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Multi-risk assessment in transboundary areas: A framework for harmonized evaluation considering seismic and flood risks

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A R T I C L E I N F O

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A B S T R A C T

Effective disaster risk management would require the analysis and the comparison of relevant risks potentially affecting a territory, also considering possible interactions among them (e.g., cascading effects). Modelling such interactions may be complex, increasing the challenge to perform exhaustive multi-risk assessment. Independent analyses are often performed for the analysis of multiple risks in a given area. However, as usually for the analysis of different risks, different methodologies and different impact metrics are adopted, results of single-risk analyses may be not comparable. The problem of comparability is exacerbated in cross-border areas, where additional challenges in risk analysis arise due to the diversity of databases and risk analysis models in neighboring countries.

This paper presents the approach for multi-risk assessment proposed within BORIS project (Cross BOrder RISk assessment for increased prevention and preparedness in Europe). Focusing on seismic and flood risks, this project aims to develop a shared methodology for cross-border multi-risk assessment in Europe. Adopting a single-layer multi-risk approach, each risk is assessed through independent analysis, but the procedures for risk assessment are harmonized in order to ensure their comparability. Also, the issue of transboundary assessment of single risks is addressed. The proposed methodology is applied in two regions in the cross-border area between Italy, Slovenia and Austria, demonstrating the usefulness of the BORIS approach for multi-risk comparison and ranking. Acknowledging the need to improve coordination between neighboring countries, the methodology of the BORIS project also reflects certain compromise solutions that allow its ease application and exportability to other countries.

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1. Introduction

To fulfil and enhance prevention and the risk management process, there is a need to perform regular risk assessment and analyses of disaster scenarios at the national and subnational level (Decision No. 1313/2013/EU, REGULATION (EU) 2021/836). Indeed, the activities devoted to improving knowledge and understanding of risk assessment, also promoted by the first priority of action of the Sendai Framework for Disaster Risk Reduction 2015–2030 [1], are at the base of consequent actions of prevention, mitigation, preparedness and response. Risk analysis is useful for the preparation of Civil Protection plans and/or Emergency plans at the level of local communities (e.g., municipalities or larger provincial districts) or even for broader cross-border areas when transnational planning for land use or investments in risk reduction is foreseen. Risk analyses can also help to improve preparedness for dealing with disasters, as they can facilitate efforts such as exercises and training organized based on pre-determined scenarios.

When different hazards threaten the same region, a joint analysis of the most relevant risks should be performed for a proper understanding of their possible impacts, to prepare suitable Civil Protection plans and put in place effective mitigation actions. For a complete Multi-Risk Assessment (MRA), risks derived from different perils potentially hitting the same area should be compared and ranked, and possible risk interactions due to simultaneous or cumulative occurrence of hazardous events over time should be considered as well [2,3]. Risk interactions can refer to both hazard and vulnerability level interactions [4]. Specifically, the multi-hazard concept may refer to (1) the fact that different sources of hazard might threaten the same exposed elements (with or without temporal coincidence), or (2) one hazardous event can trigger other hazardous events (i.e., cascade effects). On the other hand, the multi-vulnerability perspective may refer to (1) a variety of exposed sensitive targets (e.g., population, infrastructure, cultural heritage, etc.) with potentially different vulnerability degrees against the various hazards, or (2) time-dependent vulnerabilities, in which the vulnerability of a specific class of exposed elements may change with time as a consequence of different factors [5]. The difficulties in modelling hazards interactions and their potential interrelated effects impair the effective realization of MRA in its complete acceptation. Thus, the evaluation of risks derived from different sources is generally performed through independent analyses [6–8]. However, the analysis of risks derived from different sources often requires the use of different methodologies and spatial scale resolution, as different hazards may differ in their nature, return periods, intensity and impacts. The consequence of such inherent differences is that also the metrics commonly adopted to measure the risk are very different and hardly directly comparable. In Ref. [9], a first step towards a full multi-risk assessment is proposed, consisting in analyzing and comparing two or more hazards potentially affecting a given region without explicit consideration of their possible interactions, but harmonizing and standardizing the assessment procedures among the different perils. In other words, independent analyses can be performed for each risk, but the same boundary conditions (e.g., the time frame of analysis and the metric for risk evaluation) should be established a priori to ensure their comparability. This approach is known as multi-layer single-risk assessment. Even if ignoring possible interaction among hazards may lead to underestimating the overall risk, the understanding of the relative importance of different risks in a given area is just as important to assist decision-makers in the field of disaster risk management. Zschau [9] also proposes some tools to standardize risk assessment in the framework of multi-layer single-risk analysis: risk matrices, risk indices, and risk curves. Risk matrices adopt a qualitative or semi-quantitative approach for classifying and ranking risks, often preferred due to their simplicity and ease of communication [10,11]. Such tools are often adopted to represent the results of multi-risk evaluations performed in the framework of National Risk Assessment, as in Refs. [12–14]. However, they are often criticized due to the subjectivity in risk scoring, i.e., the scoring of the risk matrix may be influenced by subjective risk perceptions [15]. Risk indices are widely used as classification schemes for hazards [16,17], vulnerability [18,19] and risk [17,20]. They are also useful for measuring the multidimensional risk concept to support decisions about prevention, preparedness and response [21,22]. However, they do not allow a proper quantification of risk in terms of expected impact and losses.

Risk curves graphically represent the level of impact expected to be exceeded (horizontal axis) due to hazard events having a certain mean annual frequency of exceedance in a given time period (vertical axis). Evaluated with a probabilistic approach and expressing the expected consequences in a given metric, risk curves represent the most appropriate tool for consistent quantitative assessment of the single risks towards their effective comparability. However, to the authors' knowledge, there are very few applications of risk curves in the framework of MRA [7,23], and none of them is performed in a cross-border region.

Within the BORIS project (Cross BOrder RISk assessment for increased prevention and preparedness in Europe), a shared and harmonized framework for cross-border multi-risk assessment adopting risk curves as a tool for representing the results of single-risk analysis was proposed and applied in two pilot regions. Funded by DG ECHO (Directorate-General for European Civil Protection and Humanitarian Aid Operations) and finalized in December 2022, this project aimed to improve the understanding of the disaster risk with a particular focus on transboundary areas and also considering multi-risk issues. Global models that allow for the estimation and representation of risk and losses for broad regions over the world already exist (e.g. GEM [24], Risk Data Hub [25,26]). However, cross-border risk assessment presents an additional important challenge in disaster risk management. The scale of analysis for transboundary assessments, tailored to the needs of the countries sharing the border, may be quite smallerthan that used in the global models. Results of global models transferred to smaller regional/local spatial scales may therefore be of lower interest, especially if more refined models are available in the considered confining countries (e.g., Refs. [45,52,61]). As noted in Ref. [27], the models used in different countries to assess various relevant risks can be different. For example, referring to seismic risk, the hazard models may refer to different intensity measures and return periods, different criteria for buildings classification and methods to build fragility curves may be adopted, and variable granularity for building exposure assessment may be used. Similar issues arise when dealing with other risks. This could hinder international and transboundary cooperation towards disaster risk reduction. Thus, when dealing with risk assessment in transboundary regions, it is crucial to harmonize the methodologies and tools used for consistent single-risk evaluation before performing a multi-risk analysis. Harmonization issues are even more challenging when dealing with MRA

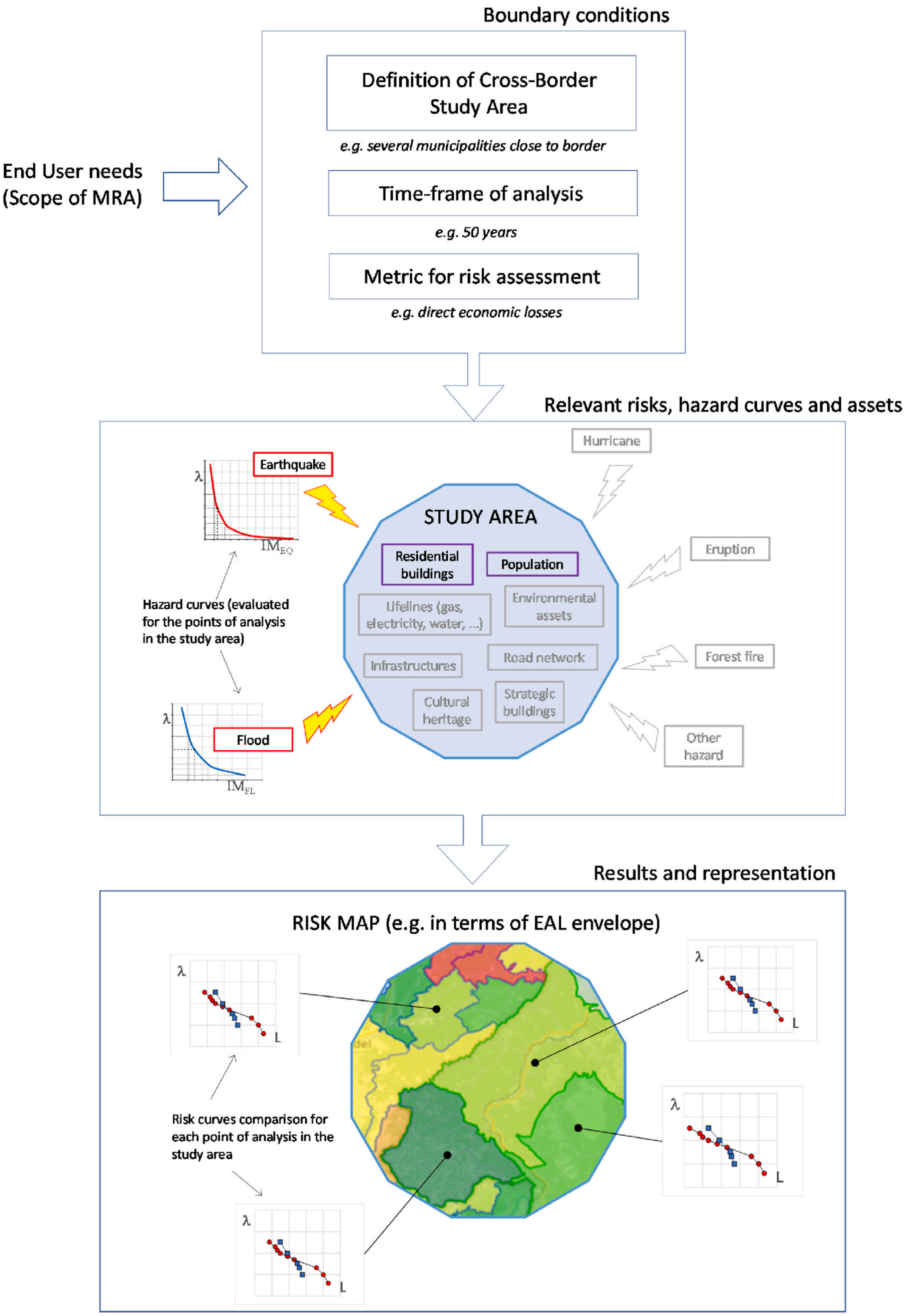


Fig. 1. Main steps of BORIS approach for multi-risk comparison and ranking.

because of the need to standardize procedures among different risks.

Specifically, the BORIS project focused on developing a) a harmonized methodology for assessment of both seismic and flood risk in cross-border regions b) a shared methodology for multi-risk comparison and raking in transboundary areas.

This paper presents the methodology developed within the BORIS project for multi-risk comparison and ranking and its application in two transboundary areas. First, the steps of the proposed multi-risk approach and the required inputs are described. Harmonization issues arising from the performing of multi-layer single risk analysis are pointed out, specifically dealing with the two risks considered in this study, i.e., seismic and flood risk. Then, the proposed methodologies for cross-border single-risk harmonization and for the multi-risk assessment are demonstrated through their application in two study areas. The cross-border areas considered in the case studies are located at the Italian–Slovenian and Slovenian–Austrian borders. Historically, these regions have been hit by many severe earthquakes, but are also prone to hydro-meteorological hazards (e.g., floods, flash floods). For each municipality in the analyzed regions the risk curves are built, allowing the comparison of annually expected monetary losses due earthquakes and flood in the area.

2. A shared framework for multi-risk assessment in cross-border regions

Within the BORIS project, a methodology for implementing MRA in the framework of multi-layer single-risk analysis in cross-border areas was proposed. In the field of multi-layer single-risk assessment, each risk is assessed through independent analysis, and the results are compared using suitable standardization tools. Fig. 1 synthetizes the approach for cross-border multi-risk analysis and representation adopted in the project.

To ensure risk comparability, certain aspects such as the area of interest, the type of the analysis (i.e., time-based or scenario-based) and the time frame for risk assessment as well as the common metric for evaluating risks are required to be established a-priori, consistently with end-users needs [2]. For instance, if scenario-based approach is employed for one risk evaluation, i.e., impacts are estimated based on a single hazard scenario characterized by specific event magnitude and its associated location, scenario-based approach should be adopted also for assessing other risks. However, this kind of approach could be hardly applicable in a multi-risk framework, due to the difficulty to find or simulate historic scenarios having comparable likelihoods for considered risks and because such an approach does not account for the relative difference between the consequences of different hazards scenarios with varying mean annual return period. On the contrary, in a probabilistic time-based risk assessment, all possible hazard events are considered with their associated probability of occurrence. Given the rates at which various hazard's magnitudes are expected to occur, the exceedance rate of losses can be estimated considering the probability of loss exceedance conditioned by the occurrence of each hazard events with a defined annual frequency of occurrence [28]. Moreover, for a consistent risks comparison, single-risk assessments included in the multi-risk assessment should focus on the same risk elements (e.g., residential buildings).

With the aim to enhance prevention with a better understanding of disaster risk, in BORIS a (probabilistic) time-based assessment is performed; this means that "unconditioned" risk is estimated (as opposed to the risk "conditioned" to a given return period) considering all the possible events, with associated return periods, that could occur in a pre-defined time window, e.g. 50 years or 1 year. This approach allows to increase preparedness facilitating preparation of Civil Protection plans at the level of local communities (e.g., municipalities or larger provincial districts) or even for broader cross-border areas when transnational planning for land use or investments in risk reduction are foreseen. The time interval for risk analysis should be chosen depending on the final goal of the risk analysis, as well; for instance, it can be set to decades or centuries for land use planning, years for studies aimed at prioritizing risk mitigation actions or days/weeks to manage an ongoing emergency. Thus, a reasonable time frame for the defined needs (i.e., prevention and preparedness) can be set to 1 or 50 years. Moreover, as the focus of the project is to develop a common and harmonized framework for transboundary risk assessment towards improved prevention and preparedness at the regional level, rather than being limited to a local city or district, the study area comprises an assemblage of municipalities close to the border of confining nations. Thus, unlike other examples of MRA presented in the literature (e.g., Refs. [2,7]), BORIS approach is meant to be applied to wider (cross-border) areas, allowing not only to understand which risk mostly threatens a given municipality but also to understand which municipalities are more threatened by a specific risk. Although other previous studies dealt with multi-risk assessments in a multi-country perspective [8], as discussed above the "global" perspective may miss the focus that might be needed for transboundary risk evaluation.

The choice of assets to consider in risk analysis depends primarily on the specific risks to be managed and possibly mitigated. For civil protection authorities, the number of exposed buildings, the degree of damage and economic loss, as well as an estimate of human casualties, the disruption of critical infrastructure such as electricity, road, and water networks are of high interest [29,30]. Direct economic losses due to residential buildings' damage (i.e., costs related to the repair or reconstruction of residential buildings) constitute about 50 % of the total costs after earthquakes [31]. In the case of flood, damages to other assets (e.g. vehicles, household goods, environmental goods) as well as indirect losses related to economic activities [32,33] may be as relevant as damages to buildings. While focusing solely on residential buildings might be perceived as a limitation, evaluating losses associated with such assets is a challenging task and direct economic losses related to damages to residential buildings remain one of the primary risk metrics used in flood risk assessment (e.g., Ref. [8]).

Thus, in this study direct economic losses due to residential buildings damage is selected as common risk metric to compare and rank seismic and flood risks in the selected cross border regions. This choice was adopted also in other studies; for example, in Ref. [8], presenting a comprehensive large-scale application in the Middle East, the metric for multi-risk assessment was the economic losses for the residential building stock due to earthquakes and floods.

Both the direct economic losses (associated to buildings' damage) and the affected population (meaning the number of people potentially affected) can be considered as indicators that give a useful measure of the expected hazards impact. Hence, in addition to the affected population, residential buildings are considered as exposed asset categories.

As discussed before, risk curves represent the most suitable tool for a quantitative multi-risk assessment comparison. They allow performing quantitative assessment of the single risks in a consistent manner, allowing comparability of single risks avoiding the bias of subjective choices affecting other approaches such as risk matrices. Therefore, they were used in BORIS for comparing and ranking risks in cross-border areas.

The steps of BORIS multi-risk analysis (adapted from Ref. [2]) can be summarized as follows:

1. Definition of the study area and time window for the risk assessment;
2. Identification of the risks impending on the selected area;
3. Definition of relevant assets at risk in the study area and selection of the metrics for expressing risks;
4. For each risk analyzed (no hazard or vulnerability interactions are considered for multi-layer single-risk analysis):
   - selection of hazard curves (or hazard maps) for the considered risks covering all possible intensities for each point of analysis in the study area;
   - vulnerability and exposure assessment for the considered assets at risk in the study area;
   - probabilistic assessment of each scenario (i.e., for each point of the hazard curve) and calculation of losses through consequence functions;
5. assemblage of risk curves and comparative loss estimation for each point of analysis in the study area;

As the project focuses on cross-border areas, the first step to perform multi-risk analysis in cross-border regions is to ensure harmonized transboundary single-risk assessment. As a matter of fact, even if no hazard or vulnerability interaction is considered and different analysis can be performed for assessing the two risks, to obtain consistent single-risk analysis results in cross-border areas, the same models for hazard, vulnerability and exposure should be employed. For instance, models used for seismic hazard in countries at the border may differ for the intensity measure adopted (Peak ground acceleration - PGA - vs macro-seismic intensity), for their spatial scale resolution (i.e., Different mesh grid for hazard values) or for local effects on ground-motion intensity considered (if micro zonation for site amplification is available). Likewise, flood hazard maps adopted in neighboring countries may differ as well. The Floods Directive (2007/60/EC) requires Member States to map the flood extent, specifically developing hazard maps according to three probability scenarios: low probability (extreme events), medium probability (likely return period ≥100 years), high probability. Despite the preparation of flood hazard maps according to Floods Directive may ensure a certain level of consistency across European countries, neighboring countries often consider different flood return periods and different combinations of intensity parameters for the definition of the low, medium, and high flood hazard classes. Similar discrepancies can be observed between seismic and flood vulnerability models adopted in cross-border countries in Europe. Thus, specific procedures towards a harmonized cross-border seismic and flood risk assessment were proposed in BORIS, as described in sections 3.1 and 3.2.

The adoption of harmonized methodologies for cross-border single-risk assessment and the definition of common boundary conditions for the analyses implicitly ensures the satisfaction of some of the requirements for cross-border risk comparability. For instance, both seismic and flood risk assessments focus on residential buildings and population as assets at risk, probabilistic (time-based) assessment is performed, adopting as input the hazard curves or hazard maps at specific sites and expected impacts are expressed in terms of direct economic losses (related to buildings' physical damage) and affected population. Nevertheless, as independent risk analyses are performed, the scale of analysis at which each risk is assessed could be still different. Also, the harmonization of consequence functions adopted for single-risk impacts evaluation is crucial to ensure a consistent comparison of risks. These issues will be addressed in the following sections (2.1 and 2.2), while in section 2.3 the use of the risk curves for comparing and ranking risks is shown.

2.1. Metrics

Despite seismic and flood risks are expressed through the same metrics, i.e., direct economic losses, they may be still not directly comparable. Indeed, direct economic losses due to earthquakes for residential buildings, expressing the costs related to their repair or reconstruction, are usually related to damages to structural elements [34]. On the other hand, such metric referred to floods usually include both the repair costs of building damages (i.e., structural damages) and the replacement costs of existing household goods [32, 33]. Thus, for comparing the two risks, the losses expressed in monetary terms should be estimated consistently, e.g., as function of the expected structural damage on buildings to be repaired, considering the same unit costs of such repair actions. This means that only vulnerability curves related to structural damages should be used to estimate losses due to floods, while damages to contents should be neglected. Furthermore, the affected population in case of flood is often estimated as the number of people located in the flooded area. In case of earthquake, the estimated number of homeless, injured and deaths are related to direct damages to buildings. Specifically, homeless can be estimated as inhabitants in buildings considered unusable, while deaths and number of injured people can be estimated as a percentage of inhabitants in collapsed or severely damaged buildings. On the contrary, a similar estimation would not be significant for flood risk since people affected are not only related to buildings' damage. A possible approach to allow comparability between seismic and flood risk indicators in terms of affected population could be to consider the affected population due to seismic events as the number of inhabitants residing in buildings having a given damage level (e.g., non-zero damage due to earthquake); however, further judgement and considerations are needed towards a more consistent comparison. For this reason, the BORIS approach was to compare and rank risks only in terms of direct economic losses due to (residential) buildings' structural damage.

2.2. Spatial scale

The optimal spatial scale considered in the risk assessment for one hazard can be different from the optimal spatial scale considered in the risk assessment for another hazard [35]. The scale of analysis refers to the basic territorial unit at which risk is calculated. This scale should be small enough to enable the use of the risk assessment results in the decision-making process, which is particularly challenging in the cross-border risk assessment. On the other hand, also the availability of exposure data in cross-border countries plays a role in the selection of the spatial scale. For example, in Italy, information on buildings and population are provided by National Institute of Statistics [36] at census tract level, but disaggregated data on construction material, age of construction and number of storeys are available only at municipality level. In Slovenia, Real Estate Register [37] provides building-by-building data for the entire country. Therefore, in BORIS project, the municipality level was selected as harmonized spatial scale for seismic risk analysis, and data in the country with a more refined spatial scale were aggregated. This scale of analysis can be considered adequate for seismic risk assessment but less for flood risk assessment. This is because floods varies spatially (e.g., inundated area extension) much more significantly than the seismic hazard within a given municipality. The extension of flood prone areas depends on several factors such as the characteristics of the hydrographic basins and the morphology of the study area. Therefore, for flood risk assessment, it is crucial to characterize the exposure at a lower scale. For this reason, exposure data for flood risk were evaluated at the building level, associating available global information to building footprint through downscaling procedure [38]. Nevertheless, as no hazard or vulnerability interactions are considered in the multi-layer single-risk approach, the spatial scales used in the two different single-risk assessments do not yet need to be harmonized. The harmonization of the spatial scales used to present the consequences of different hazards can be performed according to the principle of the common denominator. This means that the spatial scales that are used in the single-risk assessments can differ, but they should allow the aggregation of the consequences to the same spatial units. For instance, it can be acceptable if the consequences of the flood hazard are initially estimated at the micro-scale level (e.g., building level) and the consequences of the seismic hazard are estimated at the macro-level (e.g., municipality level) as long as the results of the flood risk assessment can be aggregated to the same macro-level. At the same time, one should be aware that the selection of the spatial scale may affect the ranking of different risks. In the case of the seismic and flood risks ranking, this problem appears because the flood risk is condensed mainly near the river network while the seismic risk expands over a wider area. Therefore, increasing the spatial scale in a way where the spatial units are expanded to the areas away from the river network would intensify the seismic risk while not significantly affecting the flood risk.

In the BORIS project, it was decided to define the spatial units by individual municipalities, which is also the lowest level at which administrative decisions are taken. Also, such a spatial scale is considered sufficiently small to provide risk results that can guide the end-users towards rational decision-making. Therefore, different analyses at different scales are performed for seismic and flood risk assessment. For seismic risk, municipality level is selected as the scale of analysis; the exposure model defines the number of buildings belonging to each building typology (construction material, classes of height, period of construction) at municipal level. It should be noted that with this approach the classical PSHA-based risk calculation is employed, with the output of the point-wise risk analysis expressed at each location (coinciding with the centroid of the municipality).

For flood risk, building level is selected as scale of analysis; the exposure model defines the attributes for each building in terms of height, occupancy type and presence of basement (if the latter information is also available). It is worth mentioning that for multi-risk assessment purposes the vulnerability classification ideally would involve factors crucial for the identification of both seismic and flood vulnerability. However, as no interactions at vulnerability level is considered (accordingly to the multi-layer single-risk assessment) and the scale of analysis adopted is different, there is no need to adopt a uniform vulnerability classification.

2.3. Risk curves

Risk curves relate the level of impact that will be surpassed in a given time period with the actual probability. They are also called exceedance probability curves or Loss Exceedance Curves (LEC) and they are the usual output of the full probabilistic approach [6]. Hazard curves report the Mean Annual Frequency of Exceedance (MAFE), or mean rate, λ, of a relevant Intensity Measure (IM) (e.g., peak ground acceleration for earthquakes or water depth for floods). The mean rate of exceedance λ can be related to the probability of

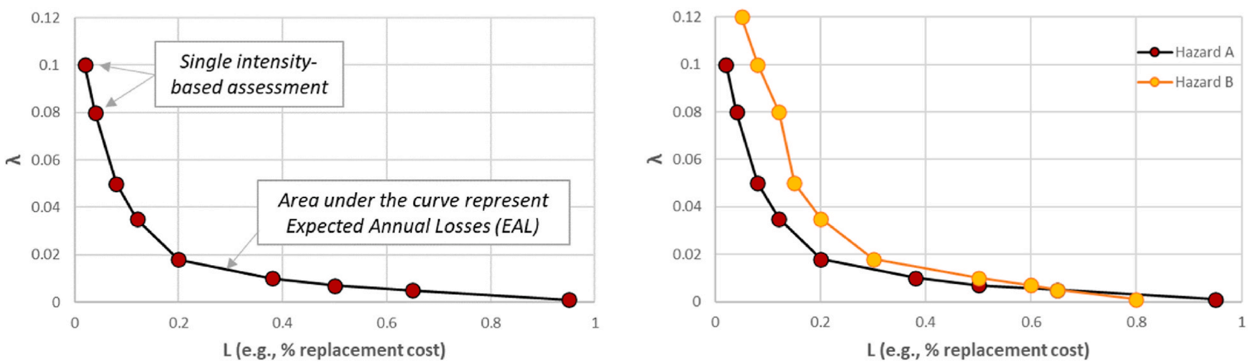


Fig. 2. Example of Risk curve (left), also known as Loss Exceedance Curve (LEC). Vertical axis shows the annual frequency of exceedance λ, while the horizontal axis displays the expected loss L (in terms of % replacement cost). An example of possible use of such curves for risks comparison and ranking is also shown (right).

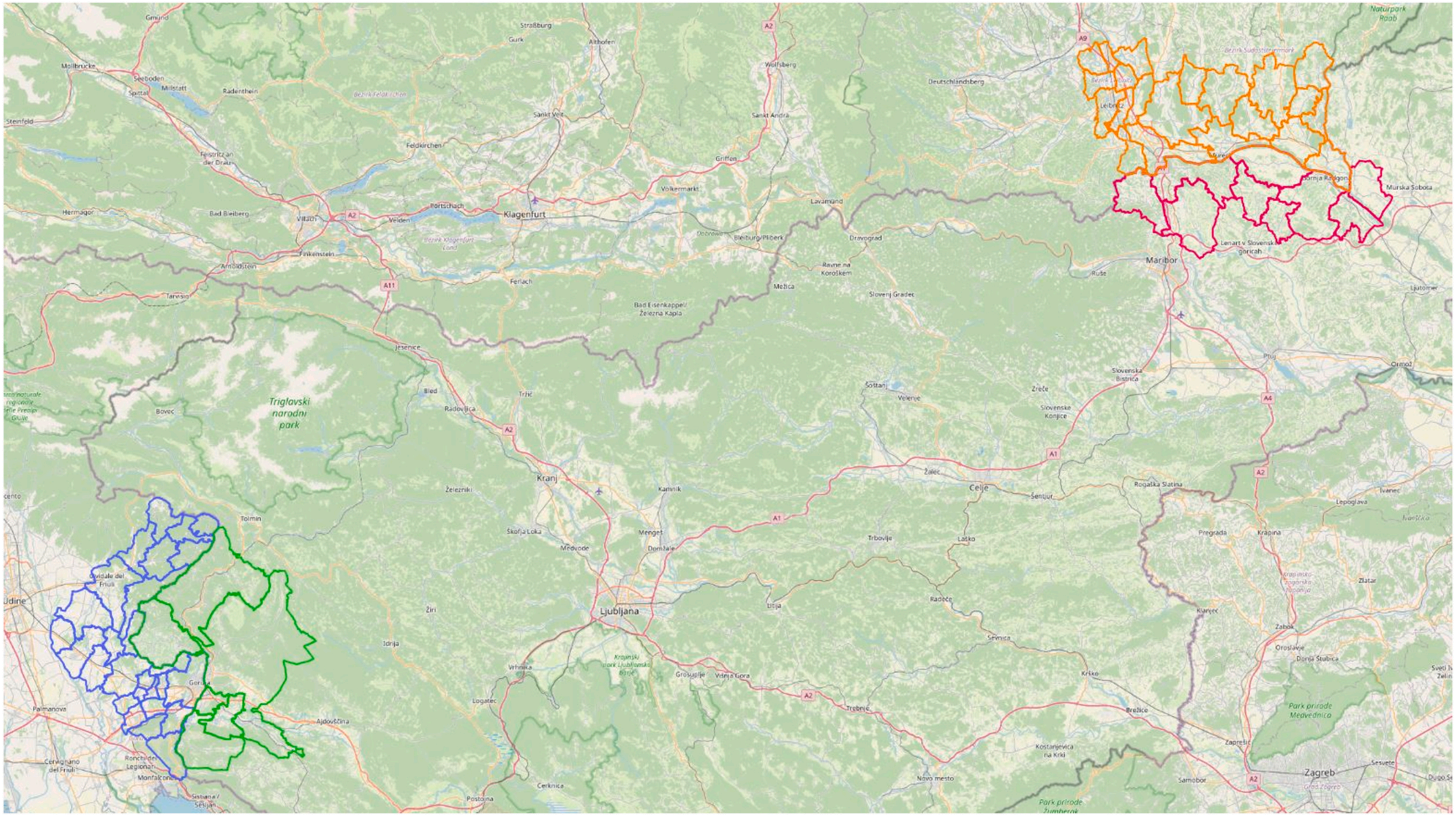


Fig. 3. Selected municipalities at Italy-Slovenia and Austria-Slovenia border.

exceedance (P_t) in t years by using a Poisson recurrence law:

$$P_t = 1 - e^{-\lambda t} \tag{1}$$

Using a series of intensity-based assessments, each intensity has a corresponding loss quantity. The loss quantity generically represents a consequence of the event, e.g., direct economic losses, the number of displaced or homeless people, injured or deaths. Such losses can be determined by adopting suitable consequence functions (see also sections 3.1.4 and 3.2.2). Once the parameter representing loss is chosen and the methodology for its calculation is established, given the hazard curve, the corresponding LEC can be calculated. As example, Fig. 2 (left) shows a risk curve, or LEC, where the loss parameter is represented by the expected percentage of replacement cost L.

Selecting a common reference metric, the different risks can be ranked on the basis of their probability to originate relevant thresholds of such loss. As example, Fig. 2 (right) shows the comparison of risk curves due to two different hazards A and B considering L as the loss parameter.

Thus, risk curves can be used to compare risks with reference to a specific exceedance probability of hazard action in t years. For instance, it is possible to identify which is the dominant risk for high probability/low loss events as well as to which is the dominant risk for a given return period of interest (e.g., 200 years). Furthermore, risk curves give the possibility to compare risks using Expected Annual Loss (EAL) as overall measure of risk. The EAL, also indicated as Average Annual Loss (AAL), represents the long-term average of the losses in one year and is determined by combining the expected losses at each intensity level with the expected annual probability, i.e., by calculating the area under the LEC curve (see Fig. 2, left).

In BORIS, EAL value is adopted as global measure of risk for comparing and ranking risks in a given area. As direct economic loss is the risk metric used, EAL expresses the average monetary losses (€) expected in 1 year due to buildings structural damage caused by earthquakes or floods.

3. Applications in neighbouring countries

The proposed methodology for harmonized single and multi-risk assessment is applied in two transboundary regions at Italy-Slovenia and Austria-Slovenia borders. The study area defined at the border between Italy and Slovenia includes 27 Italian municipalities and 6 Slovenian municipalities, located close to the cities of Gorizia in Italy and Nova Gorica in Slovenia (Fig. 3, blue and green polygons). The Slovenian and Italian parts of the area are comparable in terms of geographic extension. The selection of these municipalities was made on the basis of the path of the two main rivers in the transboundary region, i.e., the Isonzo River and the Vipava River, which are responsible for significant flood risk on both sides. In addition, among the selected municipalities there are some affected by the passage of the Natisone and the Torre River on the Italian side and by the Vrtojbica River on the Slovenian side, as well as the passage of their tributaries. The area is also prone to earthquakes; as example, the devastating earthquake of magnitude 6.5 occurred in 1976 in northern municipalities in the Italian side can be recalled.

The study area defined along the border between Austria and Slovenia (Fig. 3) encloses 21 municipalities on Austrian side of the border and 9 municipalities on Slovenian side; river Mur flows at the border between the two countries. The pilot area has a rather rural character with municipalities with detached buildings, but also more urban areas with towns such as Bad Radkersburg and Leibnitz (AUT) and Gornja Radgona (SLO). These municipalities were selected because they are located in the Austrian-Slovenian border region and in the catchment basin of the river Mur and its tributaries, which is an important part of the exposure to natural hazards in this area. Seismic hazard on Austrian side of the border is lower with respect to that on the Slovenian side.

A time-based risk assessment is performed separately for the two considered risks (i.e., seismic and flood) and the results in terms of direct economic losses are compared through risk curves and risk maps in each unit of analysis, namely each municipality in the pilot areas. First, the harmonized methodology for cross-border single-risk assessment is adopted to perform seismic and flood risk analysis in each study area. Then, risks are compared based on the expected value of direct economic losses, using both risk curves and maps reporting the EAL values for each studied municipality.

Data sources adopted for large-scale and cross-border risks assessments are specified in the dedicated sections. Further information on the availability of data used can be found in Ref. [39].

3.1. *Cross-border seismic risk assessment in pilot areas*

3.1.1. *Hazard*

In the case of cross-border analysis, in order to ensure consistency in the assumptions made in the hazard modelling across borders, it is recommended that a single transnational model is used instead of multiple national models. In BORIS, the ESHM2020 [40] is adopted as a common seismic hazard model. The outcomes of this model include hazard curves for PGA exceedance probabilities in 50 years for rock-equivalent outcrop motion. Hazard disaggregation schemes is available for more than 120,000 sites equally spaced at 10 km across Europe and Turkey. For the current analysis, a single hazard curve was used for each municipality in the cross-border area. The local soil effects are considered by applying amplification factors based on different soil classes as defined in Ref. [41]. In Italy soil map containing Vs30 values comes from Ref. [42], which allows to estimate the proportion of different soil types in each municipality. For the Slovenian municipalities a Vs30 map is not available and soil classes according to the [41] have been estimated at all locations of buildings based on the known geological characteristics and past studies [43–45]. A global Vs30 map produced by USGS [46] is utilized in the Austrian area to define soil class map, as the local Vs30 maps or studies on local geological characteristics are unavailable.

3.1.2. Exposure

The exposure model defines the classification of the assets at risk based on the parameters that have a relevant influence on seismic vulnerability [47,48]. In this paper, the focus is on (residential) buildings, which can be classified based on the material of the load-bearing structure (i.e., masonry, reinforced concrete – RC, other), the number of storeys and the construction period. Three periods of construction, reflecting the evolution of seismic codes in the countries involved (pre-1964, 1965–1982, post-1982), and two height classes (1-3 storeys,≥4 storeys) are considered. Buildings with "other" material of the load-bearing structure include steel and timber buildings, as well as all other buildings with a mixed load-bearing structure made of a combination of masonry and reinforced concrete. As these kinds of structures are not very widespread in the countries considered, they were distributed into the classes of masonry and RC buildings, as proposed in Ref. [34]. The exposure model gives the total number of buildings and their proportions in different vulnerability classes in each territorial unit of analysis, i.e., in each municipality of the pilot area. In addition, the exposure model of a building portfolio gives the characteristics that affect the consequences, such as the floor area, which is related to economic losses. These data are derived at the municipal level from National Institute of Statistics [36] in Italy and from Real Estate Register [37] in Slovenia. For compiling building inventory in Austria, available data on residential buildings collected in the AGWR (Building and Housing Register of Statistics Austria) from the province of Styria are used. The AGWR data provided by Statistics Austria should theoretically provide the data needed to identify the building typology in terms of construction material (masonry, RC and other types), construction period and number of storeys. However, it was found that there is a great lack of data about the main construction material used for the buildings, spanning from 40 to 80 % in total for the Pilot Region. Therefore, expert interviews were conducted to assign a material type to all buildings without material classification, adopting the Cartis method [49]. As also building-class-specific floor areas are unavailable in Austria, the floor area for each building typology is estimated based on the total floor area in the given municipality and by considering the ratios between building-class-specific floor areas in the Slovenian and Italian municipalities in both cross-border areas.

Residential buildings in Italian municipalities of the Italy-Slovenia study area are almost double of the buildings on the Slovenian side (27611 vs 12892). On both sides of the border, the prevailing structural type is a two-storey masonry building (69 % and 93 % respectively for Italian and Slovenian side). Buildings in the Italian municipalities are on average slightly older than those in the Slovenian area, with 67 % of masonry buildings and 24 % of RC ones built before 1945, against the 46 % (masonry) and 10 % (RC) of Slovenian municipalities (Fig. 4). Most of the residential buildings (both masonry and RC) in the area are medium-high (i.e., 2–3 storeys). It is also interesting to note that while on the Italian side of the border the percentage of buildings made of RC is relevant (31 %), the percentage of such buildings on the Slovenian side is only 7 %. This is probably due to the blanket reconstruction done in Italy after the mentioned 1976 Friuli earthquake.

The total number of exposed residential buildings on the Austrian side of the second study area is 22897, while there are 12817 buildings on the Slovenian side. Most buildings are masonry structures (87 % on the Austrian side of the border and 95 % on the Slovenian side) and only few buildings are of the RC type (13 % and 5 % for the Austrian side and Slovenian side, respectively). Fig. 5 shows the main characteristics of residential buildings in the area in terms of construction material and period of construction. It can be noted that on both sides of the border, many buildings were built after 1982.

3.1.3. Vulnerability

The vulnerability model is defined by a set of fragility curves, indicating the probabilities of assets at risk exceeding the designated damage states, considering a building classification consistent with that from the exposure model. The EMS-98 [50] is the damage scale used in this application. As the HAZUS damage scale [30] is used in the Slovenian vulnerability model [45], the conversion to the EMS98 scale is performed adopting the approach proposed by Ref. [51]. Fragility curves adopted at the national level in cross-border countries, even if referring to the same material of the load-bearing structure, may differ due to the differences in the methodology used for developing the curves (e.g., empirical or analytical methods) as well as the characteristics of buildings for which such curves are derived. For example, fragility curves for reinforced concrete (RC) buildings usually adopted in Italy are specific for frame structures, as they are the most common type of RC structures in the country, but these curves may not be representative of the seismic

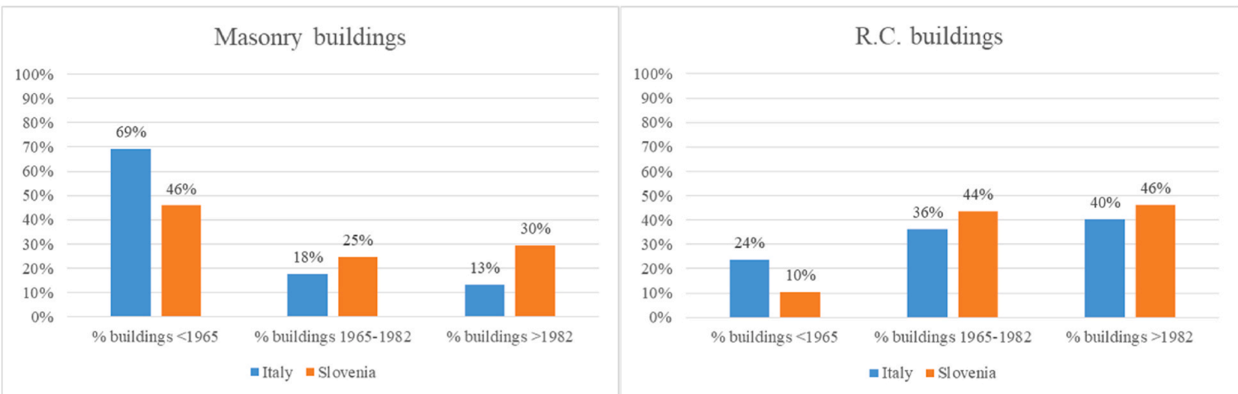


Fig. 4. Construction-period distribution in the study area at the Italy-Slovenia border for masonry buildings (left) and RC buildings (right).

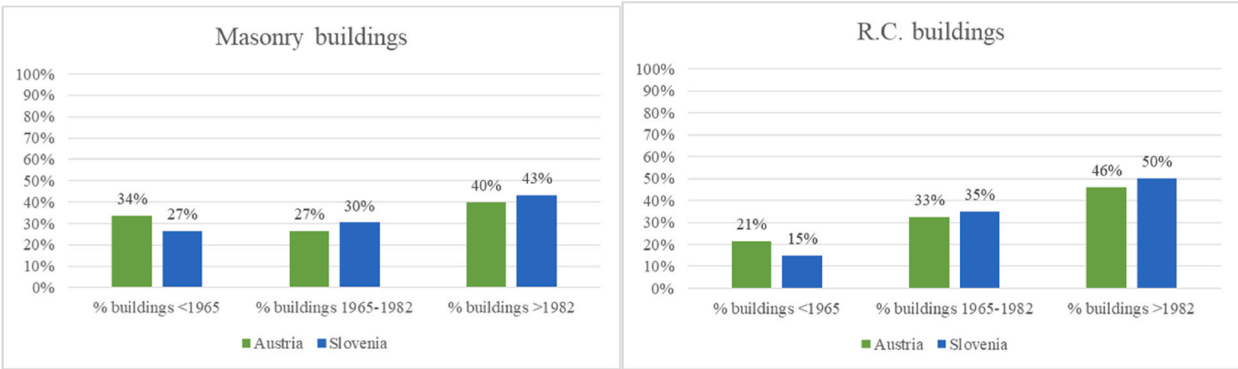


Fig. 5. Construction-period distribution in the study area at the Austria-Slovenia border for masonry buildings (left) and RC buildings (right).

performance of the Slovenian RC buildings, where RC shear walls are also widespread. Fig. 6 shows the comparison between Italian and Slovenian fragility curves for reinforced concrete buildings built between 1960 and 1982 with more than 4 storeys. The vulnerability model proposed in Ref. [52] was employed for RC Italian buildings, while the model proposed in Ref. [45] was used for RC Slovenian buildings. It can be noted that for Italian buildings the probability of reaching designated damage levels is higher, except for damage level DS2. This considerable gap may be explained by the mentioned differences in the reinforced concrete typologies adopted in the two countries. It is worth mentioning that the differences in the fragilities may also be due to differences in the methodology used for their derivation. Further comparisons between Italian and Slovenian fragility curves can be found in Ref. [53].

Therefore, in a cross-border risk assessment, the national vulnerability models should be harmonized. Within the BORIS project, a heuristic harmonization approach was proposed, in which the vulnerability model in a cross-border area is defined as a linear combination of the considered national vulnerability models. This approach defines different fragility curve parameters for each sub-area (side of the border in the cross-border area) and building class. The coefficients in the linear combination depend on (1) the similarities between the building typologies in the given sub-area and the two national territories as a whole and (2) the differences between the methodologies used in developing the national vulnerability models. More details on the heuristic approach adopted for harmonized cross-border vulnerability characterization may be found in Refs. [53,54]. As input of the approach, the Italian and Slovenian national vulnerability models are adopted [34,45]. In the other pilot area (i.e., at the Austria-Slovenia border), the Slovenian fragility curves are also used for Austrian municipalities, as no vulnerability model is available for Austria. In doing so, the differences in the evolution of seismic codes in the two countries are considered. In particular, based on the comparison of the codes evolution, the fragility curves developed for the Slovenian buildings built before 1964 are assigned to the Austrian buildings built before 1982. For the Austrian buildings built after 1982, the fragility curves developed for the Slovenian buildings built after 1982 are applied.

3.1.4. *Consequence model*

The consequence model is defined in terms of monetary losses as a function of the damage state. For the five damage states from the EMS-98 scale, the same percentage costs of building repair (relative to the replacement cost) are applied for both sides of the borders: 0.02, 0.1, 0.35, 0.6 and 1, respectively, based on previous studies [34,45]. However, the replacement cost is considered

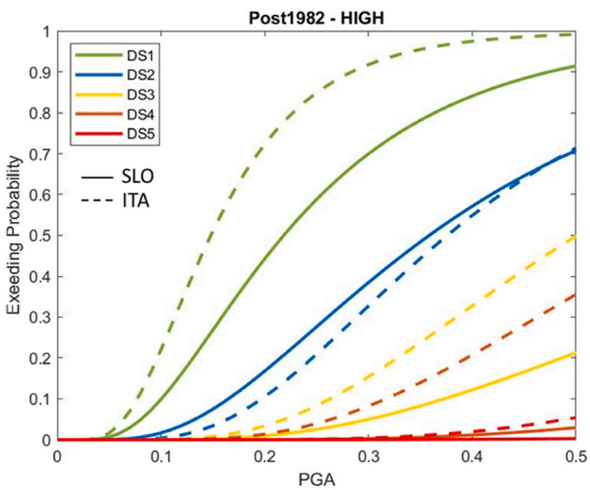


Fig. 6. Comparison between the Italian fragility curves (dashed lines) and the Slovenian fragility curves (continuous lines).

country-specific. For the Italian municipality, it is set to 1350 €/m^2 [34], while for the Slovenian municipalities it is set to 1250 €/m^2 [45]. In Austria this cost is assumed equal to Italian replacement cost.

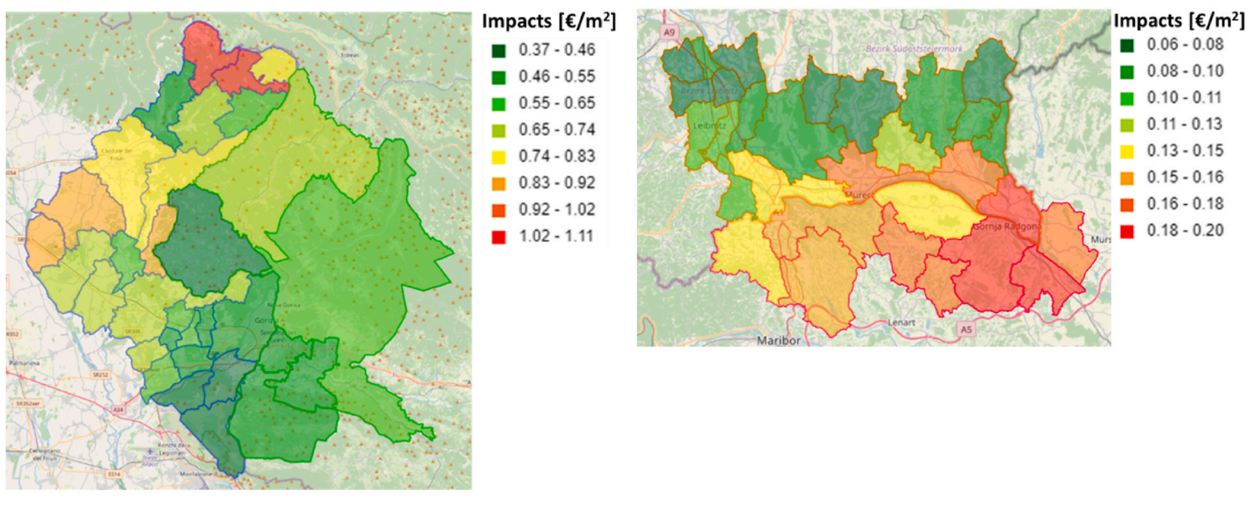
3.1.5. Results

To build LEC for each municipality, a series of intensity-based assessments are performed. Hazard intensity value at municipal level (the selected scale of analysis) is obtained considering the hazard grid points closer to municipal centroid and taking the average of related values weighted for their distance to the centroid (as coded in OPCM 3519/2006). For each municipality, the hazard curve for rock-equivalent outcrop motion is obtained by interpolating the PGA values associated with six different mean return periods (50, 101, 476, 976, 2500 and 5000 years) covered by the model (ESHM2020). The interpolation is performed log-linearly as the hazard curves are locally similar to linear functions in the logarithmic domain. The hazard curves for different soil classes are then derived by multiplying the PGAs from the hazard curve for rock-equivalent outcrop motion by the relative soil amplification factors according to Ref. [41]. For the intensity values along the hazard curves, the expected economic losses are then calculated by adopting exposure information, the vulnerability model and the consequence functions previously presented. The final losses for a given municipality is then obtained as weighted average loss of individual soil type adopting the proportions of the soil classes in the municipality as weights. Such intensity-based estimates (with their corresponding yearly frequency of exceedances) are used to build LEC curve and compute EAL.

Fig. 7 shows the map of economic losses per square meter in a time window of 1 year for both cross-border areas analyzed (i.e., EAL/m^2). In the Italy-Slovenia area, the highest values of EAL/m^2 are expected in the municipalities of Savogna (1.11 €/m^2) and Grimacco (1.04 €/m^2) in Italy. The variation in seismic risk is mostly influenced by expected hazard values. The highest seismic hazard is estimated for the northernmost municipalities on the Italian side, where the PGA for rock-equivalent outcrop motion from ESHM20 [40] for a return period of 476 years reaches 0.19 g. In the central and southern parts of the area, the seismic hazard is lower, with the 476-year PGA reaching 0.14 g, which refers to the moderate seismicity level.

Nevertheless, the exposure and vulnerability, i.e., the type and age of buildings in each municipality, also affect these results. Indeed, despite the Italian municipalities located in the north and two northernmost Slovenian municipalities, Nova Gorica and Kanal, having similar levels of seismic hazard, the expected losses for the Slovenian municipalities are lower. The reason is that the two Italian municipalities (colored red in the map in Fig. 7a) have no reinforced concrete buildings and the vast majority of the buildings were constructed before 1965 (i.e., old and vulnerable buildings). In contrast, for the two Slovenian municipalities mentioned above, the building stock is more diverse and includes more recent buildings, which are obviously less vulnerable than old masonry buildings.

For the Austria-Slovenia cross-border area, the seismic risk is relatively low. The expected economic losses on a yearly basis range between 0.06 €/m^2 and 0.2 €/m^2 (Fig. 7b). The highest EAL/m^2 in the cross-border area corresponds to the municipality of Bad Radkersburg in Austria. Among the Slovenian municipalities in that study area, the highest losses are calculated for the municipality of Gornja Radgona (0.19 €/m^2). The EAL/m^2 is the lowest in the northern part of the area, where the hazard is lower, and increases towards the south, where the hazard is the highest. However, similarly to the Italy-Slovenia study area, the hazard is not the only factor affecting the seismic risk. The importance of vulnerability and exposure is evident. For example, EAL/m^2 is the highest in Bad Radkersburg, although the seismic hazard is not as high as in some Slovenian municipalities. This is because the buildings constructed between 1965 and 1982, which represent a significant portion of the building stock, are considered less vulnerable on the Slovenian side of the border.



(a) (b)

Fig. 7. Map of the expected annual losses/m^2 due to earthquakes in the Italy-Slovenia cross-border area (a) and Slovenia-Austria cross-border area (b).

3.2. Cross-border flood risk assessment in pilot areas

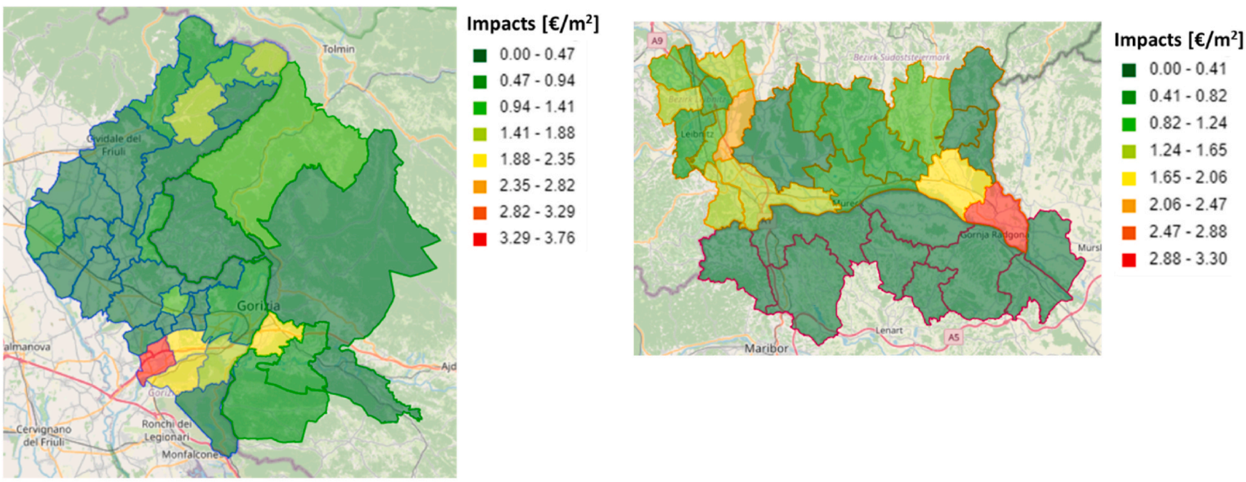
3.2.1. Hazard

The flood hazard maps produced in the three countries (Italy, Slovenia, Austria) in response to EU Floods Directive only represent the expected flooded area for assigned return period. Moreover, the flood return periods considered for the definition of the low, medium, and high flood hazard maps vary across the countries. Therefore, in the BORIS project, a new procedure to develop harmonized cross-border flood hazard maps was proposed. The procedure is quite simple and could be easily applied in other EU Member states when dealing with cross-border catchments. The steps of the harmonization procedure are the following: 1) estimation of the flood water depth associated to the flood extension map, employing existing tools such as FwDET algorithms [55,56]; 2) starting from the flood hazard maps defined in step 1, a set of additional flood hazard maps with a specific return-time step is created (e.g., 1 year) through an ad hoc interpolation algorithm, allowing to obtain maps with comparable return periods for transboundary applications. Specifically, flood hazard map (water depth and extension) for return periods ranging from 20 to 300 years are produced for this application. It is worth mentioning that maps derived with this procedure are based on statistical quantiles reconstructed with an interpolation procedure with a given return time step (e.g., 1-year) and are not calculated with hydraulic models/simulations. More details of the proposed procedure can be found in Ref. [38].

3.2.2. Vulnerability and exposure

The HAZUS curves [57] for residential buildings are used as common flood vulnerability model, to estimate buildings' structural damage as a function of the water depth. Flood exposed elements are the ones located in the hazard prone area. Thus, the spatial discretization of hazard and granularity of exposure data should be preferably coherent among them. Moreover, to be able to perform a damage assessment, it is required to find a common ground between available vulnerability curves and exposure characterization. In the scope of flood vulnerability classification, building types are distinguished based on occupancy type (e.g., residential, school, offices, industrial), number of storeys and the presence or absence of basement [57]. Characteristics and granularity of available exposure data may vary among neighboring countries (e.g., macro-scale or regional exposure vs detailed micro-scale, or building-level exposure). Accordingly, for a cross-border flood risk assessment, the first element to consider is the availability of common and homogeneous data among neighboring countries, used as an input to develop the population and built-up mask (i.e., location of the buildings allows the spatial distribution of the exposure model), together with building stock attribute table. To have information that homogeneously covers the whole cross-border territory, the GHSL (Global Human Settlement Layer, [58]) is used. This spatial raster dataset (GHS-BUILT-S R2022A - built-up surface grid), derived from Sentinel2 composite and Landsat, multitemporal (1975–2030), depicts the distribution of built-up surfaces, expressed as number of square meters. The data reports about the total built-up surface and the built-up surface allocated to dominant non-residential (NRES) uses; suitable elaboration of these data allows to associate relevant vulnerability functions (for residential and non-residential) to each building. This association has been developed in GIS through a statistical zonation and it represents the probability of being residential and non-residential building to each asset. OpenStreetMap (OSM) layer of building footprints updated to the 2020 has been adopted to obtain building position and area for purpose of flood impact analysis. From the global data, a downscaling methodology to implement the global information on the building footprints is adopted to determine a spatial distribution of the following indicators: residential population and the factors describing the vulnerability of the built-up area as the building usage and number of storeys. When possible, the downscaling procedure is controlled with the data derived from census or local data.

The flood-water depth level to which each building in the analyzed area is exposed was obtained through a GIS software, overlaying building footprints with the hazard map of the considered probability scenario.



(a) (b)

Fig. 8. Map of the expected annual losses/m² due to floods in the Italy-Slovenia cross-border area (a) and Slovenia-Austria cross-border area (b).

3.2.3. Consequence model and results

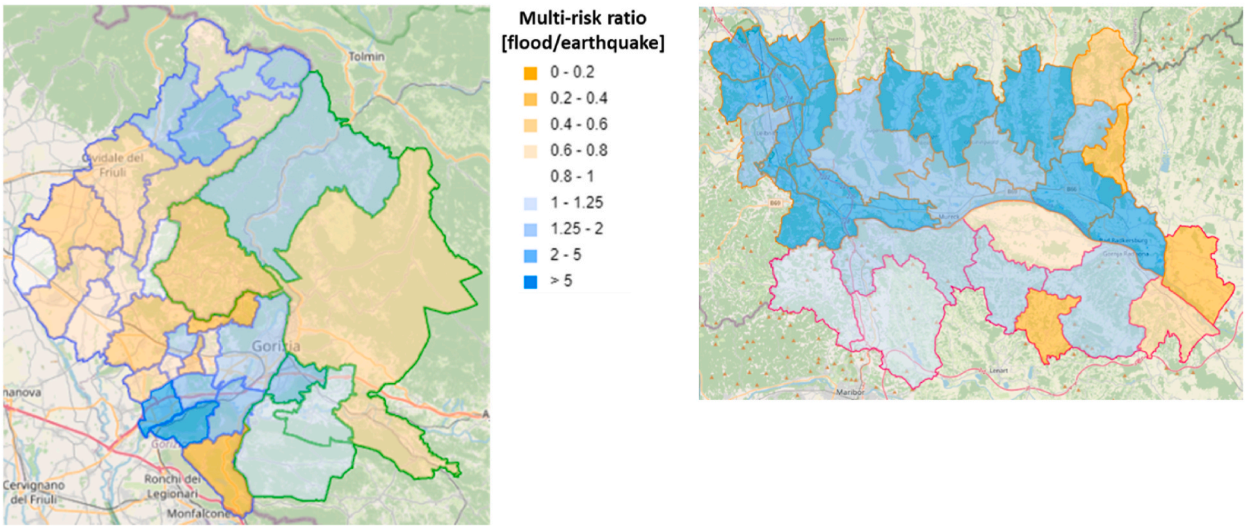
By using the specific vulnerability functions selected (i.e., HAZUS model), the expected consequences in terms of direct economic losses were evaluated. Such vulnerability curves provide the expected damage ratio, i.e., the percentage of the maximum possible damage to structures and/or contents expressed in €/m^2, as a function of the intensity measure (i.e., water depth).

Thus, the value of expected monetary losses (€) for a building was obtained by the product of the damage ratio [%], its replacement cost [€/m^2], the area of the building footprint [m^2] and the number of storeys. As replacement cost for buildings, the same value adopted in cross-border seismic risk assessment is used (see section 3.1.4). The resulting value of direct economic losses in terms of EAL/m^2 is shown in Fig. 8. It reaches a maximum value of 3.76 €/m^2 in Italy-Slovenia cross-border area, and 3.30 €/m^2 in the Austria-Slovenia one. At Italian side, the most affected municipality is Gradisca d'Isonzo, with EAL/m^2 equal to 3.76 €/m^2. It is followed by Farra d'Isonzo (EAL/m^2 = 2.11 €/m^2) and Sagrado (EAL/m^2 = 2.10). At Slovenian side of Italy-Slovenia border the most affected city is Šempeter-Vrtojba, with a value of EAL/m^2 equal to 2.04 €/m^2. The town of Kanal also shows medium-high losses, with the EAL/m^2 equal to 1.16 €/m^2. At Austria-Slovenia border, the resulting mean annual value of direct economic losses (i.e., EAL) is significantly higher in the Austrian side (€ 7.7 million) with respect to the Slovenian side (€ 0.47 million). The most affected city at Austrian side is Bad Radkersburg (EAL/m^2 = 3.3 €/m^2). It is followed by Gabersdorf (EAL/m^2 = 2.41 €/m^2). Within Slovenian area of Austria-Slovenia border, the most affected cities are Šentilj, Gornja Radgona and Sveta Ana, with values of EAL/m^2 of 0.28 €/m^2, 0.27 €/m^2 and 0.26 €/m^2, respectively.

3.3. Multi-risk comparison and ranking

The comparison between seismic and flood risks in the study area is presented in terms of total EAL, EAL ratio (EAL_{flood}/$EAL_{earthquake}$) and risk curves. The ratio between the EALs for both investigated areas is reported in Fig. 9. When the ratio EAL_{flood}/$EAL_{earthquake}$ is greater than one the losses due to flood prevail with respect to seismic ones and the color in figure tend to blue or light blue (see Fig. 9); vice versa if the ratio is lower than one expected seismic losses are higher and color in figure tends to orange-red. For the Italy-Slovenia study area, no clear dominance of losses due to flood or earthquake can be observed. In four municipalities on the Italian side, the EAL due to flood is significantly higher than the seismic risk, with a large EAL ratio: Gradisca d'Isonzo (6.7), Sagrado (5.7), Savogna d'Isonzo (4.7) and Farra d'Isonzo (3.81). In the municipalities of San Leonardo, Drenchia, Capriva del Friuli EAL ratio is above 2 (2.3, 1.9 and 1.8 respectively) still indicating the criticality of the flood risk but to a lesser extent. In Gorizia, flood risk is more relevant than seismic as well (EAL ratio = 1.3). Two municipalities, Grimacco and Dolegna del Collio, have a ratio basically equal to 1, indicating equal levels of flood and seismic risk. On the contrary, in the city of Doberdò sul Lago the ratio is 0, which means that the total EAL (which is about 30′000 €) is due only to earthquakes. In such municipalities where this ratio is lower than 1, the seismic risk is predominant (e.g., in Cividale del Friuli where EAL ratio is 0.5). On the Slovenian side of this border, the highest ratio (about 4) is estimated for the municipality of Šempeter-Vrtojba, but also Kanal shows a quite high ratio (1.7). In the municipalities of Nova Gorica and Brda, seismic risk is more critical (it is about three times higher than flood risk).

The ratio between the expected losses due to floods and earthquakes indicates that flood risk is predominant in the Austrian part of the analyzed Austria-Slovenia cross-border area (Fig. 9). For six Austrian municipalities, the flood risk is at least ten times more critical than the seismic risk. Specifically, this ratio reaches a value of 24 in Gabersdorf, 20 in Tillmitsch, 17 in Ragnitz, 16 in Bad Radkersburg, and 13 in Lang and Ehrenhausen an der Weinstraβe. For only two Austrian municipalities, the seismic risk is the predominant one, Sankt Anna am Aigen (EALs ratio of 0.26) and Klöch, where the flood risk is absent (EALs ratio = 0). Differences between flood and



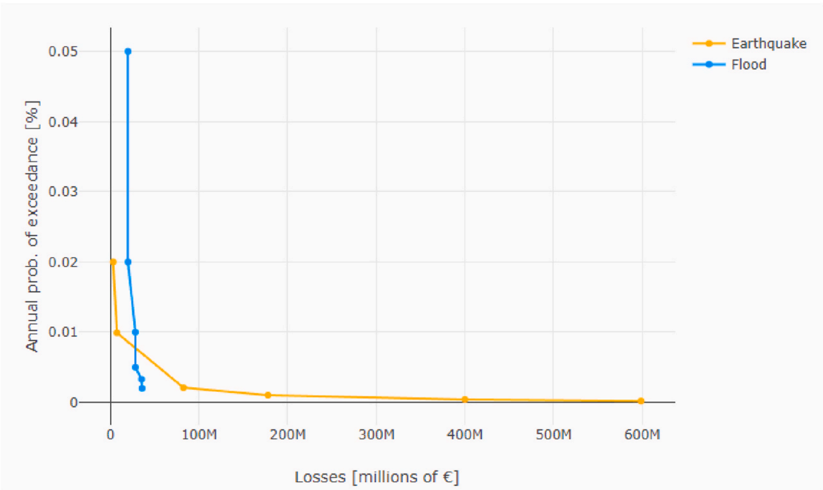
(a) (b)

Fig. 9. Map of multi-risk ratio (EAL_{flood}/$EAL_{earthquake}$) in Italy-Slovenia cross-border area (a) and Slovenia-Austria cross-border area (b).

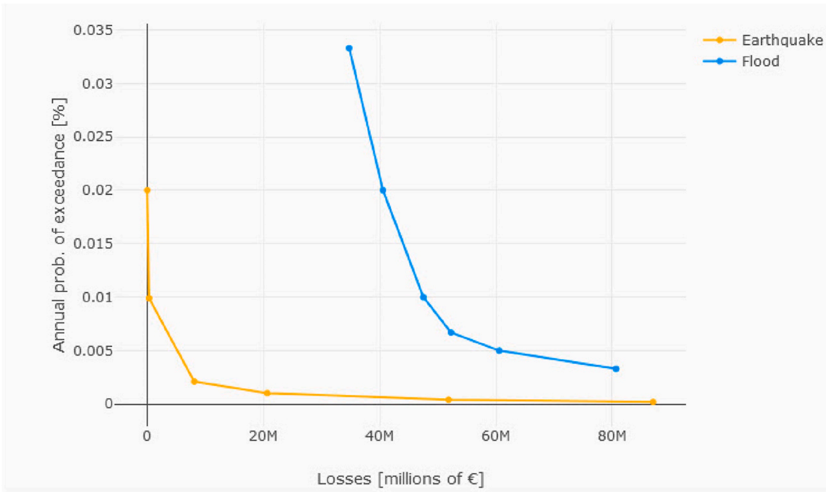
seismic risk levels are less significant on the Slovenian side of the Austria-Slovenia border. The flood risk is predominant in four out of nine Slovenian municipalities (Pesnica, Sveta Ana, Šentilj, Gornja Radgona), where ratio between the losses due to floods and earthquakes is between 1.2 and 1.8. The highest ratio is estimated for the municipality of Šentilj (1.7). In another four municipalities, the seismic risk is higher. This includes the municipalities of Tišina and Benedikt, where the seismic risk is at least ten times higher than the flood risk (0.13 and 0). Overall, the seismic risk in the Slovenian part of the area is estimated to be about 6 % higher than the flood risk, which can be considered a negligible difference.

The difference between the seismic and flood risk is reflected by the differences in the risk curves generated for the two hazards. For instance, Fig. 10a shows the risk curves for Gorizia (in Italy) and Fig. 10b for Bad Radkersburg (in Austria). The comparison of the risk curves for the municipality of Gorizia indicates higher flood risk at high probabilities of exceedance (low return periods) and higher seismic risk at low probabilities of exceedance (high return periods). On the contrary, in Bad Radkersburg, flood hazard leads to higher impacts almost for all return periods, which means that flood risk is the prevalent risk in that area regardless of the probability of exceedance of the event. In order to obtain an unbiased ranking of risks, several return periods for the events are considered, and the risk levels are compared based on the EAL rather than the consequences of a single return period.

Fig. 11 shows the map of the total multi-risk EAL, calculated as the sum of EAL due to earthquakes and EAL due to floods. In Italy-Slovenia area, the total multi-risk EAL for the Italian municipalities is almost two times the Slovenian one (about 7.2 millions € for Italian area and 3.8 millions € for Slovenian area), but the highest EAL values correspond to two Italian (Gorizia and Gradisca d'Isonzo)

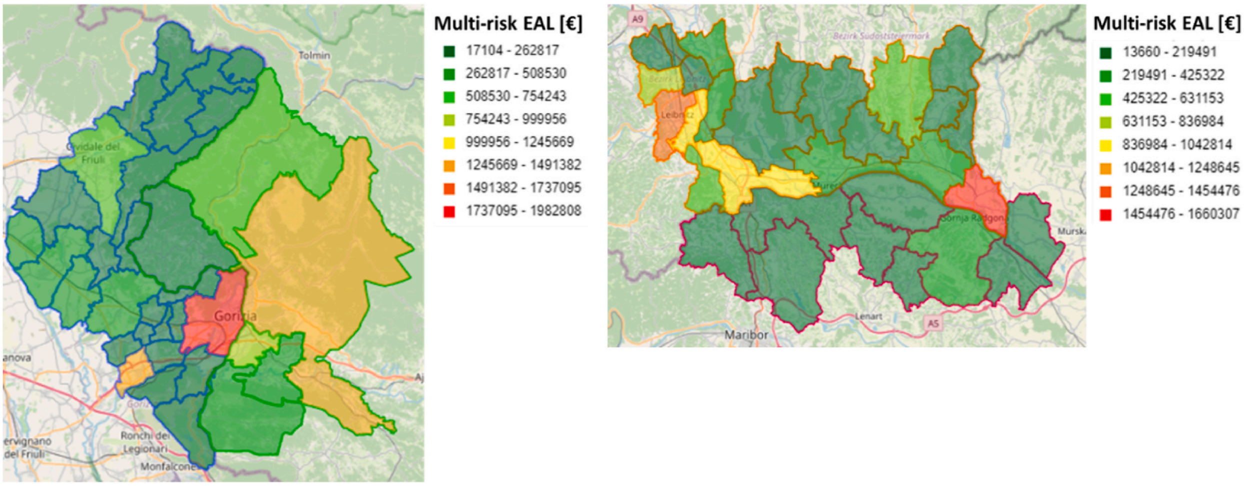


(a)



(b)

Fig. 10. Risk curves for the municipality of Gorizia in the Italy-Slovenia cross-border area (a) and for the municipality of Bad Radkersburg in the Slovenia-Austria cross-border area (b).



(a) (b)

Fig. 11. Map of the total multi-risk EAL ($EAL_{flood} + EAL_{earthquake}$) at the Italy-Slovenia (a) and Austria -Slovenia border (b).

and two Slovenian municipalities (Nova Gorica and Šempeter-Vrtojba). The total expected annual losses observed at the Austria-Slovenia border imply that the Austrian municipalities in the cross-border area are exposed to higher combined risk due to floods and earthquakes (Fig. 11). For 12 Austrian municipalities, the total expected losses are higher than those estimated for the most threatened Slovenian municipality. The highest total EAL on the Austrian side of the border were identified for the municipality of Bad Radkersburg (1.7 million €), while in Slovenia, the highest losses on a yearly basis were calculated for Gornja Radgona (0.23 million €), a neighboring municipality to Bad Radkersburg. The difference in the total losses results from the flood risk, while the seismic risk in the two municipalities is almost the same.

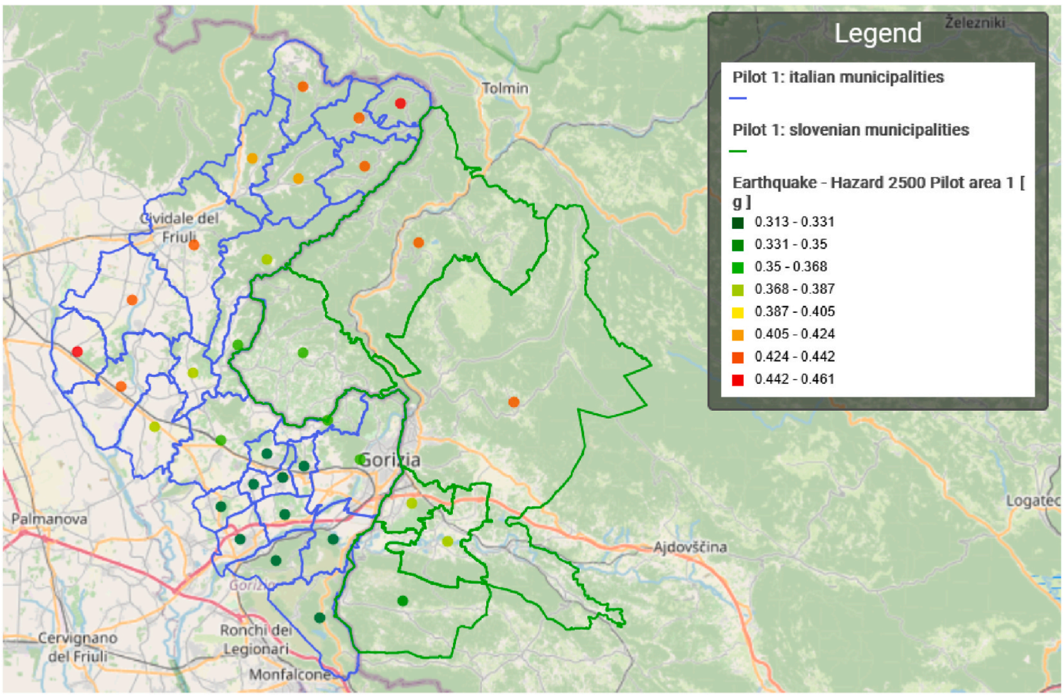


Fig. 12. Hazard map for earthquake: PGA for a return period of 2500 years.

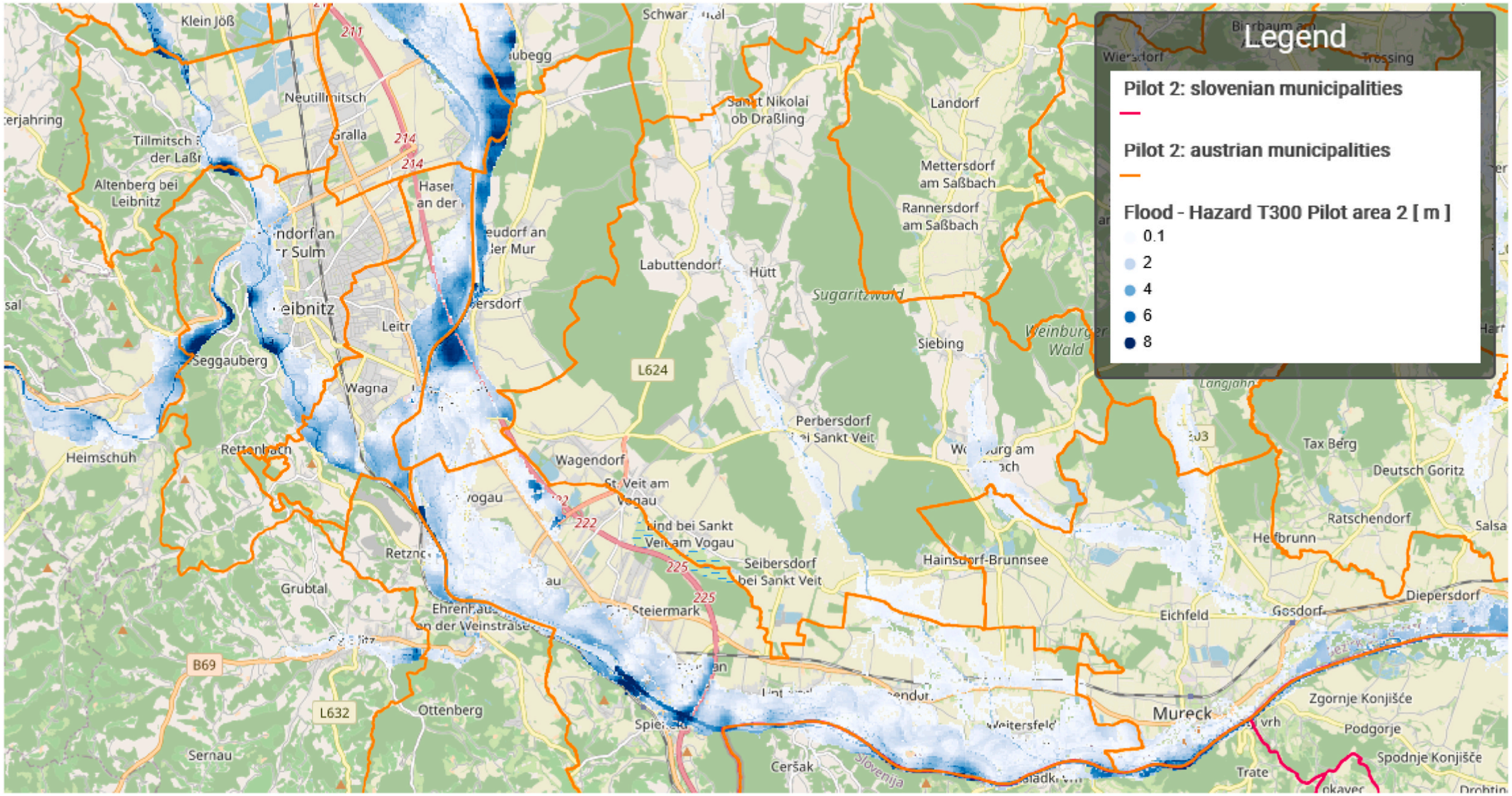


Fig. 13. Hazard map for flood: flood extension and depth for a return period of 300 years.

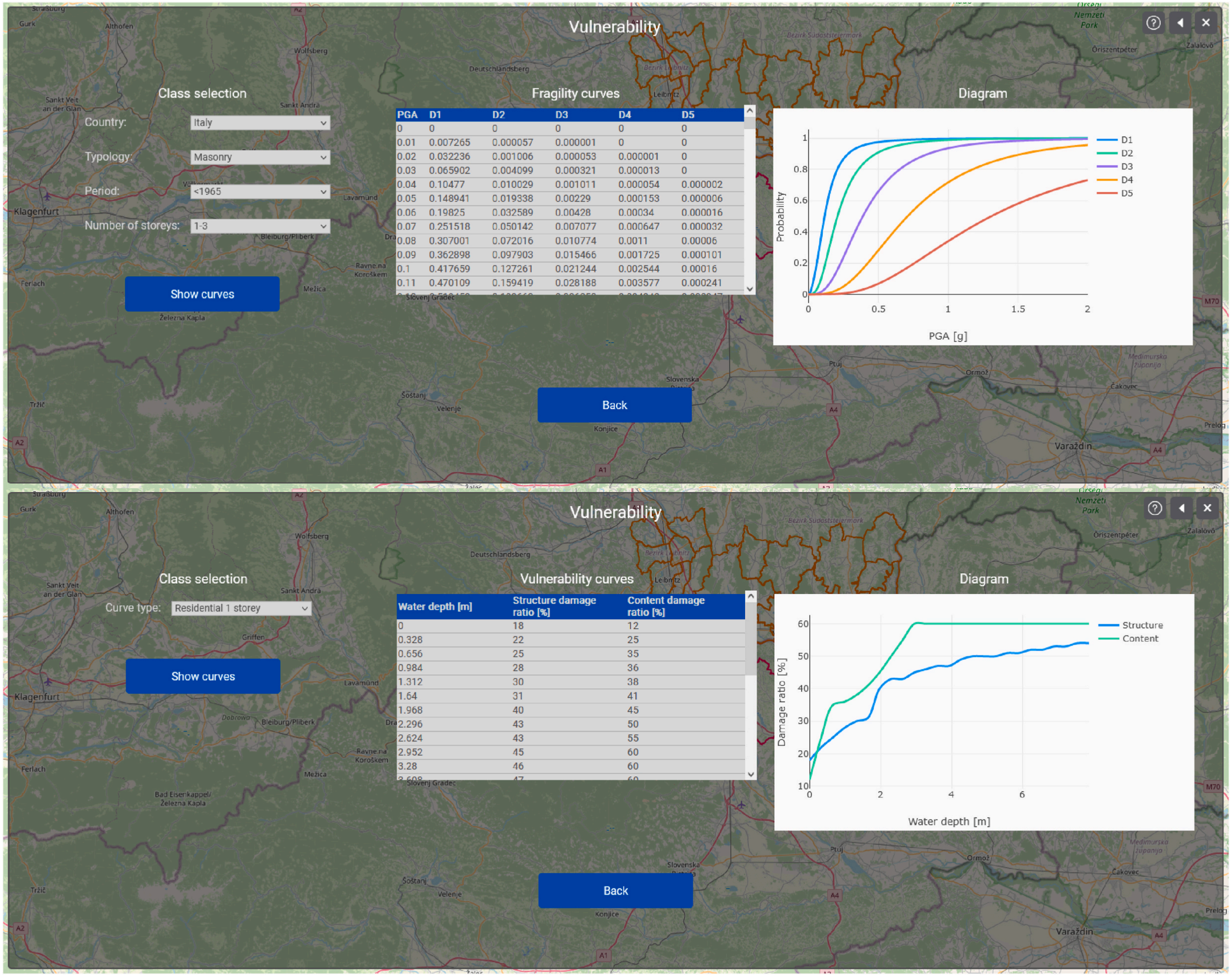


Fig. 14. Fragility curves for earthquake (on the top) and for flood (on the bottom).

4. A web-platform for results visualization

The results of the cross-border analysis performed in BORIS as well as the input data used, can be visualized in a web-based platform purposely implemented in the project (https://www.borisproject.eu/web-based-platform/) and are also shared through Risk Data Hub (https://drmkc.jrc.ec.europa.eu/risk-data-hub/#/project/BORIS). The BORIS platform is designed compliantly with stakeholder requirements, national and regional civil protections as well as local administrators. It was developed in English, but the supporting material is organized in the form of online help translated into five different languages to cover the mother tongues of the BORIS project partners (Slovenian, Italian, Turkish, German and Serbian). The visualization of different aspects considered in risk assessments is organized in dedicated panels. Specifically, the dedicated panels are: (a) hazard, (b) vulnerability, (c) exposure, (d) damage, and (e) risk-impact indicators. In the hazard panel (a), the user can visualize the maps related to earthquake and flood hazard. The earthquake hazard maps show the PGA (from ESHM20 model, [40]) calculated at the barycenter of each municipality for six return periods, i.e., 50, 101, 476, 976, 2500, and 5000 years. Concerning flood hazard maps, they represent flood extension and depth for a specific probability of occurrence (return period). As mentioned before, they were developed starting from the hazard maps provided in the framework of the EU Floods Directive (DIRECTIVE 2007/60/EC) and applying a suitable interpolation procedure specifically developed within this project. Figs. 12 and 13 show example of hazard maps for earthquake and for flood visualized in the platform, respectively.

In the vulnerability panel (b) (Fig. 14), the fragility curves produced and adopted in the seismic risk calculation are reported for residential masonry and reinforced concrete buildings, classified according to age class (before 1965, between 1965 and 1982, after 1982) and height (low buildings up to 3 stories, tall buildings with more than three stories). For each building class, five fragility curves were produced for the five damage levels defined by the European scale EMS98 [50]. For flood, the vulnerability curves proposed in HAZUS [57] are reported, based on occupancy (residential or not) and number of floors, and distinguishing the curves for structure and content.

In the exposure panel (c), it is possible to view the exposure for each municipality in terms of number of residential buildings, number of dwellings within residential buildings, living area, and resident population.

The last two panels allow viewing the risk results in terms of damages (d) and Risk-Impact indicators (e). Results in terms of damages can be visualized only for single-risk (separately for seismic and flood). Expected damages are shown in terms of number of buildings and percentage of buildings that reach the different damage levels of the adopted scale (i.e., EMS-98), with reference to two time windows (1 year and 50 years).

The Risk-Impact indicators panel (e), allows visualizing the consequences of the damage suffered by residential buildings and population. These consequences were calculated for the two time windows (1 and 50 years) separately for earthquake and flood. Specifically, results of seismic risk analysis performed are shown in terms of direct economic losses, economic losses per square meter (Fig. 7), the number of victims, injured and displaced people, and finally the number of unusable buildings in short and long term. For flood, the indicative number of inhabitants potentially affected and direct economic losses (Fig. 8) are the impact metric shown. On the contrary, multi-risk impacts were calculated only in terms of (direct) economic losses for a time windows of 1 year (i.e., EAL). The multi-risk results on the BORIS platform are presented in tables, maps and graphs displaying the 1) the total Expected Annual Loss, determined as the sum of the EAL due to floods and EAL due to earthquakes (see e.g. Fig. 11); 2) the ratio between the EAL due to floods and EAL due to earthquakes (see e.g. Fig. 9); 3) the comparison of risk curves estimated for seismic and flood risk (see e.g. Fig. 10).

The results of the BORIS project, as well as the platform and its potential use, were presented to local stakeholders, such as regional civil protection authorities, during various dissemination and training events [59]. A general appreciation to the results was expressed, particularly concerning the usefulness of the methodology to highlight which municipalities are exposed to higher risk (referring to single risk) and to rank and compare the risks from the multi-risk perspective; also, the potential benefit for insurance companies or other stakeholders that could benefit from long term risk management strategies were evidenced. However, local authorities also noted that it could be useful to perform scenario analyses (for single risks) at a lower scale, e.g. sub-municipality, as such type of results could be useful for emergency planning and to support preparedness activities such as trainings for responders.

5. Conclusions

This paper presents the methodology for cross-border multi-risk assessment proposed in BORIS, which is intended for seismic and flood risk assessment, and the results of its application in two transboundary regions in Europe (i.e., Italy-Slovenia and Slovenia-Austria cross-border regions). Multi-risk analysis was performed in a multi-layer single-risk assessment framework, consisting of two individual risk assessments, neglecting possible risk interactions but harmonizing the assessment procedures to make their outcomes comparable. In addition to the harmonization across different hazards, the proposed approach foresees the harmonization of single-risk assessments across borders. It is shown that such a cross-border harmonization can be achieved by using common models if they exist (e.g., ESHM2020 for seismic hazard) or by introducing ad hoc procedures for harmonizing national models available in the participating countries.

The selection of common assets at risk (e.g., residential buildings and population) and the type of analysis to perform (e.g., probabilistic risk assessment) with reference to a common time frame (e.g., 50 years) are essential assumptions for risks comparability. Concerning seismic and flood risk, it was also found that the harmonization of the scale of analysis and the metrics used for expressing risks could be also required. As no hazard or vulnerability interactions are considered, territorial scales adopted for single analysis could be different, provided that the results are compared with reference to the same scale (e.g., municipal level). To ensure a consistent multi-risk evaluation, direct economic losses due to structural buildings damage are suggested as risk metric. Risk curves are the proposed tools to show and compare risks analysis results. These tools allow a quantitative evaluation of risks, for instance in terms of direct economic losses through the calculation of expected annual losses EAL as the area under the risk curve. The latter can be used as the metric for risks comparison and ranking. Thus, the evaluation of ratios between the EAL resulting from flood analysis and EAL due to earthquakes allows the identification of areas where one risk is more relevant with respect to the other.

The methodology of the BORIS project has been developed to a level that enables relatively easy implementation in any cross-border area, but reflects certain compromise solutions due to the treatment of two selected natural phenomena and due to coordination between neighboring countries. During the project, it was realized that the most significant challenges in risk analysis in cross-border areas predominantly arise from the diversity of databases and risk analysis models, which is a consequence of the insufficient regulation of this area at the European level. For instance, the issues of data availability, the need to define proxies that might generate unnecessary discontinuities, the possible mismatch of administrative borders in terms of area and shape as well as the differences in vulnerability models adopted neighboring countries (for example, due to the differences in building stock typologies) are usually the most critical issues to address when a transboundary risk assessment is performed. Also, additional research is needed to harmonize the estimation of direct losses, regardless of the damage caused by various natural hazards. For example, although the losses estimated for earthquakes and floods are presented with the same measure, i.e., EAL, these losses are not necessarily directly comparable due to the inconsistencies between the methodologies for seismic and flood risk assessments. In particular, seismic and flood risk assessments depend differently on the same given assumption. For example, the impact of early warning can significantly affect the losses due to floods, while it cannot notably alter the seismic losses. The difference in the impact of such an assumption on the results of different risk assessments can introduce bias into the comparison between their results and need to be properly considered in future studies.

To ensure the exportability of the proposed methodology to other countries, the tools and methods proposed were also checked for consistency with methodologies applied by project partners in Montenegro and Turkey and tested with preliminary application in Montenegro [60]. Limitations of using or transferring the methodology may be originated from the potential limitations in the input data and models needed for the analysis. Indeed, the availability of the necessary input data in different countries can vary, partly due to restrictions on access and use of building data related to individual national regulations.

Further enhancements of the BORIS approach will be performed in the two years BORIS2 project (BORIS2: Cross BOrder RISk assessment for increased prevention and preparedness in Europe: way forward, GA. 101140181) starting on January 2024. Acknowledging the requirements expressed by local stakeholders and building on the BORIS results, BORIS2 will focus on multi-risk analyses at sub-municipal scale and allowing also scenario type analyses.

CRediT authorship contribution statement

Maria Polese: Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing. **Gabriella Tocchi:** Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Anže Babič:** Conceptualization, Formal analysis, Supervision, Validation, Writing – original draft, Writing – review & editing. **Matjaž Dolšek:** Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing. **Marta Faravelli:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Davide Quaroni:** Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Barbara Borzi:** Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing. **Nicola Rebora:** Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing. **Daria Ottonelli:** Formal analysis, Writing – original draft, Writing – review & editing. **Susanna Wernhart:** Conceptualization, Formal analysis, Supervision, Validation, Writing – original draft, Writing – review & editing. **Jelena Pejovic:** Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing. **Nina Serdar:** Conceptualization, Supervision, Writing – original draft. **Klaudija Lebar:** Formal analysis, Supervision, Validation, Writing – original draft, Writing – review & editing. **Simon Rusjan:** Conceptualization, Supervision, Validation, Writing – original draft. **Rocco Masi:** Supervision, Validation, Writing – original draft. **Christian Resch:** Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing. **Hannes Kern:** Conceptualization, Formal analysis, Supervision, Validation, Writing – original draft. **Ivana Cipranić:** Conceptualization, Supervision, Validation, Writing – original draft. **Milena Ostojic:** Conceptualization, Supervision, Validation, Writing – original draft. **Andrea Prota:** Conceptualization, Supervision, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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