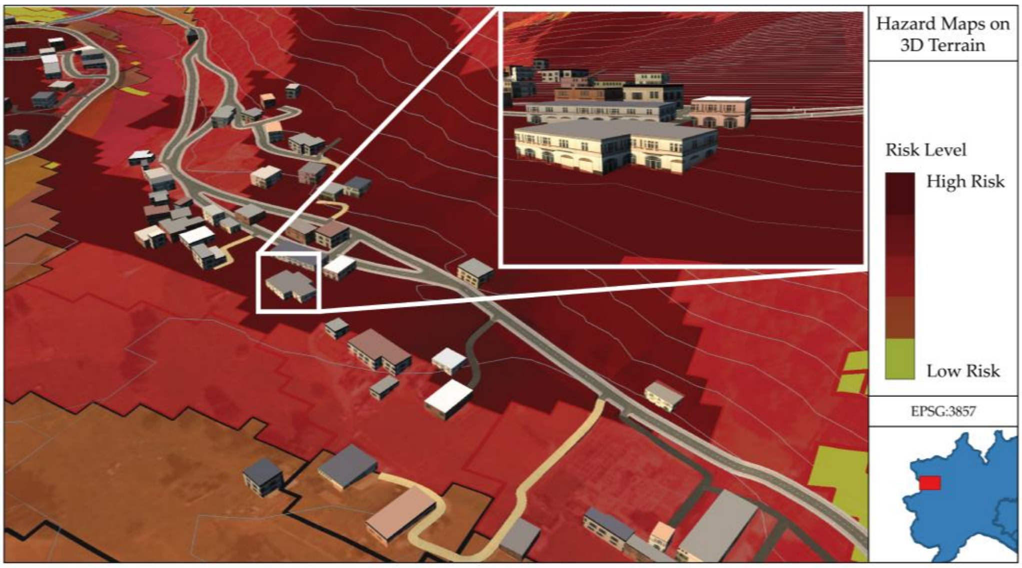

Figure 17. Infraworks 3D hazard risk map visualization of the Orco Valley from GIS.

Such visualization help stakeholders to better envision the related information, and it clarifies which zones need to be checked for critical assets of structures. The aim is to identify the valley region that may be damaged by natural hazards from the GIS methodology with the 3D BIM approach. Consequently, studies can be carried out on the measures that can be taken after detecting the risk zones and defining critical structures and how to avoid the harmful effects of natural hazards.

Through GIS-BIM modeling representations and simulations, it will be possible to more effectively identify hazards that might occur and consciously take measures against them. Representation and simulations made with GIS-BIM modeling will ensure that the dangers of natural movements, which may occur in the future in the geographical region on the environment. In addition, artificial intelligence systems such as fuzzy logic and neural networks can play a role in developing such predictions. IoT sensors could benefit from updating real-time risk maps.

Finally, BIM is of great importance in implementing sustainable environment-integrated design. In fact, sustainability, integrated design, and BIM are interrelated concepts that support each other within the design process. Thanks to this approach, design alternatives are evaluated, and the opportunity to reach the ideal result is offered. More efficient and sustainable findings are obtained when BIM is applied from the beginning to the end of the design and supported by analyses. With these models to be applied during the design phase, environmental problems can be minimized, measures can be taken against natural hazards that may arise in the future, and the negative effects of climate change can be reduced.

5. Conclusions

The topic of multi-hazard analysis is considered to be of great interest as it represents an area of research development where industries, governments, and universities are investing considerable resources. The insight aligns with the National Recovery and Resilience Plan (PNRR) [52], which is the Italian response to the Next Generation EU (NGEU) program [53]. Digitization and innovation, ecological transition, and social inclusion are the three strategic axes shared at the European level to accompany nations towards an ecological and environmental transition path.

The contribution presents a timely exploration of the complex interactions between changing environmental dynamics and landscape vulnerabilities. It emphasizes the need for a synergistic strategy for hazard mitigation based on a thorough knowledge of the territory and these phenomena, resulting in complete land planning and management through suitable communication tools.

The proposed method combines qualitative and quantitative research outputs to generate comprehensive risk analysis maps, starting from the correlation of open-source datasets characterizing the territory, the hazards, and the risk indicators. This study assessed road network conditions and vulnerability by comparing RNA results under different scenarios: basic (no hazard), disrupted due to floods, and disrupted due to landslides. The critical road segments or nodes most vulnerable or impacted by network performance and accessibility are identified. Service maps represent the output of the qualitative approach and illustrate the spatial distribution of risk scores for different typologies of points of interest and the areas most affected by natural hazards regarding reduced or disrupted service provision. O-D matrix graphs come from quantitative research and help identify the POIs most affected by natural hazards in terms of increased or decreased travel costs. The risk formula is used to estimate the potential impact of natural hazards in a POI based on a combination of factors that influence risk. Service maps were used as input for calculating the exposure of a POI to a hazardous event in the risk score formula, while O-D for calculating their vulnerability.

The GIS environment works for the knowledge static database (storage layer), for the analysis (integration layer) and data display (visualization layer). However, this study is part of a more extensive to correlate geospatial datasets with a GIS-BIM integrated approach and a multi-hazard framework. BIM is fundamental to achieving increased detail in the analyses by querying and integrating facilities characteristics, moving from territorial to building scales. The concept of a landscape digital twin emerges as a novel and promising solution, offering a multi-disciplinary and multi-scalar perspective on hazards. The matrix framework operates across time and space, suggesting a dynamic and adaptable approach. Concerning the increasingly challenging issues characterizing this millennium, technology must be put at the service of communities to change the quality of life for all citizens. Hence, making a digital twin of an area cannot be considered a spot intervention but an integrated process that must be carefully designed in its overall vision and implemented through precise and well-coordinated steps for the result to be truly effective. The research has practical implications by providing helpful information and insights for authorities, stakeholders, and communities.

- The identification of the most vulnerable areas and populations to natural hazards.
- The evaluation of the potential impacts and risks of different scenarios of natural hazards.
- The support for the decision-making process for disaster preparedness and mitigation.
- The enhancement of the resilience and recovery of affected populations and areas.

The relevance is reinforced by the fact that the method and the results obtained can be used in several fields and ways and adapted to other study areas.

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www.pcn.minambiente.it/mattm/], [https://data.europa.eu/en], [https://www.geoportale.piemonte.it/cms/], [https://land.copernicus.eu/pan-european/corine-land-cover] (accessed on 21 July 2023).

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