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Sustainable Approach of a Multi-Hazard Risk Assessment Using GIS Customized for Ungheni Areal Situated in the Metropolitan Area of Iasi

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Abstract: Hazards associated with natural factors annually result in significant human and economic losses. An accurate and up-to-date assessment of various hazards can limit their impact and bring benefits both in the modeling phase and mostly in the risk mitigation plan stage. The article presents the results of a multi-hazard analysis that considers floods, landslides, and earthquakes carried out in the Ungheni area, located in the eastern part of Romania at the border with the Republic of Moldova. The research focused on producing harmonized hazard maps for the two countries since the area spreads jointly between the two countries. Common geospatial data were used for modeling and risk assessment, such as airborne laser scanners, global navigation satellite systems, rasters, and vectors from analog and digital sources. Among hazards, the flood maps for the studied area, Ungheni, were designed using 2D hydraulic modeling in HECRAS software (version 6.3.1); the landslide maps considered the ArcGis platform following Romanian methodology; and the seismic analysis collected onsite measurements on the built environment. The shared use of geospatial data in modeling the three hazards led to high accuracy of the results and determined their spatial homogeneity. It was observed that only two areas, Mînzătești and Coada Stîncii villages from Ungheni Areal, are highly vulnerable to all three hazards. The research findings, along with mitigation recommendations, have contributed to the development of a more precise action plan for natural hazards events by local authorities and decision-makers.

Keywords: landslide risk; flood risk; seismic risk; ArcGIS; hazard maps

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1. Introduction

A natural hazard is an extreme event that has environmental causes and may produce various losses, such as human life and property damage, and may disrupt human activities. Hazards are differentiated from disasters in general and, in the majority of cases, contain natural and artificial components. The artificial feature refers mainly to people's behavior, who, on one the hand, prefer to build in coastal areas or in low-lying areas, and, on the other hand, strongly influence climate change through actions such as extensive deforestation, building unwisely in protected areas, extensive use of pollutants, or not protecting the environment [1].

According to the information provided by the International Disaster Database (EM-DAT), about 2/3 of disasters are associated with natural hazards [2]. These can be classified into: geological (earthquakes and volcanic eruptions), meteorological (heat/cold waves, cyclones, hurricanes), hydrological (floods, doubt, mudslides, tsunamis), and biological (diseases). Some of the natural hazards, such as flooding, can occur anywhere in the world, while others, such as tornadoes, occur only in certain areas or require specific conditions (ex. tropical storms or volcanic eruptions) [3].

In the last few years, a range of environmental disasters have struck the world, including heavy rains and floods in Brazil, Iran, and Madagascar; heavy snowfall in Turkey, Pakistan, and the US; wildfires in Spain and Argentina; volcanic eruptions of Ecuador's Wolf volcano and Tonga from the pacific nation; and earthquake in Japan, Turkey, and Syria [1]. According to Global Catastrophe Recap-Q1, total economic losses in 2023 are estimated to reach at least $63 billion. These totals are largely driven by the devastating earthquakes in Turkey, and Syria, which cost approximately $39.1 billion [1].

Understanding when, where, why, and how natural hazards occur can help people take proper measures in order to reduce the disaster impact on communities in general and on individuals in particular. In this direction, mitigation plans for evacuation and to increase life safety should be elaborated by local authorities, as well as educating the population on how to behave in case of a disaster. For this reason, scientists are permanently interested in adapting and improving safety measures before a dangerous event and elaborating a sustainable plan to recover from a disaster with minimum losses (human and costs).

The article presents the results of research conducted on the border area between a European Union (EU) country (Romania) and a non-EU country (Republic of Moldova), focusing on a multi-hazard approach aiming at bridging the gap between the two countries' national strategies associated with dangerous events. Current national strategies are established based on existing hazard maps and apply European directives for Romania and respectively, Russian recommendations for the Republic of Moldavia, resulting in different approaches to the same event. The work carried out in this border area has resulted in joint hazard maps and a joint risk mitigation plan. This approach at the Eastern Romanian border was based on the fact that disasters have no borders. The manifestation of a natural hazard can be brutal without taking into consideration national legislation, strategies, development level, approaches, or social preparedness. For this purpose, the paper made its contribution to natural hazards and associated disasters by envisioning, using hazard risk maps, potential affected areas, and local vulnerability. Action and approach in case of a disaster are prone to each country's legislation and strategy. Still, international assistance and joint actions can be of great significance in difficult situations. In this context, it is important to elaborate on a cross border vision and approach to hazards and their consequences.

The paper presents the results obtained only for Romania with respect to the considered hazards: landslides, floods, and earthquakes. The multi-hazard analysis emphasizes the most vulnerable area, considering the combined effect. This approach was chosen because frequently one hazard may represent the origin of another (as is the case of earthquakes which can cause landslides or floods).

Due to the multitude of spatial data sources involved in the current projects and the processing of geodesic measurements on different reference surfaces, a separate presentation of the reference and coordinate systems for planimetric, altimetric, and three-dimensional positioning was required [4]. Working with these reference and coordinate systems, the implicit need for coordinate conversions arises, which must be carried out within acceptable limits in accordance with the requirements of the research. The causes of these differences are mainly due to the increasing development of Geographic Information Systems (GIS), the widespread use of satellite navigation systems (GNSS), as well as the introduction of web mapping services [5]. In particular, the need to establish a unique spatial reference system arises as a result of the positioning and mapping of the phenomena pursued in the project, by combining digital data between different organizations as part of the collaboration between two neighboring states.

Once the on-site data was collected and analyzed, the next step was their conversion into harmonized maps by means of ArcGIS Pro 3.3 software. In the end, a mitigation guide was elaborated to be distributed to the local population and authorities.

2. Literature Review Regarding Natural Hazards

2.1. Natural Hazards in the World

Natural hazards pose a major threat to human health, the environment, cultural heritage, and economic activities. The deadliest disaster of all time in world history (not counting pandemics) is considered to be the 1931 Central China floods, which killed three to four million people [6].

Between 1998 and 2009, Europe faced more than 213 major floods, resulting in about 1126 deaths, the displacement of about half a million people, and losses of at least €52 billion in insured economic damage [7]. This increase in severe floods, resulting in notable loss of life and extensive damage, has prompted numerous authorities and stakeholders to reassess the existing flood mitigation strategies. The extreme hydrological phenomena produced in the last decades both globally and in Romania, highlight, the fact that society can be affected not only by floods produced on rivers with medium and large river basins but also by fast floods, which are characteristic of small basins. There is a growing tendency to increase the frequency of rapid, severe floods, which cause significant material damage and often even human losses. World practice has shown that floods cannot be prevented, but they can be managed, and their effects on the social, economic, environmental, and cultural heritage can be reduced. These results can be obtained through a process that involves complex analyses and assessments in order to establish specific prevention and control measures at the local, regional, and national levels, designed to help reduce the risk associated with these phenomena.

Among recent floods from Europe can be mentioned the ones that occurred in July 2021 and particularly affected Western Europe, especially Germany, Belgium, Switzerland, Luxembourg, and the Netherlands, leading to over 200 casualties [8,9]. Based on the number of victims, the event is considered one of the greatest natural hazards of the early 21st century. In addition to the loss of life, the floods have caused widespread power outages, forced evictions, as well as damage or destruction of infrastructure and agricultural land in the affected areas. Infrastructure damage has been particularly severe in Belgium and Germany [10]. The European Floods Directive 2007/60 proposes that every six years, member states have to identify the risk of floods and propose updated action plans.

Another hazard that caused significant property losses is represented by landslides. These are major factors in the evolution of terrain in mountainous and hilly regions of Europe. Landslides usually cause extensive erosion and sediment production and sometimes lead to lake development in areas with rugged terrain by damming river courses, as are, for example, Santa Croce, Antrona (formed in 1642), Alleghe (formed in 1771) and Scanno in Italy, Eibsee and Obersee in Germany, and Red Lake in Romania (formed in 1837). However, most landslides often formed temporary lakes that later destroyed the dam, causing catastrophic flash floods and debris flows [11]. Some major landslides that occurred in Europe are: Goldau (1806), Elm (1881), and Gondo (2000) in Switzerland; Piuro (1618), Monte Antelao (1814, 1925), Vajont (when almost 2000 deaths were caused by a man-made landslide in 1963) and, more recently, Valpola (1987), the events with several landslides in the region of Piedmont (1994), Sarno and Quindici (1998), Messina (2009), and the train accident at Laces (2010), all in Italy; Plateau d'Assy (1970), in France; Felanitx (1844), Azagra (1874), and the province of Granada (event with several landslides triggered by the earthquake, 1884) in Spain; Getå (1918) and Tuve (1977) in Sweden [11].

Over the years, it has been noticed that landslides can also be the consequences of earthquakes, as is the case with soil liquefaction, tsunamis, or fire. Major earthquakes are concentrated along the plate-tectonic boundaries. The movements of the tectonic plates can build mountains or cause volcanoes to erupt. Earthquakes represent the Earth's natural way of releasing stress and are considered sudden shakings of the ground produced by the seismic waves passing through Earth's rocks. The type of earthquake depends on the region where it occurs and the geological structure of that region. Around 90% of earthquakes have shallow focal depths (smaller than 70 km) and occur within the lithospheric plates, in contrast with the remaining earthquakes that have intermediate and deep focal depths being associated with the subduction of plates [12].

The strongest earthquake recorded occurred in Japan, with a magnitude of 9 on the Richter scale, on 11 March 2011. Strong accelerations of the soil were recorded in Miyagi, Iwate, Fukushima, and Ibaraki prefectures, east to which a huge landslide occurred. Initial research on the size of this landslide showed that the difference between two points located on opposite sides of the fault reached 30 m. The maximum displacement of the terrain exceeded 100 cm in the Sendai area and 50 cm in the area from Tohoku to Kanto. It caused about 15 million deaths and injuries; more than 250,000 buildings were damaged; and it was close to causing a nuclear disaster, damaging reactors at the Fukushima plant [13,14].

More recent information provided by EOS Data Analytics reports on 2023 disasters with a significant number of 240 calamities worldwide that had a devastating effect mostly on rural and developing nations. Building communities' capacity to face environmental hazards requires three elements: assessment of existing information, community engagement and evaluation of local knowledge, and development and implementation of strategies to enhance this capacity [15]. Based on the statistics, 2023 can be considered one of the deadliest years associated with natural disasters. Among hazards, floods increased in frequency and severity all over the world and were associated with factors such as urbanization, industrialization, and the extraction of natural resources. Another natural hazard that strongly manifested during 2023 were the earthquakes, with a significant value of 147 geological movements with registered values of 6.0 or higher on the Richter scale, according to EOS. The most significant record for earthquakes in 2023 was registered in Turkey-Syria 7.8 and 7.5 magnitude on February 6, with an epicenter 23 miles (37 km) southeast Turkey, close to the border with Syria, that had associated significant human losses (more than 55,000 people) but also economic and administrative losses [16].

Taking into account that usually several dangerous events occur at the same time or in cascade, the international community is interested in developing complex scenarios to address a multi-hazard approach. In this direction, different projects that involved researchers from various countries were developed, such as Risk-UE, CAPRA, or MATRIX [17,18].

2.2. Natural Hazards in Romania

According to European and international statistics, Romania is among the top 10 countries in the world in terms of earthquake exposure by area and has a growing exposure to floods [19]. Between 1960 and 2010, 400 major floods were recorded in Romania, which led to 237 deaths. In addition, the more recent history of floods in Romania showed a severe impact of this type of hazard on population and infrastructure. For example, the floods from 2005 and 2006 affected over 1.5 million people, destroyed some of the specific infrastructure for flood risk management, and caused an estimated damage of over €2 billion.

Research indicates that floods are estimated to occur more frequently in many water basins as a consequence of climate change, especially in winter and spring, although estimating this hazard in terms of frequency and magnitude, similar to other hazards, is uncertain. Of all the countries in the Danube basin, Romania is expected to be the most affected by climate change. In reality, damages of approximately €1 billion are avoided annually thanks to current hydrotechnical works performed across Romania, as well as due to the operational measures in the field and the early warning and response measures that are part of the flood risk management policies implemented by the Romanian authorities.

Considering the geomorphological hazards, the landslides represent the movement processes of some masses of earth under the action of gravity along landslide surfaces, which separates them from the stable part of the slope. The majority of landslides are recorded on slopes with moderate inclinations, consisting of clays and alternating clays, marls, sandstones, and sands. An equally important role is played by anthropogenic causes, especially those related to deforestation. Landslides are usually predictable phenomena, as evidenced by some precursor signs such as the appearance of cracks in the upper part of the slopes or the inclination of the trees. In Romania, the largest areas with landslides are found in the Subcarpathians, the Transylvanian Depression, the Moldavian Plateau, and the Eastern Carpathians, where buildings and infrastructure destruction are possible. Landslides are included in the 575 Law of 2001 and considered in the Territorial Plan-section V as Natural risk areas. The guide considers a methodology that takes into account several factors such as lithology, geomorphology, geological structure, hydrology, climate, seismicity of the area, degree of afforestation, and human activity [20]. Figure 1 shows the landslide map for Romania, where it can be seen that the north-east part of the country is susceptible to medium-high levels of landslides. In this area, the current study was conducted.

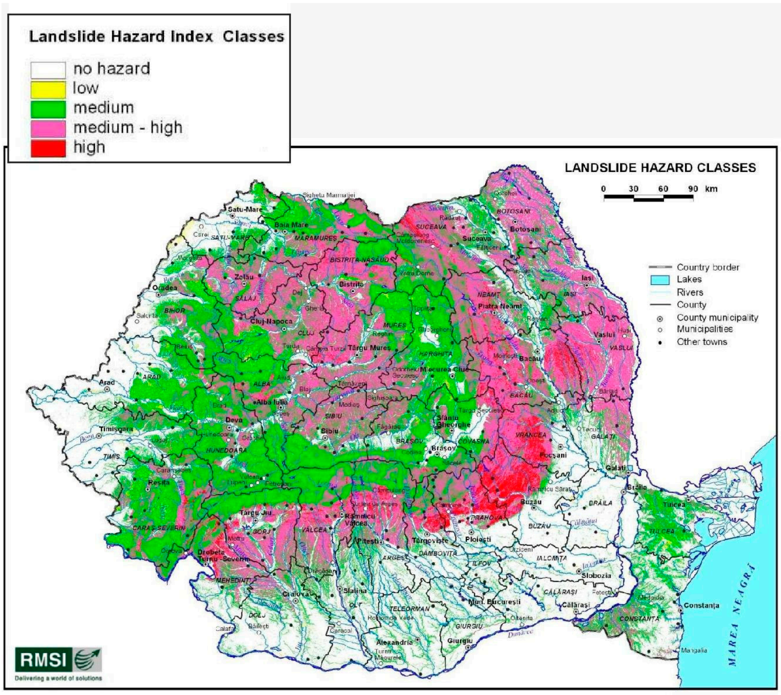


Figure 1. Romanian hazard maps for landslides [20].

Moreover, according to several statistics, in Romania, every 10 years an earthquake with a magnitude of 6 may occur, every 30–40 years there can be an earthquake with a magnitude of 7, and every 80 years there can be an earthquake with a magnitude greater than 7.5 degrees on the Richter scale. Two major earthquakes were recorded in Romania: one on 10 November 1940, and the other on 4 March 1977. Both earthquakes occurred in the Vrancea seismic area, causing huge disasters (human and material losses). The 1977 earthquake caused 1641 deaths and required $2 billion euros for Romania to recover. The event led to the collapse of more than 35,000 houses, and it was felt in Bulgaria, Moscow, and Sankt Petersburg [21]. The two major earthquakes significantly contributed to the rethinking of seismic codes. Currently, Romania is aligned with European norms and has its national annexes based on existing recordings from the 1977 earthquake. Romania is divided into several seismic areas, each with its own particularities. Of all the seismic areas, the Vrancea region is considered to have the highest destructive potential. The other areas are shallow seismic sources of local importance for seismic hazards. The Vrancea region is a complex seismic area of continental convergence, located at the contact of three tectonic units: the Eastern-European, the Intra-Alpine, and the Moessian platforms. The seismic activity on Romanian territory occurs at depths between 60 and 200 km. In this depth interval, higher activity was recorded in two depth ranges: between: 80 and

100 km, and between 120 and 160 km, respectively. If the earthquakes from the majority of the areas are slightly felt, a strong earthquake produced in the Vrancea area can generate damage in neighboring countries such as Bulgaria and the Republic of Moldavia. A map of the earthquake events that occurred between 1977 and 2019 is presented in Figure 2, from which it can be noticed that the Vrancea area is the most active one in Eastern Europe.

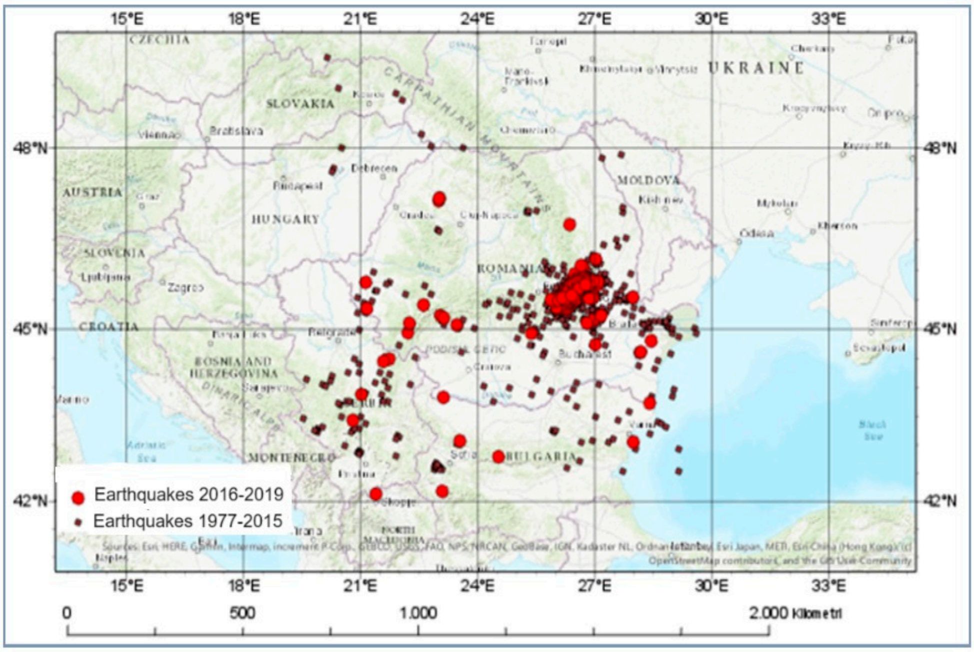


Figure 2. Earthquake distribution between 1977 and 2019 (authors composition).

In order to reduce the effects of hazards in general, in particular floods, landslides, and earthquakes, researchers from Romania got involved in national and international projects aimed at raising awareness and designing updated mitigation plans and strategies for future events. In this direction, the National Administration "Romanian Waters" implemented in the last two decades several projects, from which the authors mention: the DESWAT PROJECT (2005–2014), the WATMAN PROJECT (2007–2013), the EAST AVERT (2007–2013), and RO-FLOODS (2019–2022) [22,23]. The WATMAN component was centered on technology, equipment, and organizational structuring to address water management issues throughout Romania. These projects addressed problems such as floods, droughts, dam safety, acid mine drainage, pollution, accidental spills, public involvement, and environmental impacts [24]. Regarding the seismic activity in Vrancea area, respectively the assessment and seismic risk mitigation, Romania was involved in projects as: Risk-UE (2001–2005), JICA Project (2001–2008), World Bank Hazard and risk mitigation in Romania (2004–2010), IRPP/SAAH (2008–2011), SERA-Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (2017–2020), DACEA (2010–2013), Balkan Geohazard Assessment and Map (2007–2008), Progress on Seismic and Geotectonic Modelling Across CEI Territory and Implications on Preventing and Mitigating Seismic Risk (2007–2008), Seismic Early Warning for Europe-SAFER (2006–2009), Network of Research Infrastructures for European Seismology-NERIES (2006–2010), SHARE-Harmonization of Seismic Hazard in Europe (2009–2012), MARINE GEOHAZARD (2010–2013). Currently, Romania, as an EU country, has a well-established approach and involvement in hazards risk management and disaster risk management, in line with European policies. On the other hand, Moldova, a non-EU country, has a different approach to the topic due to significant gaps, action delays, and a lack of financial support. Table 1 presents a comparative EU versus non-EU country Strategy for Disaster Risk Management (DRM).

Table 1. Comparative EU versus Non-EU Country Strategy for Disaster Risk Management (DRM) [25,26].

	Romania (EU Country)	Republic of Moldavia (Non-EU Country)
Risks	Earthquakes, floods, doubt, landslides, wildfires, and extreme weather events	Earthquakes, floods, doubt, and extreme weather events
Strategy for Disaster Risk Management (DRM)	✓ accelerated investments to modernize emergency infrastructure ✓ policy reforms in disaster risk management (DRM) ✓ received financial support from World Bank (WB) and Global Facility for Disaster Reduction and Recovery (GFDRR) ✓ created DRM Development policy loan with a Catastrophe Deferred Drawdown Option ✓ Romania's Ministry of Regional Development and Public Administration works with WB to develop a strategic framework to renovate and improve the seismic safety and energy efficiency of buildings ✓ support citizen engagement and empowering civil society and volunteer organizations ✓ created robust partnerships with WB and GFDRR, EU, government, civil society, research institutes, academia and private sector	✓ limited resources ✓ some of core institutions and legislative structures from DRM are in place ✓ the Government of Moldova has been strengthening institutions to better prepare for and respond to disasters ✓ strengthened regional collaboration and knowledge sharing on DRM ✓ Moldova developed a draft National Strategy for Natural Hazard Mitigation in 2015, but it was never finalized ✓ need to gradually move the focus of DRM from reactive to proactive ✓ high priority actions: - development an overall DRM framework in order to fill the existing legislative gap - risk identification by shared platform - risk reduction by non-structural and structural measures - emergency response and preparedness by increasing citizen' awareness - financial protection by DRM budget allocation - develop a resilient recovery framework

3. Methodology and Data Collection

3.1. HAZARM Methodology

The research presented in this article was carried out along the "Integrated Networks for Hazard Risk Management" (HAZARM) EMS-ENI 2SOFT/4.2.77 Project, a cross-border research partnership with the Republic of Moldova intended to establish common directions with respect to safety and security in cases of natural hazards. The project supported joint activities for the prevention of natural and man-made disasters as well as joint action in case of possible emergency situations appeared across the border area. The focus of the HAZARM team was to elaborate updated hazard maps having a common approach, raise awareness among the population, and investigate the area through a multi-hazard approach, in order to propose risk mitigation measures aimed at reducing the effects of disasters.

The main objective of the project was to harmonize the two border countries (Romania and Republic of Moldova) emergency action plans and strategic approaches in case of three natural hazards such as floods, landslides and earthquakes. The cross-border hazard management network integrated professionals from two correspondent cities in East European countries: an EU member Iași from Romania and Chișinău from the Republic of Moldova. The topic addressed the disparities identified in the Program Core Area from the point of view of prevention and monitoring procedures, management and emergency actions associated with natural hazards. The approach is based on a Micro to Macro evaluation process supported by a mixed team of professionals.

The project developed a joint and unitary program of high interest for the two cross-border regions, but in the frame of a disparate and different approach to natural hazards, and a lack of extensive and systemic mechanisms. As shown in a 2016 report from the World Bank Sustainable Development Department and valid today, the Republic of Moldova needs to perform several improvements in the risk assessment and mitigation plan [27].

In this context, the project relevance for the program area made a direct contribution to the achievement of the foreseen indicators stipulated in the Joint Operational Program Romania-Republic of Moldova 2014–2020. Joint challenges in the area of safety and security, includes support for joint activities to prevent natural and man-made disasters, as well as also joint actions in emergency situations. Figure 3 presents the workflow used in elaborating the hazard maps for each disaster. It can be identified that common data was used as well as specific ones. Particular challenges were encountered in each direction, which were solved by the joint efforts of the team members from the two participating countries.

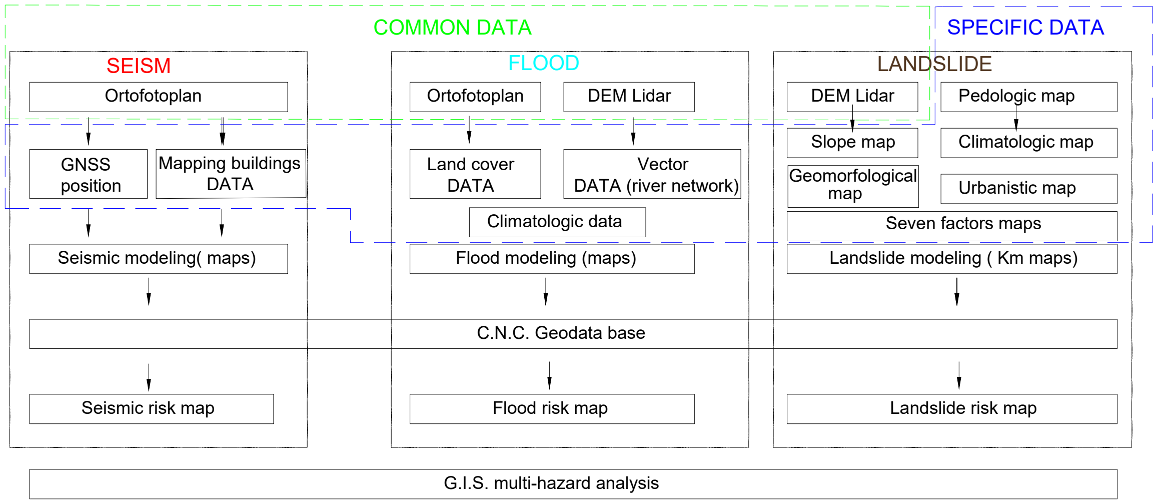


Figure 3. Workflow for the G.I.S. multi-hazard analysis.

The main project results consisted of elaborating detailed hazard maps indicating the vulnerability to natural hazards associated with a specific area named Ungheni Target Area, which was considered a micro-level approach. The studied area was chosen based on considerations such as border proximity, cross-border residence symmetry, and high hazard risk. The cross-border hazard maps imply time monitoring of the area, detail on its hazard vulnerability, and customized risk analysis. The results were used to draw conclusions about prevention measures and regional planning. The network activity conclusions and results were integrated and disseminated in a cross-border strategic guide for sustainable hazard management. This guide represents an emergency assistance manual in case of natural hazards, which was elaborated considering all three hazard maps for both countries. For the HAZARM project, the guide was customized for the targeted area, with further potential for extension to other areas. The guide is being disseminated to local authorities and administrations, emergency units, education units, and other representatives.

The novelty of the research consisted of obtaining a common map for the two neighboring countries with respect to three important disasters possible that could occur in the area. The overlapping of their effects leads to the necessity of raising awareness not only for the population, but also for authorities and decision makers regarding the mitigation plan. In the hazard design, common data sets (DEMs) were partially considered, which needed to be converted into the same spatial resolution by successive interpolation in order to obtain a spatial final resolution of 1 m for the two countries.

Hence, the results of each disaster are comparable to previous results, only more complete. The risk for the three hazards was assessed by a common geospatial database, having as a resulting in a homogeneously computed multi-hazard analysis. This type of evaluation leads to a better and more uniform understanding of the risks and vulnerabilities in general and proposes correct and rapid mitigation steps. Also, it highlights the importance of prevention activities and preventive measures.

Among the limitations of the approach are the insufficient geospatial data and the technical difficulties in harmonizing the technical parameters, such as spatial resolution and common reference systems. Along with the project, another limitation refers to the difficulties in exchanging geospatial data between different countries due to geopolitical reasons.

The administrative officials from Ungheni Target Area and the local population are the main beneficiaries of the results. They were informed of the identified local risks and occurrence probability, but, most importantly, they received information on the most vulnerable areas. In this context, the Ungheni administration should consider the results when giving building permits or starting different construction projects. The information is even more useful since the Ungheni area is considered part of the A8 highway Târgu Mureș-Iași-Ungheni.

3.2. Data Collecting and Processing

The HAZARM project's target area is Ungheni. The existence of two similar settlements in the neighboring countries helps the project analyze different approaches to comparable surfaces, populations, and buildings. The commune from Iași County, Romania, represents a component part of the Iași metropolitan area, with a population of 4173 assessed in 2011. Ungheni's geographic position locates it as the closest commune from the NE countries of the EU towards non-EU countries. It is composed of four villages: Bosia (the commune center), Coada Stâncii, Mânzătești, and Ungheni.

3.2.1. Flood Hazard Maps

Flood damage assessment and analysis is a key component of sustainable risk mitigation and management strategies, especially considering the global changes due to climate change and the increasing human activities and high-value assets in vulnerable areas. Methods and tools for estimating and mapping economic damage are essential for comparing the efficiency and sustainability of a portfolio of flood mitigation measures to support decision-makers in delineating flood risk management plans as required by the Flood Directive Department. Therefore, a comprehensive approach that considers all three components of risk— hazard, exposure, and vulnerability— is essential to identify exposed areas, design the most appropriate strategies for flood management, support decision-makers to prepare, respond, and recover, and, thus, improve the sustainability and resilience of risk-based flood management practices [28].

In order to create updated flood hazard maps, several types of data are required, such as hydrological data (provided by the National Institute of Hydrology and Water Management Institute, INHGA, in the form of synthetic hydrographs), topographic data as cross-sections, measurements of hydrotechnical structures, and a digital terrain model (DTM). Using all the data collected, mathematical models are generated using hydraulic modeling software HEC-RAS version 6.3, that simulates flood propagation and flooding of major river beds (when the water level exceeds the river banks), with some limitations in terms of fully reproducing reality, taking into account the fact that the simulated flows are statistical flows [29–31]. Hydrological modeling anticipates rainfall in a river basin with the aim of assessing the possible flooded area in case of an event. The workflow used in order to generate risk maps for floods is presented in Figure 4.

3.2.2. Landslide Hazard Maps

The geospatial information resulting from the modeling of landslide risk maps is considered in urban planning documents or used by local authorities in risk management. The correct modeling of this risk leads to adequate and efficient decisions for safe urban development. In order to reduce the impact of landslides and the damage they cause, it is important to estimate the corresponding risk before their occurrence, as this can help monitor and plan preventive measures for future similar events [32].

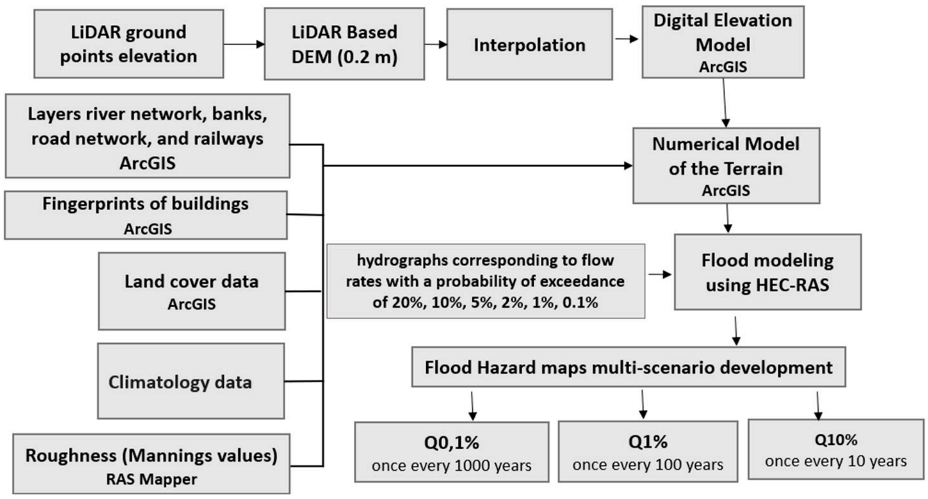


Figure 4. Workflow diagram of the flood modeling process.

In the Republic of Moldova, landslide evaluation works were carried out starting in the 1980s by the Institute of Geology and Seismology and the Institute of Geography MAS [33] depending on the morphological and morphometric characteristics of the relief, taken in the topographic maps at scale 1:5000 and geological at scale 1:25,000 [34]. Later, other modeling and mapping studies of landslides and their related phenomena were carried out using multivariate statistical methods from the variables: digital elevation model (DEM), land cover, forest, and landslide models [35], but still using analog geospatial data sources. In the present work, the modeling was based on a DEM obtained by airborne LiDAR technology with a spatial resolution of 5 m resampled in ArcGIS 10.8.1 by linear interpolation at 1 m, the modeling method used being the one adopted in Romania according to HG447/2003 [32], with the aim of standardizing risk assessment in the two neighboring countries, but also for the method to be recommended for adoption as a good practice in the Republic of Moldova.

Hazard maps in Romania are carried out following the prescription given in the methodology described in HG447/2003 [32]. According to this, the most important factors with the highest weight are the lithological factor, Ka, and the geomorphological one, Kb. The landslide maps for the Ungheni area were performed considering the specific coefficients according to Annex C [32] requirements of the Methodological Norms corresponding to Law 575/2001 regarding the approval of the National Territory Planning-Section V-natural risk areas [20].

The thematic maps, except Kb, result from combined data given by the National Cartographic Centre (NCC), provide information from onsite activity, and scan after georeferenced images (geological maps, structural maps, hydrological maps, etc.).

In situations where the characteristics of an influencing factor are not explicitly found in the criteria described in Annex C [32], the quantification of specific coefficients was completed by analogy with those similar in effect and existing in the other hazards legislation (as is the case for seismic factor Kf which was evaluated according to the P100-1/2013 code [36]). All the maps were designed in digital format according to specific factors, with the vectorization achieved manually in ArcGIS software (version 10.8.1). The topographic base for producing the factorial maps with the values and geographic distribution of specific risk coefficients, such as Ka, Kc. . .and Kh, use the orthophoto plan from 2015, Bucharest, NCC archive.

Each thematic map is associated with a database, similar in format. The geomorphological factor map (of the slopes), Kb, is based on the Digital Elevation Models (DEM) made on Airborne Laser Scanner (ALS) data. The data was taken from Prut-Barlad Basin Administration and bought by SC TRP SRL in 2012 in order to do the Digital Model of the Surface and Digital Model of the Terrain, further used in the development of hazard and risk maps for floods in the river basin.

The considered LiDAR points have a 15 cm precision in the horizontal direction and 10 cm on the vertical one, according to the sensor specifications, and one point per 4 m^2 density according to the flyplan. The flat coordinates were computed in WGS84 Universal Transverse Mercator area 35 N, while the altitudes were considered in the WGS84 ellipsoid reference system [36]. In order to obtain the DEM, two stages of LiDAR data processing were necessary: automatic and manual processing, classification, and filtering stages. The automatic filtering was performed in two software programs OPALS 2.13.1 and FugroViewer 3.4, while the manual one was performed in ArcGIS. After obtaining the terrain points, the conversion of the ellipsoid elevation into Black Sea elevation is mandatory in order to obtain a correct DEM compatible with other data sources. This is carried out by means of algebraic functions applied to DEM by using the "raster calculator" from ArcGIS on the terrain points DEM's and on those from the geoid model [37].

The geomorphological factor map, Kb, was performed by extracting the necessary information from the DEMs obtained based on LSA data (Level layer). The slopes are classified into 4 classes: low (slopes of 0–5%), medium 2 (slopes of 5–10%), medium-high 3 (slopes 10–20%) and height (slope 20%). The slope is a variable often used in landslide analysis since higher slopes are usually associated with increased landslide risk [37]. According to the methodology described in the current technical rules regarding the preparation and content of landslide hazard maps [32], based on existing information about specific works collected from the city of Ungheni and the data obtained from the direct observation of the on-site evaluation, the values of the risk coefficients Kc-Kh were estimated, as well as their spatial distribution, as follows:

Structural factor, Kc: was evaluated at 0.30 for the entire surface of Ungheni, corresponding to the geo-logical structures characteristic of geosynclinal areas in flysch facies, strongly folded and dislocated geological formations, affected by a dense network of cleavage, fissures, and stratifications;

Hydroclimatic factor, Kd: was evaluated on the basis of the existing climate maps and on the basis of the precipitation history in the area, the Kd coefficient being estimated at 0.04–0.50-slow, long-lasting precipitation with high possibilities of water infiltration into the rocks, which during fast rains generate high velocities runoff with transport of solid flows, vertical erosion processes predominating;

Hydrogeological factor, Ke: was evaluated on the basis of information on the level of underground water from observation boreholes in the hydrogeological network, wells, and springs. The values of the hydrogeological coefficient are included in the range: Ke 0.05 (low average probability) for areas where aquifers are found at great depths and which do not influence the stability of the slopes; 0.40 (medium-high probability) for areas with exfiltration;

Seismic factor, Kf = 0.9: was evaluated according to the P100-1/2013 code [36], Metropolitan Area of Iași is placed in seismic zone C, corresponding to a value of coefficient Ks = 0.20, a value of Tc (s) = 0.7, and, for the seismic intensity, MSK VIII;

Forestry factor, Kg: was carried out on the basis of the orthophoto plan of the studied area as well as on the topographical map. Thus, the areas with arboreal vegetation, with the role of supporting the slopes, and the hydrophilic vegetation, which indicate areas with excessive humidity and other types of existing vegetation, were identified on the map through the following coefficients: 0.10 forests with large trees, 0.30 vineyards, pasture, arable land, and 0.50 residential area;

Anthropic factor, Kh: was made on the basis of cadastral, urban planning, and orthophoto maps. The anthropogenic factor varies in the ranges: 0.10 uninhabited area for areas where no important constructions are carried out on the slopes and water accumulations are missing; 0.80 inhabited area for areas where slopes are affected by a dense network of water supply and sewage pipes, roads, railways, coastal canals, and quarries.

The corresponding values for the eight factors that influence the stability of the slopes are presented in Table 2.

Table 2. Values for the slope factors.

Factors		Class	Value	Range of Values
Name	Label			
lithological factor	Ka	medium-high high extreme	0.7 0.8 0.95	0.7–0.95
geomorphological factor	Kb	low medium medium-high high	0.05 0.4 0.7 0.9	0.05–0.9
structural factor	Kc	medium	0.3	0.3
hydrological and climatic factors	Kd	medium medium-high	0.4 0.5	0.4–0.5
hydrogeological factor	Ke	low medium-high	0.05 0.4	0.05–0.4
seismic factor	Kf	high	0.9	0.9
forestry factor	Kg	low medium-high high	0.1 0.3 0.5	0.1–0.5
anthropic factor	Kh	low high	0.1 0.8	0.1–0.8

Based on the previously presented coefficients, the mean hazard coefficient, K(m) is computed using the following relation:

$$\mathrm{K(m)} = \sqrt{\frac{\mathrm{K(a)} \times \mathrm{K(b)}}{6} \times \mathrm{K(c)} + \mathrm{K(d)} + \mathrm{K(e)} + \mathrm{K(f)} + \mathrm{K(g)} + \mathrm{K(h)}}, \quad (1)$$

Following the calculation of the influence coefficients, their geographical distribution, and the establishment of the potential damage degrees (low, medium, high), a certain probability of a landslide degree was established. This was performed by ArcGIS 10.8.1 software, following the intersection of the surfaces corresponding to each layer and the application of the mathematical value of K(m) from the previous computation for each new- generated polygon. Prior, each thematic map was analyzed in order to remove any digitization defects such as polygon overlaps, gaps between polygons, and duplicate points.

After the elaboration of the factorial maps, a mathematical operation was performed in order to generate a unitary grid (for the 8 factorial maps and for the average factor map, in a hypothetical network of 1×1 m^2). The final product contains a dense mosaic of polygons defined by extremely variable K(m) values in the 0–1 range. The final Km map synthesized this extreme variability in summary value bands (the same for the entire national territory), which will induce the restriction of the area distribution polygons to six categories. In the end, the map with the geographical distribution of the average hazard coefficient made using ArcGIS software was obtained.

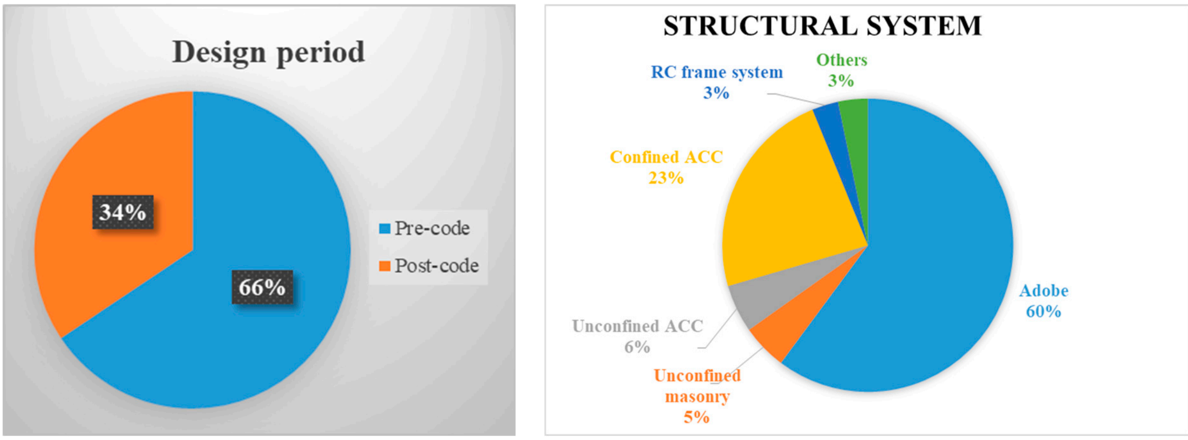
3.2.3. Seismic Hazard

Estimating seismic risk requires investigating several factors, such as the seismicity of the area, geological characteristics, hydrological properties, vulnerability of buildings, social impact, and economic distribution. Similarly, the majority of countries, Romania already has a deterministic seismic hazard map based on the recording from the 1977 earthquake that shows the possible distribution of the intensity (or acceleration) of earthquakes based on various recurrence periods. The soil influence is also taken into account, as it can amplify the damaging effects of the seismic action. It was also observed that, starting with a slope greater than 4 degrees, the effect of the terrain relief becomes significant. The earthquake's effects can be amplified further by the social risk factor, which contains: population density distribution, poverty rate, crime rate, health care, as well as the economic factor [38,39].

The seismic vulnerability of the built environment refers to the intrinsic possibility of buildings suffering degradation in the event of a dangerous event of known characteristics—intensity and period of time [40].

The building stock in Romania in general, in particular in the studied area, dates back several years before the elaboration of the anti-seismic design codes. This means that many of the existing buildings do not meet the current restrictions, making them more likely to suffer major damage in the event of an earthquake. In order to get a real picture of the condition of the buildings in the four villages, an onsite survey was developed, and accurate measurements were performed using ArcGIS Survey123 software. 1734 recordings were made, collecting information such as the construction period (pre-code or post-code), the material from which the construction is made, the height regime, the structural system, and the level of current damage.

Figure 5a presents a statistic regarding the construction period of the buildings, having as reference the year 2006, when a seismic code considered the European norm was implemented in Romania. In this code, the ductility concept was widely discussed, along with the necessary measures that should be taken into consideration in order to reduce the earthquake effect, considering the lessons learned from previous events at the national and international level [41]. 66% of the investigated houses were built before 2006 without following any seismic specifications.



(**a**) (**b**)

Figure 5. (**a**) Buildings classification based on the design period with respect to 2006; (**b**) Buildings classification with respect to the structural system.

It was also noticed that, in the area, several structural systems were used, such as, for example: unconfined autoclaved concrete (ACC), unconfined masonry, confined ACC, adobe, frame systems, and others. In Figure 5b, it can be seen that the adobe structure covers more than half of the investigated buildings, or to be exact, 60%. Adobe structures are low-budget, based on eco-friendly materials such as local soil covered with hay, and usually self-made. Usually, these types of structures are only on the ground floor and behave very well in cases of seismic action [42].

Regarding the damage degree, several classes were considered, according to the European Macroseismic Scale (EMS-98) [43]. The EMS 98 scale is the basis for assessing seismic intensity in European countries. If magnitude scales for earthquakes express the seismic energy dissipated by the earthquake, the EMS 98 intensity scale expresses how strongly an earthquake affected a particular location. The earthquake damage, according to the EMS scale, is assessed on the basis of three factors: people, objects, and structures [43]. Five classes of damage level were considered based on the visual inspection of cracks and structural or non-structural damage: class A (no-damage), class B (negligible to slight damage), class C (moderate damage), class D (substantial to heavy damage), class E (very heavy damage), and class F (destruction).

A distribution of the build environment in the Ungheni area with respect to the damage level is presented in Figure 6. This classification was done based on the visual inspection in accordance with the recommendation for EMS-98. It is observed that around 50% of the buildings can be considered to have no damage due to prior hazards. This is only an approximation because houses might have in-depth damage that was covered by the exterior plaster.

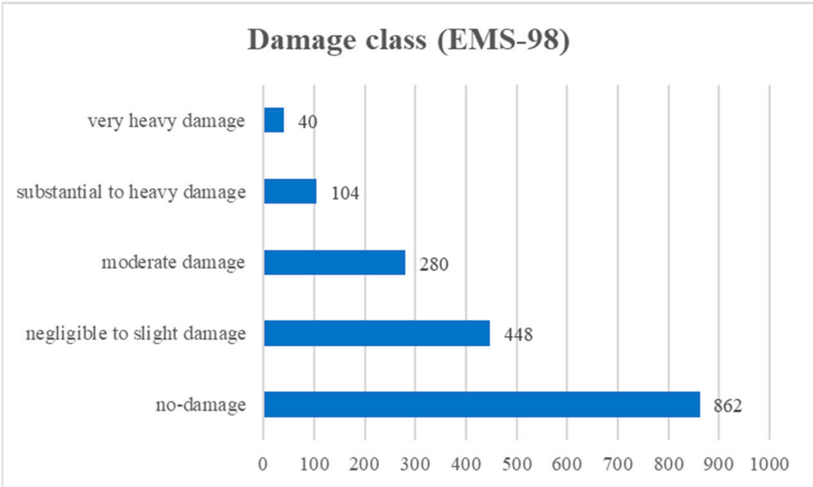


Figure 6. Building classification according to the damage class.

4. Results

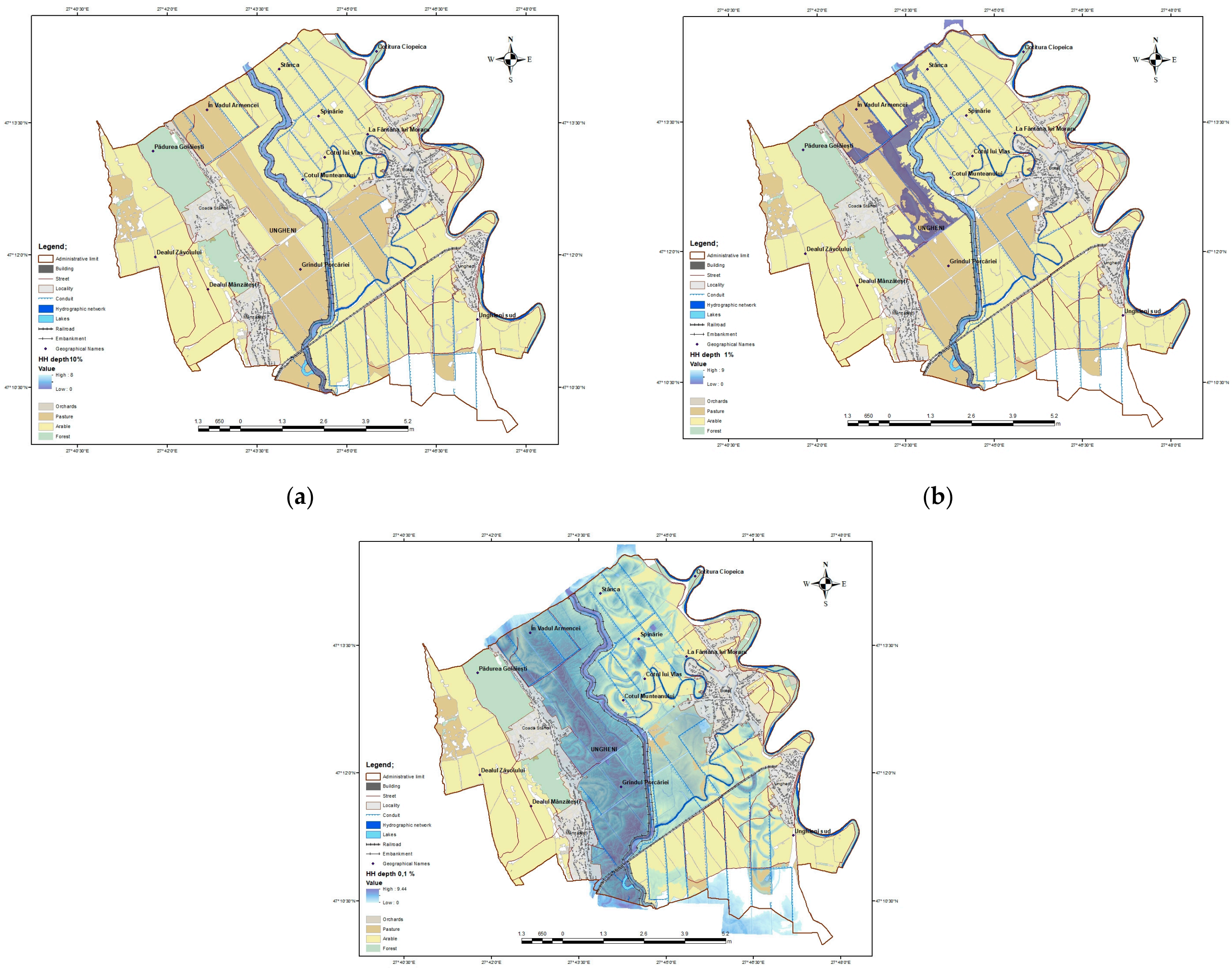
In the following the results for each specific hazard are presented in a graphical representation.

4.1. Flood Risk Map

The hazard map for floods shown in Figure 7 was designed by HAZARM team members in accordance with the requirements of the Floods Directive for areas designated as having a potentially high flooding risk and covers geographical areas that could be flooded in the following scenarios: low probability (Q0.1%-floods that can occur, on average, once every 1000 years); average probability (Q1%-floods that can occur, on average, once every 100 years); and high probability (Q10%-floods that can occur, on average, once every 10 years) [44,45]. It can be stated that only in the case of low probability floods the inhabitants of the area will suffer. In a high-probability scenario, the agricultural area will be significantly damaged, as will the infrastructure of the area, which connects Manzatesti to Bosia village, because it is designed at a low altitude. In order to better understand the flood risk of the area, the following maps have been developed:

The flood risk map indicates the floodable areas in various scenarios (considering different probabilities of exceeding the maximum water flow), the potential material and human losses, in accordance with the requirements of the 2007/60/EC directive [28], with reference to vulnerable economic activities from the potentially affected area, including infrastructure, potentially affected protected areas, other useful information, cultural objectives, etc.

As shown in Figure 8 and Table 3, the houses along route DJ249A present the highest risk. A total of 882 houses would be affected by a flood with a 0.1% probability due to their placement on one hand and the fact that there are no major dams to limit the effects of a possible flood.



(**a**) (**b**)

(**c**)

Figure 7. Flood hazard map for the Ungheni area, Romania, depicting (**a**) high probability, (**b**) moderate probability, and (**c**) low probability scenarios.

Table 3. The elements exposed to the flood hazard in the study area of Ungheni.

Risk	**Buildings**		**Land Use Categories**		**Infrastructure (Roads)**		**Urban Area**	
probability	units	surface area (mp)	parcels	surface area (ha)	sections	length (km)	localities	area (ha)
0.1%	882	62,653.4	42	842.16	55	13.50	2 (Coada Stancii, Manzatesti)	122.95
1%	2	4.5	18	151.88	3	0.71	1 (Ungheni)	3.81

It can be concluded from the analysis results that for the scenario of 0.1% flood risk with a low probability of occurrence, the territories of Coada Stâncii and Mânzătești villages are exposed. In these areas, the risk of floods can affect 882 buildings (62,653.4 sqm), 42 plots with various categories of use (842.16 ha) and 55 sections of infrastructure with a total length of 13.50 km. In the scenario of 1% flood risk with an average probability of occurrence, the territory of Ungheni village in Romania is exposed. In this area, the risk of flood influence is significantly diminished, affecting only two buildings with an area of 4.5 square meters, 18 plots with various categories of use (151.88 ha) and 3 sections of infrastructure with a length of 0.71 km.

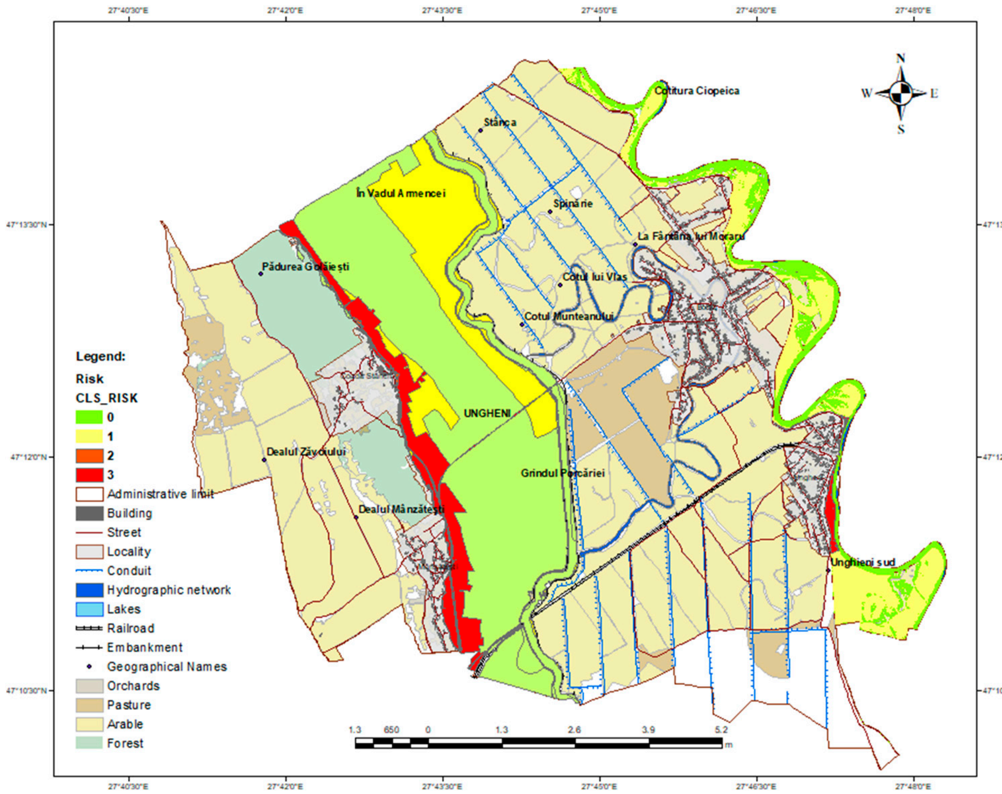


Figure 8. Risk flood map for Ungheni area, Romania.

4.2. Landslide Risk Map

The landslide hazard map is presented in Figure 9. It can be noticed that out of the six categories of probabilities, the landslide hazard map includes values in only three of them: medium probability (10–30%), medium-high probability (31–50%), and high probability (51–80%). The medium-high probability is significantly represented, especially along route DJ249A.

Predominantly, the possible landslides were encountered along the Jijia and Prut riverbeds, representing approximately 78.60% of the total studied area. In the low probability range, $K(m) \leq 0.10$, and in the very high probability range, $K(m) \geq 0.80$, no polygon is outlined. The polygonal surfaces generated on all slopes, mainly for K(m) between 0.31 and 0.5, belong to a medium-high probability range. This interval encloses approximately 17.80% of the studied surface. The values of the average hazard coefficient K(m) = 0.51–0.72612 correspond to polygonal surfaces with smaller dimensions, sufficiently compact, and a wide distribution, which are found on all surfaces. They belong to a high probability range when landslides are triggered and represent approx. 3.60% of the studied area. This type of landslide occurs permanently along the roads where the road profile is sloped or mixed. It can be easily seen that on the ridge of a hill, the average slip hazard coefficient has low values, which increase to the maximum local values at the intersection with roads and towards the base of the slopes. The values of the average slip coefficient are in the range of 0.11 and 0.53, which means a potential for landslides ranging from medium to high. In order to categorize the landslide type, the classification presented to current codes was used, meaning that: medium landslide probability is considered for K(m) between 0.1 and 0.3 and is usually represented with yellow; medium to high landslide probability is considered for K(m) between 0.31 and 0.5 and is usually represented with green; and a high landslide probability is considered for K(m) greater than 0.51 and is usually represented with red. The areas with medium and high risk of landslides in the Ungheni area are located in Coada Stîncii and Mînzătești villages. In these areas, the slope values are between 120 and 380 which generates an average risk factor K(m) with values between 0.31 and 0.53. In these areas, the landslide risk can affect 157 buildings in Coada Stîncii village and 265 buildings in Mînzătești. At the same time, a potential landslide risk is observed for some of the roads, with a total length of 5.5 km in Mînzătești and 3.8 km of roads in Coada Stîncii. The current percentage of land use (POT) in the two villages previously mentioned is 2.6% for Mînzătești and 1.4%, respectively, for Coada Stîncii. Considering that it is recommended to limit it to 10%, it can be concluded that the analyzed villages comply with this restriction.

This shows an increased vulnerability of the settlements placed in that area not only to landslides, but also to the combined hazards of floods and landslides.

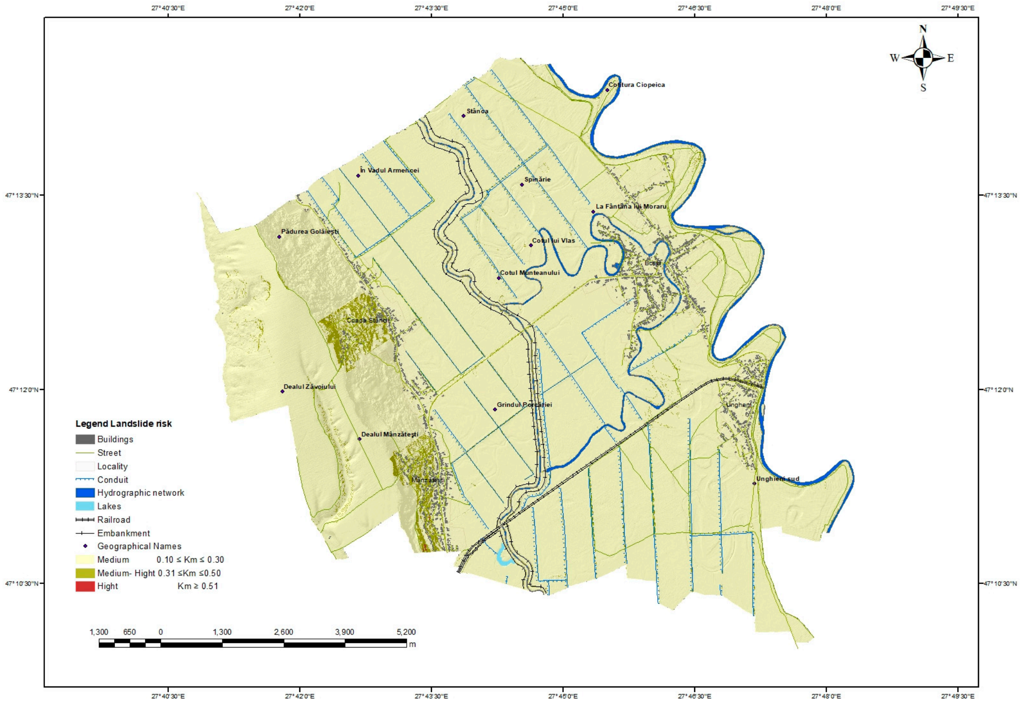
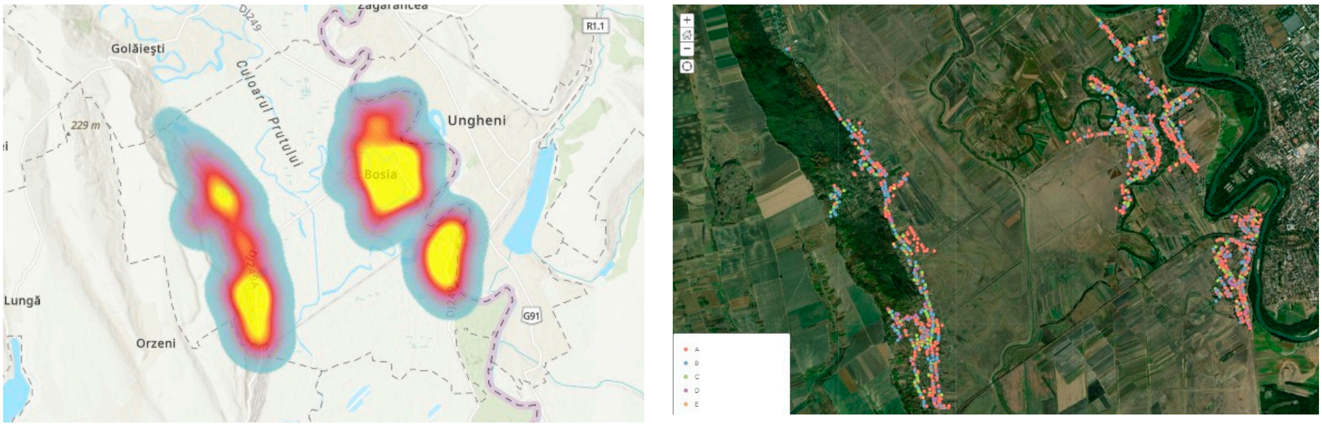


Figure 9. Landslide hazard map for Ungheni area, Romania.

4.3. Seismic Risk Map

Figure 10 gives a visual distribution of the houses in the studied area based on their damage class previously determined. The areas with a high density of population are emphasized. In Figure 10a the area represented with red color are those in which major damage might occur affecting a significant number of people. It can be seen that in the center of the villages are mainly newer buildings, done according to current regulation that can withstand future earthquakes. These maps were done in order to be able to assess the effect of the previously presented hazards, namely floods and landslides, on the population of the area if combined with a seismic event. The area from the left side is prone to be affected by both landslides and earthquakes, meanwhile the area from the right side has an increased risk of floods and earthquakes.



(**a**) (**b**)

Figure 10. (**a**) Building distribution in Ungheni area, Romania; (**b**) Building layout according to the damage class.

5. Discussion

The paper topic refers to the analysis of multi-hazard risks customized for a specific area, named Ungheni, positioned at the eastern border of Romania with the Republic of Moldova. This area was particularly chosen due to its particularities, since in both border countries there is a city (Moldova or a village (Romania) with a similar name, positioned at their country's border, with similar climate and geographic features, and subjected to similar natural hazards. The difference between them consists in the approach of multi-hazard risks by country. As already presented in the paper, in comparison with Moldova, Romania has a well-developed and implemented strategy for multi-hazard risk management. Our country benefited significantly from EU involvement from an economic, social, and informational point of view. On the contrary, Moldova is fighting a lack of resources, assistance, and implications in hazard management; the actions taken in this direction are limited. In order to support this country, the EU created several cooperation programs, providing funds for research, public acknowledgement, and acquisitions. Joint Operational Program Romania-Republic of Moldova or Interreg NEXT Romania-Republic of Moldova Programme are just several examples of cooperation. In fact, the relationship between the two border countries is tight since our nations cooperate at all levels.

The purpose of the present paper was to perform an analysis of multi-hazard risk management for a particular village in Romania. The obtained results can be used to create predictions for the reduction of social and economic losses and also to provide support and assistance for our Moldavian neighbors in their activities for hazards management.

The analysis of the exposed elements to flood hazards in the studied area, Ungheni, Romania, took into consideration several scenarios described in detail in the results section.

Regarding the landslide hazard, from the analysis of the average landslide coefficient (K(m)), polygonal surfaces for different K(m) values can be highlighted, as can some specific characteristics for the Ungheni area regarding the manifestations of current dynamic factors. It is noticed that on all landforms there are values from the average probability range for landslide occurrence (K(m) = 0.10–0.30). In the close by area, where the same slope regime is in the same geological conditions, an average landslide coefficient K(m) much lower is obtained in the 0.10–0.31 range, due to land cover with forest vegetation. This suggests that the average landslide coefficient could be reduced by expanding the available areas.

Regarding the seismic risk, a correlation between the design period and the structural system is noticed since the majority of the pre-code buildings have an adobe structural system, which was discouraged from being used after 2006 due to poor behavior in the event of a seismic action. The potential good results regarding the damage class of the building presented in Figure 8, where around 50% are considered non-damaged are related first of all to the fact that the majority of the houses (80%) are low-rise buildings having only one floor, but also to the fact that 34% are relatively new (build after 2006) and several beneficiaries performed current maintenance works. The results regarding the damaged state are approximate because only an exterior inspection was performed. Also, it was observed that many of the non-damaged buildings benefited from current maintenance work, meaning that the exterior plaster was redone. This can mislead the results since in-depth damages might exist, which are hidden by recent construction works. The extensive use of adobe as construction material is mainly because the studied area is a rural one, where people tend to build cheaply due to a lack of funds, and because this material can be completed in the courtyard without specialized workers. These kinds of houses behave well both in winter and in summer but do not have any anti-seismic elements to dissipate the energy produced by this action. Figure 10b shows that there is a mixture of damage classes in all villages, which actually leads to a rather homogeneous seismic risk distribution, with the researchers not being able to identify only one risk area.

If the maps from the three separate hazards are compared, it can be concluded that the houses from Coada Stâncii and Mânzătești are the most vulnerable ones, being susceptible to suffering damage in case of all the hazards.

These conclusions were shared with the local authorities in order to pay more attention to future buildings in the area by restricting superficial projects and preventing owners in that particular area. Raising awareness not only among decision-makers, but also among the local people was one of the objectives of the HAZARM project.

The research team considers that the results obtained in the studied area can be extrapolated to the entire north-east rural area of Romania, and can even be applicable to the majority of rural areas in the country. The economic changes in Romania led to the exodus of rural populations towards big cities or foreign countries, leaving behind thousands of houses shattered and overseen by an old population that could not perform maintenance or current works.

6. Conclusions

The research presented in the article responds to the globalization direction regarding the elaboration of harmonized hazards and risk maps around the globe. According to international trends, it is recommended to avoid using a one-hazard approach but rather a multi-hazard one. For this reason, the article considers floods, landslides, and earthquakes as natural hazards because, from a historic point of view, they are the most frequent ones in the studied area. The work presented is only for Romanian territory, but similar results were also obtained for the Republic of Moldova. On the joint hazard and risk maps, common risk mitigation plans will be developed.

If a hazard map usually presents characteristics of a possible event (for floods: area that could be flooded, the depth of the water, the speed of the water, for landslides: areas with slip potential: medium, medium-high, and high classified based on the Km factor value, for earthquakes: magnitude, acceleration, depth), the risk maps give information regarding the event consequences (damages and losses).

From the research carried out on the Ungheni area, it was found that Mînzătești and Coada Stîncii are the most vulnerable to all three hazards. Outside these settlements, in the same slope regime, the landslide risk is significantly reduced due to land cover with forest vegetation. This suggests that the average slip coefficient could be reduced by afforesting available areas. At the same time, in the case of flood risk modeling, the roughness of the surfaces on which the flood waves propagate, expressed in Manning numbers, has a positive influence in the sense that their value increases, if the respective areas are covered with forest vegetation; therefore, multi-hazard analysis can lead to more effective prevention decisions given the potential for a positive impact of some measures in order to reduce several hazards (floods, landslides) by a single measure, in this case afforestation.

The existing landslide hazard maps in Romania were modeled on DEMs obtained by digitizing the basic plans at SC 1:5000. In the present study, the source of the altimetric data was the LSA, which was also the basis for flood hazard maps, being superior in terms of geospatial accuracy, thus obtaining better sliding hazard modeling. Adding to these findings the seismic risk of the area and taking into consideration the damage level on the building stock, it can be concluded that many of the buildings do not comply with seismic requirements, being susceptible to suffering damage even in the case of a small earthquake.

The risk assessment for the studied natural hazards was made on the same geospatial database, CNC 2015 edition, obtaining a homogeneous assessment from a geospatial point of view; therefore, it can be seen that a multi-hazard approach can lead to significant benefits from the shared use of geospatial data sets.

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