BORIS

Cross BOrder RISk assessment for increased prevention and preparedness in Europe

D5.2

Consolidated version of the guidelines for cross-border risk assessment

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1. SUMMARY

Cross-border risk assessment is an essential tool for enhancing disaster preparedness and prevention in transboundary areas. It builds on the findings of national risk assessments performed within neighbouring countries and upgrades such risk assessments by harmonizing the methodological differences. However, harmonizing national risk assessment methodologies is not an easy task. It requires bridging the differences in the assumptions, level of detail, and input data. The task becomes even more challenging when dealing with the cross-border risk posed by various hazards. In such cases, the harmonization of the methodologies is required on two levels, across borders and across hazards.

Developing a methodology for cross-border multi-risk risk assessment is one of the main objectives of the BORIS project (GA. 101004882; sponsored by Directorate-General for European Civil Protection and Humanitarian Aid Operations – ECHO), which focuses on the assessment of seismic risk and flood risk in a multi-risk framework. The objective was already addressed in Work package 4 (WP4), entitled "Shared methodology for multi-risk assessment". The results of WP4 encompassed two deliverables, D4.1 (BORIS, 2022a) and D4.2 (BORIS, 2022b), which included the analysis of the differences between national risk assessment methodologies and tools, as well as the solutions proposed to overcome those differences. The methodological guidelines proposed in D4.1 and D4.2 were the basis for Work package 5 (WP5), entitled "Pilot application in cross-border sites". The guidelines were already applied in two pilot applications focusing on cross-border areas on the Italian-Slovenian and Slovenian-Austrian borders. The results of the pilot applications in terms of risk estimates were presented in deliverable D5.1 (BORIS, 2022c). However, one of the goals of the pilot applications was also to identify and fill potential methodological gaps not recognized within WP4, thus complementing the initial methodology outlined in WP4.

This deliverable includes the final consolidated version of the guidelines for cross-border risk assessment. The guidelines are presented as a list of actions to undertake for an effective risk assessment. First, the guidelines are presented for the assessments of single risks considered in the BORIS project. The seismic risk assessment is addressed in Section 2, and the flood risk assessment in Section 3. Each of these sections includes general guidelines for performing cross-border risk assessment as well as specific guidelines for modelling the hazard, exposure, vulnerability and consequences. Then, the guidelines for the comparison and ranking of different risks, which are required for multi-layer single-risk assessment, are given (Section 4). The last part of the document includes an analysis of the proposed methodology's transferability to regions other than those considered in the pilot applications (Section 5). In particular, a region in Montenegro is used for this analysis. It is shown that the proposed guidelines are general enough to be transferred to the borders of Montenegro. A discussion on the transferability of the methodology is also given for cross-border areas in Türkiye. It is concluded that the framework proposed in the BORIS project might also be adopted in Turkish cross-border areas through similar international projects and collaborations.

2. Cross-border seismic risk assessment

2.1 General guidelines for performing cross-border seismic risk assessment

The seismic risk depends on seismic hazard, the vulnerability of the assets at risk and their exposure. These risk factors can be characterized by different approaches, encompassing scenario-based and time-based seismic risk assessments. The recommended approach is the time-based risk assessment, which has several advantages. Within this type of risk assessment, all possible earthquake scenarios, defined by the source location, magnitude and other parameters, are considered, thus enabling an unbiased estimation of risk. Moreover, the result of a time-based seismic risk assessment can be expressed in terms of average consequences in a selected time window (e. g. average economic losses on a yearly basis). Such results are directly comparable to the results of risk assessments performed for other natural hazards, as they do not depend on a single earthquake or a single return period.

In order to perform a time-based seismic risk assessment, four models are required, i. e. the seismic hazard model, vulnerability model, exposure model and consequence model. The seismic hazard model expresses the probability of exceedance of different levels of ground motion in a certain time window at a given site. It is usually presented in terms of hazard maps, where the ground-motion intensity is presented for an entire investigated region and a given return period, or hazard curves, where the ground-motion intensity is given for a specific site and different return periods. The seismic vulnerability model represents the susceptibility of assets at risk of being damaged by earthquakes as a function of the seismic intensity. It is defined by a set of fragility curves, indicating the probabilities of assets at risk exceeding designated damage states. Each fragility curve corresponds to one vulnerability class (represented by the type of assets) and one level of damage (i. e. damage state). The consequence model defines the expected consequences as a function of the damage state and building characteristics. Different kinds of consequences can be considered, depending on the risk indicators selected in the risk assessment (e. g. economic losses, number of fatalities, injured people, unusable buildings). The exposure model defines the characteristics of the assets at risk in a way that allows them to be associated with the vulnerability and exposure models. For example, referring to a building portfolio as assets at risk, the exposure model gives the total number of buildings and their proportions in different vulnerability classes, thus allowing the allocation of fragility curves to each type of building. 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.

The models are input into the risk integral according to the conventional performance-based earthquake engineering framework (Cornell and Krawinkler, 2000). In the risk integral, the consequences related to different ground-motion intensities are weighted by the rate of the ground-motion intensity and then summarized, thus obtaining the average consequences in a selected time window. However, it is also possible to calculate the average number of buildings exceeding a certain damage state in a selected time window. In this case, the consequences in the risk integral are replaced by the number of buildings exceeding the selected damage state.

The integration is performed for the entire range of ground-motion intensities that cause damage to the assets at risk. Selecting the lower and upper bounds of this ground-motion intensity range can affect the estimated loss (e.g. Lazar and Dolšek, 2014). It is suggested to set the lower bound to a value where the economic losses are expected to be equal to 0. In the BORIS project, the value of 0.03 g was selected consistently with previous studies (Dolce et al., 2021). However, the upper bound should be selected so that the intensities above it do not change the risk estimate significantly. Such a bound can be found by iteratively calculating risk several times.

The procedure described above can be applied to a single asset or a group of assets. However, additional considerations should be made when analyzing a group of assets. In such a case, a spatial scale of the analysis should be selected. The spatial scale selection should consider the requirements of the end users and the availability of the exposure data. In the BORIS project, it was decided to define the spatial units by individual municipalities, which is the lowest level at which administrative decisions are taken and the level at which the exposure data were available for the pilot areas. The calculation of risk at the municipality level is point-wise, meaning that it is performed for one point in each municipality (e. g. the geographical centre of a municipality). This means that the hazard, vulnerability, exposure and consequence models need to be defined at the municipality level, but it is also possible that a model is constant over all municipalities (e. g. in the pilot application, the consequence model was constant). In order to obtain global results of the risk assessment for the entire investigated area, the results of individual municipalities then need to be summed up.

In order to obtain consistent results in a cross-border area, consistent models for hazard, vulnerability, exposure and consequences should be employed. Harmonization of models across borders is a challenging task and is explained in more detail in the following sections.

2.2 Guidelines for modelling the hazard

The seismic hazard model can be defined by a set of hazard curves defined by the relationship between the selected seismic intensity measure and yearly exceedance probability. In this deliverable, the PGA is considered as the intensity measure, consistently with the BORIS pilot applications (BORIS, 2022c). However, other intensity measures can also be employed.

Each hazard curve refers to the centroid of one municipality. If a hazard assessment has been performed for the entire investigated cross-border area, then the result of that assessment can be employed as the hazard model. However, if no hazard assessment has been performed specifically for the cross-border area, then a hazard model developed for a wider area can be used. One such model is the European hazard model (ESHM2020) (Weatherill et al., 2020; Danciu et al., 2021), which is available on the ESHM2020 webpage (EFEHR, 2022).

Regardless of the hazard model, the set of yearly exceedance probabilities covered by the model may be insufficient for a time-based risk assessment. In such a case, interpolation and/or extrapolation of the hazard curves is needed. For example, the ESHM2020 model considers six yearly exceedance probabilities corresponding to the return periods of 50, 101, 476, 976, 2500 and 5000 years. In order to obtain the seismic intensity for other yearly exceedance probabilities, the hazard curves need to be interpolated and extrapolated. The interpolation can be performed linearly in the logarithmic domain, as the hazard curves are locally similar to linear functions in the logarithmic domain. However, for the extrapolation, the assumption of a log-linear hazard curve can be too conservative. A more suitable approach is to use the following expression:

$$\log_{10} p = -bPGA^k \tag{2.1}$$

where p is the yearly probability of exceedance, and parameters b and k are determined based on the two points on the hazard curve corresponding to the lowest and highest return periods.

Another limitation of many hazard models is that they provide the hazard curves only for rock-equivalent outcrop motion. Therefore, the effects of local soil have to be taken into account by supplement models. It is suggested that one or more local maps with Vs30 values are used to account for the local soil effects on the analysed cross-border area. Based on the Vs30 values, the proportions of different soil classes can be determined. Then, the amplification factors can be calculated for each soil class by considering, e.g., the guidelines from wdEN 1998-1-1 (CEN, 2022). However, if the local Vs30 maps are unavailable, a global Vs30 map can be used. A database of such maps was proposed by Worden and Heath (2019). These maps default to the global slope-based Vs30 map, but smoothly insert regional Vs30 maps where available.

Based on the initial hazard model (e.g., the ESHM2020 model) and supplemental soil amplification model, the hazard curve for a given municipality can be developed by taking the following steps:

1. Obtain the hazard curve for the given municipality from the initial hazard model. This hazard curve is defined by several points connecting the PGA to the yearly probability of exceedance.
2. Calculate the soil amplification factors for the PGA values obtained in Step 1.
3. Define the hazard curves for different soil classes by multiplying the PGAs from the hazard curve for rock-equivalent outcrop motion (Step 1) by the soil amplification factors (Step 2).
4. Interpolate the hazard curves from Step 3 to increase the number of points on the curves. The interpolation can be linear in the logarithmic domain.
5. Calculate the weighted average of the probabilities from the hazard curves for different soil classes (Step 4). A weighted average should be calculated for each PGA of the curve. The weights should be equal to the proportions of the soil classes in the municipality.
6. Assemble the "final" hazard curve from three parts. The middle part, which corresponds to the range of yearly exceedance probabilities from the initial hazard model, should be equal to the weighted average curve from Step 5. The first and last parts can be defined by extrapolating the weighted average curve from Step 5.

An example of the hazard curves for different soil classes, their weighted average and the extrapolated weighted average curve is presented in Figure 2.1. The dashed lines in the figure together constitute the "final" hazard curve, which is used in the risk calculation.

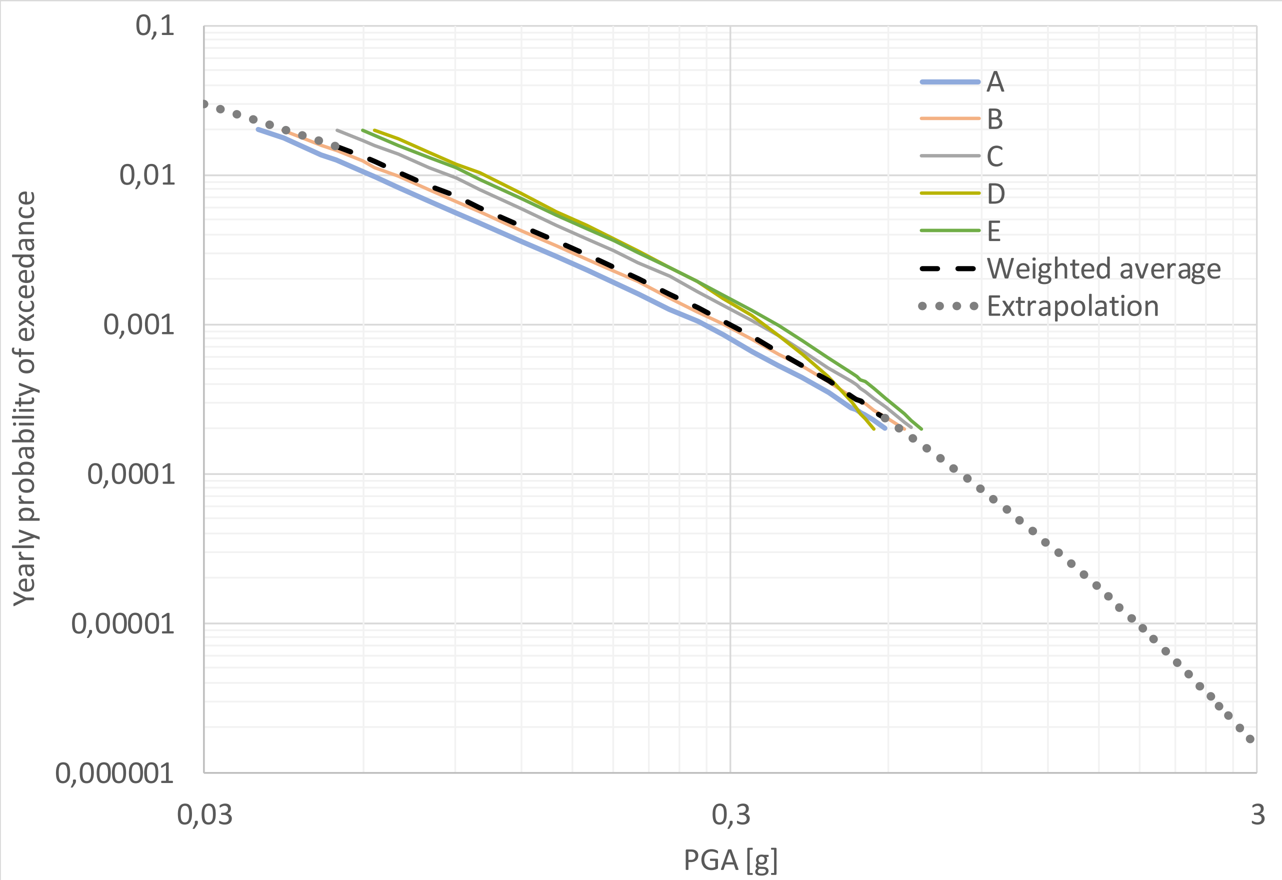

Figure 2.1: The hazard curves for individual soil classes, their weighted average and the extrapolated weighted average curve for the municipality of Kanal in Slovenia.

2.3 Guidelines for modelling the exposure

Exposure refers to the assets at risk, i.e. people, housing, infrastructures, as well as cultural heritage and the environment, that could be adversely affected by a hazard. Due to difficulties and obstacles related to the high level of detail and the amount of data required for considering all those elements in assessing risk for a large cross-border area, in this project, we focus only on residential buildings and population.

Several sources can be used to compile inventory for buildings, such as census, real-estate register, building-by-building survey or remote sensing detections (Polese et al., 2019). Although the information on buildings provided by census is often limited to basic information on construction material, age of construction and number of storeys, this source is particularly suitable for large-scale applications. As a matter of fact, generally, census data are publicly accessible and cover the entire national territory. For this reason, within the BORIS project, a harmonized exposure modelling approach based on poor census information is proposed. More specifically, information on the construction material (e.g., masonry, reinforced concrete or other), number of storeys (e.g., 1–3 storeys and 4 or more stories) and the period of construction are the adopted criteria for building typologies identification. Moreover, in harmonizing cross-border exposure modelling, also the scale of analysis should be selected considering available data in cross-border countries involved. For privacy reasons, disaggregated data on building typologies may be available only at a wider scale, e.g., at a province or municipality level. Therefore, the municipality level has been adopted as the scale of analysis herein and building inventory has been compiled at the municipal level (see also BORIS, 2022c). In the case of the availability of data at a lower scale for a country (e.g., building-by-building data), such data then needs to be aggregated according to the larger scale adopted (i.e., the municipal scale).

The exposure model should provide the distribution at the territorial scale of exposed buildings belonging to different classes of structures. The latter need to be defined according to the classification adopted by the vulnerability model used. Buildings can be grouped into different classes based on their expected seismic performance using different approaches. For example, in typology-based classification, building classes are defined based on the building typologies identified by construction material (e.g., masonry, reinforced concrete, steel, mixed structures), the number of storeys and age of construction. In the vulnerability-based classification, buildings are grouped in vulnerability classes not only based on the construction material but also on the load-resisting system type, eventually taking into account more specific buildings' features as well (e.g., the horizontal structural types or the presence of tie rods for masonry buildings). An example of this kind of classification is the EMS-98 one (Grünthal, 1998). However, for compiling building inventory starting from census data and using the above-mentioned approach, specific rules for assigning census building typologies to vulnerability classes are required. A suitable exposure model defining such rules is usually calibrated on available refined data on buildings (e.g., post-earthquake surveys) and/or on expert judgment. Because such a model may not be available in all countries, for cross-border harmonization purposes, we propose the typology-based classification that requires basic information which is easily detectable. More specifically, in defining building typology classes, buildings should be grouped in different periods of construction, considering the evolution of the main seismic codes in the countries involved. Thus, in the BORIS applications, six typological classes for masonry buildings and six typological classes for RC, defined by a combination of period of construction (i.e., buildings built before 1965, between 1965-1982, after 1982) and the number of storeys (1–3 storeys, 4 or more storeys), have been identified. If the required information for building classification is not available, an alternative source of information and interview-based approaches have also been proposed in BORIS (2022a,c).

2.4 Guidelines for modelling the vulnerability

There are different approaches to developing the vulnerability model. However, the following steps should generally be taken (Polese et al., 2019):

1. A suitable classification of the exposed assets has to be established.
2. A damage scale has to be defined.
3. The propensity of assets belonging to selected classes to suffer damage due to earthquakes of assigned intensity and according to the damage scale has to be evaluated and expressed by suitable functions.

The classification of the exposed assets can be based on their typology, which is defined by the characteristics that affect seismic vulnerability. Hereinafter, we will focus on buildings, which are also the assets considered in the BORIS pilot applications. The characteristics that should be considered in the classification of buildings include the material of the load-bearing structure, the number of storeys and the construction period. However, a more detailed classification can be performed if sufficient data is available (e.g. the type of the structural system). In the case of a cross-border seismic risk assessment, the classification of buildings should consider the building typologies from both neighbouring countries. Two countries sharing a border may have a similar historical and cultural background, in which case their building stocks are similar enough to use the same building classification. However, the differences in the building stocks may still exist for politico-economic or other reasons. In such a case, different building classifications can be used for the two countries.

The damage scale defines the designated levels (states) of damage that the exposed buildings can reach in the case of an earthquake. Different scales can be adopted. One option, commonly used in Europe, is the EMS98 damage scale (Grünthal, 1998), which identifies five damage states in addition to the no-damage state. Among other damage scales, the HAZUS scale (FEMA, 2015) is also commonly used. It includes four damage states in addition to the no-damage state. In the case of a cross-border seismic risk assessment, the damage scale should be unified to obtain comparable damage analysis results. If the participating countries use different damage scales, a conversion to a common damage scale is needed and can be performed as described in Section 3.2.3 of Deliverable 4.1 (BORIS, 2022a).

The propensity of buildings to suffer damage due to earthquakes can be defined by a set of fragility curves. A fragility curve represents the conditional probability of reaching or exceeding a damage state given the level of PGA (or a different intensity measure) and is most often defined by the cumulative lognormal distribution function. A separate fragility curve should be defined for each building class and each designated damage state. Thus, the total number of fragility curves should be equal to $N_{classes} \cdot N_{DS}$, where $N_{classes}$ and N_{DS} are the number of building classes and the number of designated damage states, respectively.

The definition of fragility curves for the building stock in a cross-border area is straightforward if exactly one vulnerability model has been developed specifically for that building stock. However, this is rarely the case, as the vulnerability models are usually developed for a wider area (e.g., for the entire national territory). In such cases, national vulnerability models can be applied. Suppose a national vulnerability model is available only for one country in a cross-border area. In that case, that vulnerability model can be applied in both sub-areas (sides of the border in the cross-border area), thus assuming that the available vulnerability model provides a suitable proxy for the vulnerability of buildings in the entire cross-border area. This approach was taken in the seismic risk assessment of the Pilot 2 area (Slovenia-Austria cross-border area), where the vulnerability model developed for the Slovenian building stock was applied (BORIS, 2022c).

However, if a vulnerability model is available for both countries sharing the border, two different vulnerability models can be used when dealing with a cross-border area between two countries. In such situations, a separate vulnerability model for each sub-area can be used if the building classes in the two neighbouring countries differ. However, if the buildings in the two countries are similar enough to use common building classification, the two national vulnerability models should be harmonized. Within the BORIS project, a heuristic harmonization approach has been proposed, in which the vulnerability model in a cross-border area is defined as a linear combination of the two national vulnerability models. This approach defines a different vulnerability model for each sub-area (side of the border in the cross-border area) and building class. The linear combination of the vulnerability models may be expressed as:

$$M_{c,A}^{comb} = w_{c,A,A} \cdot M_{c,A} + w_{c,A,B} \cdot M_{c,B} \tag{2.2}$$

$$M_{c,B}^{comb} = w_{c,B,A} \cdot M_{c,A} + w_{c,B,B} \cdot M_{c,B} \tag{2.3}$$

Where:

- $M_{c,A}^{comb}$ and $M_{c,B}^{comb}$ are the linear combinations of the vulnerability models for the c-th building class to be used in sub-areas A and B, respectively;

- $M_{c,A}$ and $M_{c,B}$ are the vulnerability models for the c-th building class originally developed for countries A and B, respectively;

- $w_{c,A,A}$ and $w_{c,A,B}$ are the weights assigned to models $M_{c,A}$ and $M_{c,B}$, respectively, when defining the combined vulnerability model for sub-area A and the c-th building class ($w_{c,A,A} + w_{c,A,B} = 1$);

- $w_{c,B,A}$ and $w_{c,B,B}$ are the weights assigned to models $M_{c,A}$ and $M_{c,B}$, respectively, when defining the combined vulnerability model for sub-area B and the c-th building class ($w_{c,B,A} + w_{c,B,B} = 1$).

In general, the weights in Eqs. (2.2) and (2.3) reflect two types of differences:

- the methodological differences between the vulnerability models $M_{c,A}$ and $M_{c,B}$;

- the typological differences between the building stocks in countries A and B on the one hand and building stocks in sub-areas A and B on the other.

If the methodological differences are small, the weights depend only on the typological differences. In such a case, the weights $w_{c,A,A}$ and $w_{c,B,B}$ can be calculated as follows:

$$w_{c,A,A} = \frac{w_{c,A,A}^T}{w_{c,A,A}^T + w_{c,A,B}^T} \tag{2.4}$$

$$w_{c,B,B} = \frac{w_{c,B,B}^T}{w_{c,B,A}^T + w_{c,B,B}^T} \tag{2.5}$$

Where $w_{c,A,A}^T$, $w_{c,A,B}^T$, $w_{c,B,A}^T$ and $w_{c,B,B}^T$ are the typological weights (ranging from 0 to 1). Each of the typological weights indicates how similar are, statistically, the buildings in the given sub-area to the buildings in the given country. For example, $w_{c,A,B}^T$ indicates how similar are, statistically, the buildings in sub-area A to the buildings in country B. The typological weights can be defined based on the comparison of the vulnerability factors, determined based on advanced building data not yet considered in the definition of the building classes. An example of the definition of the weights can be found in the description of the seismic risk assessment for the Pilot 1 area (Italy-Slovenia cross-border area), where this approach was applied (BORIS, 2022c).

Finally, it is also possible that a vulnerability model does not exist for either of the two countries in the cross-border area. In such situations, global vulnerability models can be applied (e. g. Crowley et al., 2021).

2.5 Guidelines for modelling the consequences

Negative consequences of a seismic event are usually expressed in terms of the expected number of collapsed and unusable buildings (or dwellings), the expected number of displaced people, casualties and injured people as well as the direct economic losses. Their evaluation requires the definition of consequence functions, also called damage-to-impact functions, that relate expected structural damages to the above-mentioned impact indicators.

The expected number of collapsed buildings could be determined as a portion of buildings reaching a given damage state. However, as in this project, the EMS-98 scale is adopted, the heaviest damage state (D5) already corresponds to buildings' collapse. Therefore, all buildings reaching this damage state are considered collapsed.

Similarly, unusable buildings can be evaluated assuming a percentage of unsafe buildings in short and long term for each structural damage level Dk of the adopted scale (i.e., EMS-98). Thus, 40% of buildings reaching damage states D2 and D3 are considered short term unusable; the remaining 60% of buildings reaching damage state D3 and the totality of buildings reaching damage state D4 are considered long term unusable.

The number of injured people and fatalities are estimated as a percentage of occupants in buildings experiencing damage states D4 and D5: an earthquake is considered to be fatal for 1% and 10% of occupants in buildings reaching damage states D4 and D5, respectively. Moreover, it is considered that 5% and 30% of occupants in buildings reaching damage states D4 and D5 will suffer injuries. The number of displaced people is estimated as the number of inhabitants in unusable buildings, in the short and long term, subtracting the estimated number of deaths.

Direct economic losses, associated with the physical damage of structures, are usually calculated defining a cost ratio, i.e., a ratio of the reconstruction cost, for each damage state. The cost ratios assumed in this project for each damage state of the EMS-98 scale are the following: 0.02, 0.1, 0.35, 0.6 and 1, respectively, for damage states from D1 to D5. Thus, for the evaluation of expected economic losses for a given class of structures, the inputs required are: the probability of attaining damage state Dk, the built area associated with the considered building class, the cost ratio relative to damage state Dk and the unit cost (Euro/m2) of a building (i.e. the reconstruction cost, estimated taking into account the demolition cost and the cost of a new construction). The formula adopted for the calculation is reported in BORIS (2022a). Although the consequence model has been harmonized defining the same cost ratios, a unique value of the reconstruction cost for the entire transboundary area cannot be defined, as it is obviously country-dependent.

3. Cross-border flood risk assessment

3.1 General guidelines for performing cross-border flood risk assessment

Risk assessment is the process of combining the risk components of hazard, exposure, and vulnerability to determine the level of risk. Various approaches can be used, which vary in the degrees of detail depending on the purpose of the analysis and data available, as well as on how they address uncertainties arising in different stages of the risk assessment process (EU Guidelines, 2010). Specifically, flood risk means the combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage, and economic activity associated with a flood event (EU 2007). Commonly used methods are either qualitative, semi-quantitative, or quantitative (deterministic and probabilistic). Qualitative risk analysis methods describe the risks based on expert assessments. The qualitative approaches represent subjective risk perception and serve as a starting point for a discussion on assumptions and risk recognition in participation of wide variety of experts and stakeholders in the process (DRMKC, 2017).

Qualitative risks analyses are typically used to determine whether further investigation is needed. Sometimes the qualitative approach is the only option when almost all components of risk are not quantifiable or have a very large degree of uncertainty. In order to facilitate the replicability of qualitative approach, the processes must to be transparent and structured, so different experts can repeat the analysis. The quantitative risk assessment, that is suggested and adopted in the scope of the BORIS project, can evaluate potential impacts in two ways: deterministically or probabilistically. Deterministic risk assessment method estimates the impact from a single hypothetical risk scenario or from a combination of scenarios. However, the probability of the events in quantitative terms it is not necessarily considered; moreover, it is not guaranteed that all possible events are captured within a deterministic scenario set. Probabilistic risk assessment method simulates the future disasters which are based on the scientific evidence likely to occur. Probabilistic models complement historical records by reproducing the physics of a large number of simulated events.

A simple example of a quantitative approach is when we perform multiple calculations of risk for a larger number of representative flood scenarios separately to obtain a comprehensive overview of the overall risk in the area of interest. For instance, the basic approach described in the Floods Directive (EC 2007) requires to quantify the population, type of economic activity, and sources of pollutions (industrial installations), which can be potentially affected by the occurrence of at least three different scenarios (high, medium and low probability). However, the scenario-based approach does not allow to consider the full range of possible relevant extreme events, nor the influence of analysed risk scenarios to determining overall risk. For this manner a risk integral method can be used. The integral method estimates the average annual impact of floods over the area of interest by computing the integral of the impact-probability curve, or risk curve (see Alfieri et al., 2016). In standard applications practice, the method requires the calculation of the impact values (in economic terms or people affected) for a selected range of return periods (probability of occurrence) to construct a piece-wise risk function describing impacts according to the event frequency. Therefore, as proposed in BORIS project, the expected annual impact values (e.g., expected annual damage) is given by the integral of the risk curve across the return periods. As an alternative method, probabilistic or stochastic risk modelling can be used, where all potential events with their associated probabilities and outcomes by running probabilistic simulations of flood processes over a long period of time are modelled. Stochastic methods derive robust risk probability distributions, including the effect of low-probability events. derive robust risk probability distributions, including the effect of low-probability events.

It is important to note that the Floods Directive does not provide specific indications on the methodologies to be applied for evaluating flood hazard and flood risk, thus leaving the decision on the most suitable approach to each Member State.

As explained in detail by Poljanšek et al., 2021, and as outlined by the Floods Directive, the first requirement is the identification of relevant flood processes than can produce significant consequences in the area of interest. The identification of relevant processes is generally based on the analysis of past flood events, which had significant adverse impacts on human health, the environment, cultural heritage, and economic activity.
Several natural and man-made processes can be a source for flood events. In practical applications, flood events are classified according to the main drivers and the type of a water body that causes the event itself. The following list, obtained from Poljanšek et al. (2017) distinguish between the following types: (i) fluvial floods

(riverine floods) occur when river levels rise and burst or overflow their banks, inundating the surrounding land; (ii) flash floods can develop when heavy rainfall occurs suddenly, particularly in mountainous river catchments, although they can occur anywhere; (iii) heavy rainfall may cause surface water flooding, also known as pluvial flooding, particularly in cities where the urban drainage systems become overwhelmed; (iv) floods can also be generated by infrastructure failure (e.g., dam breaks), obstructions caused by avalanches, landslides or debris, glacial/lake outbursts and groundwater rising under prolonged very wet conditions, which cause waterlogging; (v) coastal flooding is caused by a combination of high tide, storm surge and wave conditions. In many cases, flooding occurs as a result of more than one of the generating mechanisms occurring concurrently, making the prediction of flood hazards and impacts even more challenging.

Following the identification of relevant flood processes, it is indispensable to identify and collect any relevant data related to risk components, namely hazard, exposure, and vulnerability. The process of data collection is closely linked to the selection of adequate methodologies to evaluate risk components, because different methodologies would require different types of data. At the same time, data availability is one of the main drivers in selecting risk assessment tools, because the quality of any model depends on the quality and availability of the input data.

Starting from these assumptions and elements, to performing cross-border risk assessment one additional step must be considered in the evaluations, that is the harmonization of the data and methodologies, also considering feasibility and viability in another context. This aspect is a challenging task and is explained in more detail in the following sections.

3.2 Guidelines for modelling the hazard

The deterministic flood hazard zoning is based on the deterministic flood hazard maps for selected return periods – typically, the inundation maps prepared across EU generally excluding any uncertainty in the models used for its production. In the project partner countries, water velocity or the product of water velocity and water depth is usually also considered as an intensity parameter for defining the food hazard classes. Flood inundation boundaries are typically depicted as sharp lines/borders in the flood maps based on deterministic model results, indicating the expected inundation borders for predefined flood return periods. When proposing guidelines for modelling the flood hazard is worth noting that the flood hazard maps are subject to various sources of uncertainty, among others: the hydrological uncertainty related to estimated design discharge for chosen return period; the floodplain topography and river cross-sections; the choice of effective hydraulic roughness coefficients; the choice of a hydraulic model and its physical representation; the consideration of floodplain infrastructure and flood defences performance; and the possibility of non-stationarity due to catchment and climate changes (Bales & Wagner, 2009; Beven et al., 2014; McCarthy et al., 2014). The quantification of the uncertainties affecting the whole process chain of flood hazard assessment usually requires an evaluation of a large number of uncertainty scenarios, which can be computationally complex and demanding. Most of the existing hydraulic modelling tools are too demanding to enable numerous simulations runs to assess the uncertainties. Given the nonlinearity of these hydraulic models in space and time and the complexity to apply analytical methods for the uncertainty propagation, approximate approaches, such as the one proposed in the BORIS project, could be widely employed to assess different aspects of flood hazard uncertainty.

In general, during the work done in WP2 (BORIS, 2021), it was found out that the procedures for elaboration of flood hazard maps are relatively consistent across the neighbouring countries. However, as noted also in BORIS (2022a), different countries are applying different return periods (Tr), from 10-year to 500-year return period in the analysis of the flood hazard. Moreover, it was found that neighbouring countries use different flood return periods and different combinations of intensity parameters for the definition of the low, medium, and high flood hazard classes. The most common return period used overall in all partner countries is the 100-year return period; therefore, it was suggested to use this flood return period as a basis for future cross-border flood hazard analysis and harmonisation.

In the flood modelling process and following elaboration of flood hazard classes, it is therefore necessary to implement expert decisions on different sources of uncertainty (such as the ones mentioned above) for a specific site in order to properly propagate these uncertainties through inundation models, and further analyse and evaluate them. Implementation of an uncertainty analysis generally consists of two steps: (1) assessing the interaction between different sources of uncertainty and (2) propagation of the assumptions about the different sources of uncertainty through uncertain flood maps (McCarthy et al., 2014).

In scope of the BORIS project, a relatively simple but effective procedure to generate flood hazard maps in cross-border catchments has been proposed. The procedure enables (1) analysis of hazard maps over wide range of pre-defined return periods and (2) a cross-border harmonisation of the resulting flood hazard maps. The generated flood hazard maps are fully compliant with the results provided by each Member State within the EU Floods Directive. This approach allows for further elaboration of the flood hazard maps provided by individual countries to comply with the EU Floods directive by defining flood scenarios (extension and depth) with, in case of the BORIS project, return periods from 10/30 years to 300/500 years with a yearly timestep. In this way, flood hazard curves can be defined for each cell of the cross-border catchments. This methodology can be applied also in similar cross-border catchments in different EU Countries.

In order to develop harmonized cross-border flood hazard maps, the following procedure was defined to be applied and tested within the BORIS project. The general idea is that this quite simple procedure could be replicated also in other EU Member states when dealing with cross-border catchments. The basic steps of the cross-border flood hazard harmonization procedure are the following:

1. Add to each flood hazard map provided by each country the corresponding flood depths by using the FwDET algorithm (Cohen et al., 2019; Peter et al., 2020). The FwDET water depth calculation follows the procedure below:
    a. Conversion of the flood polygon to a line that represents the flood level.
    b. Creation of a raster layer from the line layer that has the same size and alignment as the DEM grid cells.
    c. Extraction of DEM (elevation) value for these grid cells (called boundary grid cells).
    d. Assignment of the local tie value for each grid cell within the flooded domain from its closest boundary grid cell.

e. Calculation of the draft by subtracting the local draft of the flood water from the topographical elevation in each cell of the grid within the flooded domain.

2. Starting from the flood hazard maps defined in the first step, a set of flood hazard maps with a specific return-time step is created using interpolation procedure. On BORIS project, time step of 1 year was used. Interpolation is implemented in the following way:
   a. Ordering of tie rod maps for each percentile
   b. Creation of an array of maps
   c. Calculation of the total volumes
   d. Calculation of the flooded area by adding the number of non-zero leaf cells;
3. Cross-border post-processing and final harmonization.

The potential limitations of the proposed procedure which uses layers the "official" flood hazard maps as input data, might be related especially to potential errors in the interpretation of flood inundation modelling results while defining the flood inundation areas and flood hazard classes and further, in possible discrepancies in the flood area extension in cross-border areas which should be identified a priori.

3.3 Guidelines for modelling the exposure

Exposure can be defined as "the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas" (UNDRR 2017). The identification of elements at risk regarding their quantity, spatialization, vulnerability characteristics, and value is assessed through an exposure analysis. It covers several dimensions, as for example the physical (e.g., building stock and infrastructure), the social (e.g., humans and communities), and the economic dimensions (DRMKC, 2017).
The Floods Directive indicates the following mandatory elements of exposure to be considered in the exposure analysis (EU 2007): the indicative number of inhabitants potentially affected; type of economic activity of the area potentially affected; installations which might cause accidental pollution in case of flooding and potentially affected protected areas as by the Water Framework Directive (EU 2000); areas subjected to floods with a high content of transported sediments, or with significant sources of pollution. Other aspects of exposure that are mentioned by the directive are critical infrastructure (e.g., transport and energy networks, hospitals etc.), and cultural heritage. In the cross-border multi risk analysis proposed in the BORIS project the elements considered in the exposure are: population and residential buildings.

As described in Bertsch et al. (2022) various exposure models are available for different purposes and scales. Especially the scale needs to be correlated to the other components of the risk equation, above all the spatial resolution of the hazard. Therefore, depending on the scale and the aim of the risk analysis, the characteristic and granularity of exposure data may vary depending on the purpose of the risk analysis and the scale of analysis. For example, on a macro-scale or regional level, exposure analysis focuses on countries or large flood plains. It entails a simplification of information, through aggregating hazard grids to coarser resolutions or polygons, as well as representing buildings as single points. This type of analysis is useful on a strategic-level decision making, while they are not suitable for the purpose of a detailed micro-scale, or building-level exposure analysis – particularly in the context of flooding in densely built-up areas, as for example in some of the municipalities in the study cases proposed in the BORIS project. The features of the urban topography influence runoff pathways and consequently the locations and magnitude of pluvial floods. Furthermore, as shown in the drainage rate of storm drain, the inlets are highly sensitive to surrounding elevations impacting the surface water depth. It is therefore necessary to conduct urban flood models at finer grid resolution (i.e. less than 5m) to correctly represent flow pathways between buildings, along roads and into storm drainage networks. Furthermore, modelling and testing the impact of flood adaptation measures requires a detailed representation of the building geometries. A detailed, building-level flood exposure is therefore required to process the high-resolution hazard data. For this reason, this approach is also pursued in the BORIS project, where the proposed model captures the location and distribution of buildings along with their vulnerability characteristics, which include information about the main occupancy (residential and not-residential) and number of storeys, together with the residential population. The following paragraphs describe the assumptions and methodology utilized to develop the inventory, which was based on open data.

The first element to consider is the availability of data used as an input to develop building stock attribute table. In fact, it is quite common to start from already existing data, even if they couldn't be directly applied for risk assessment purposes. If only data from global data are used, the exposure model is suitable for an assessment that homogeneously covers the whole territory. However, when finer resolution data can be obtained (local), the evaluation can be significantly refined; this goal sometimes can be reached also by integrating the different types of information. The integration of different types of data was intentionally followed in BORIS, ensuring the greatest homogeneity among countries.

The location of the buildings allows the spatial distribution of the exposure model, through Geographical Information Systems (GIS) files. It can be realized by vector or raster representation. In the first group, for building footprints we may use different sources, such as the OpenStreetMap (OSM) layer of building footprints, which should be available all over the world, or national layers as in the case of Austria. Raster representation is adopted when the single assets and the characteristics for each element may not be identified, and we prefer to map a unique variable over the whole area under analysis.

For population, the standard approach is to use population maps derived from national-scale census data. The data are available at the municipal level, but also at more detailed levels as census tracts.

The exposure of economic activities and built-up areas is generally evaluated with land use maps, which describes the extent and location of built-up and natural areas with similar characteristics (e.g., residential areas, industrial districts, etc.). These maps can be based on national-scale census data or derived from satellite images. In the present project, this type of data is adopted to depict 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 that have been implemented to associate a vulnerability characteristic, as for example the building usage (residential and not-residential) to each building.

Finally, characterizing economic exposure require data regarding building market values, values of building inventory and machinery (e.g., for industrial buildings) etc. Alternatively, proxy variables such as gross domestic product (GDP) at various administrative levels can be used to infer the value of exposed assets.

As mentioned before, the global data on population distribution, settlement identification and land use have the advantage to cover the whole territory and therefore to ensure a minimum exposure knowledge to perform

acceptable risk analyses. Global data can be downscaled by applying a specific methodology, where the global information on the building footprints can be used to determine a spatial distribution of the following indicators (this is true for the methodology proposed in the scope of the BORIS Project) residential population and the factors describing the vulnerability of the built-up as the building usage and number of storeys. When possible, the downscaling procedure is controlled with the data deriving from census or local data.
The evaluation of exposure to flood events is usually carried out by combining the described exposure maps with hazard maps describing different flood scenarios. It is possible both, to define exposure related to specific flood scenarios (e.g., total population exposed to the 1-in-100-year flood extent), or to elaborate statistical estimates that take into account a range of possible extreme flood events (e.g. expected annual population exposed to floods).

3.4 Guidelines for modelling the vulnerability

Vulnerability relates to the susceptibility of assets such as objects, systems (or part thereof) and populations exposed to disturbances, stressors or shocks as well as to the lack of capacity to cope with and to adapt to these adverse conditions (DRMKC, 2017). Vulnerability can be divided in the following categories: physical, economic, social, institutional, environmental, agricultural. and health (UNISDR, 2017). In the scope of the BORIS Project physical vulnerability has been considered.

In this framework, as described in Molinari et al. (2020) the variety of flood damage models presented in the literature is significant. First, the models are classified according to the intended spatial scale of the analysis, e.g., microscale models refer to the individual exposed building, mesoscale models are used at more aggregated scales, for example, land use or administrative units, where large-scale spatial units (regions or countries) form the base of macroscale models. Moreover, the second major difference is in the approach adopted for model development, with empirical models using damage data collected after flood events and synthetic approaches. Still, both categories are characterized by a variety of methods; for example, empirical data can be interpreted by means of different statistical and mathematical tools ranging from simple regression to more sophisticated machine-learning algorithms and data-mining approaches. A distinction can also be made between absolute- and relative-damage models: the first directly return a value in a specific currency, while relative-damage models estimate the physical vulnerability or the degree of loss of an exposed asset to be multiplied by its monetary value to assess the damage.

In standard practice, direct damages are usually evaluated using flood damage curves, which relate different hazard variables (such as water depth and flood duration) with physical consequences to different types of buildings and their related content (e.g., residential buildings and furniture, industrial buildings and machinery). The technical and scientific literature reports a wide range of methodologies to estimate damage functions, as well as established catalogues of functions (see for instance Huizinga et al., 2017).

Focusing on the relationship between exposure and vulnerability, different vulnerability functions for different construction typologies can be used. Each vulnerability function links the intensity of a potential event to the percentage of the damage to the building. Let’s assume that for each region three vulnerability functions at building level are available, and that each of them is suitable to describe the vulnerability conditions of a specific building typology. In addition, let's assume that such building typologies are distributed non-homogeneously within the area; if a building block representation is used, the possibility of associating the more suitable vulnerability function to the assets is lost. Summarizing, it should be noted that: the level of detail of stock information must be sufficient to associate the proper vulnerability models. In addition, as the further details associated to the assets should be taken into account, it will also influence the level of aggregation and accuracy of the final risk assessment results. The matching between the vulnerability functions and the exposed elements is done according to different characteristics of the considered element, depending on the chosen vulnerability library.

Therefore, in order to be able to perform a damage assessment it is required to find a common ground between available vulnerability curves and exposure characterization. Finally, the spatial discretization of hazard and stock should be preferably coherent among them. Once the stock information is defined, the exposed elements can be extracted, namely the one that are located in the hazard prone area.

The damage analysis is based on the spatial intersection of the surface water depth grid and the exposure model based on the building location and geometry using the RASOR Platform (Arrighi et al., 2018). Initially, a buffer is created around the building geometry in order to extract the depth information from cells adjacent to the building outline. In the BORIS project, the library selected for describing the relationship between the state variables describing the forcing affecting a specific asset in case of flood event and the damage suffered is the HAZUS (FEMA, 2009). They are function of occupancy and number of floors, and they are provided separately for structure and for content.

3.5 Guidelines for modelling the consequences

When considering the consequences of floods, the literature often distinguishes between tangible/intangible and direct/indirect flood damage. Direct damages (and consequent economic losses) are defined as physical, for example short term consequences such as physical damage to buildings, assets and consequent repair costs. Direct losses may be also measured in terms of flows of foregone production, but for the scope of this guidance, this is not pursued. As such, vulnerability diagnoses should be carried out to assess the possible consequences of flooding. In addition, loss data collection should be carried out with the aim of quantifying all the mentioned aspects with an adequate spatial and temporal resolution (e.g., for several flood events, and including all relevant assets in the area of interest).

Indirect losses identify impacts that are not directly caused by floods, such as consequences of electricity cut-offs, roads closures, or loss of revenue due to closing of commercial activities (Merz et al., 2010). In a similar manner a vulnerability diagnoses and loss data collection must be carried out to characterize all relevant consequences at different time periods.

Consequences of floods on population range from the risk of death and major injuries, to displacement and evacuation of people, to short- and long-term physical and psychological consequences. Similarly, to economic impacts, characterizing social vulnerability requires to analyze and record all relevant consequences on population at different time periods.

The Economic impact can be evaluated multiplying the percent damage and the economic value of the considered asset: Damage [EUR] = Damage [%] X Economic Value [EUR]. The way in which this economic value is estimated changes with respect to the type of exposed element. As described in the Arrighi et al. (2018), for buildings, it consists of the recovery and replacement costs that are the cost per unit area to be sustained to reconstruct the previous building (i.e. the maximum possible damage due to floods) and the cost per unit area to replace existing contents respectively. The replacement/recovery cost assessment on one hand may rely on insurance data, while on the other hand on socio-economic proxies.

In the simplest case, the vulnerability function for population is just a binary function 'affected/not affected', which considers as affected the population located inside the flooded area, beyond a certain water depth threshold.

In the shared methodology the indicative number of inhabitants potentially affected and the economic consequences in terms of Annual Average Loss (AAL) and Probable Maximum Loss (PML) are considered as indicators for the consequences analyses. Among the economic risk metric, AAL can be interpreted as an opportunity cost given that resources set aside to cover disaster losses could be used for development. Monitoring AAL in relation to other country economic indicators, such as GDP, capital stock, capital investment, reserves, and social expenditure, would provide indications on country fiscal resilience, broadly defined as comprising internal and external savings to buffer against disaster shocks. Also, the PML curve is particularly useful in economic terms. The PML curve describes the loss that can be experienced for a given return period. Knowing the different level of losses expected on a certain frequency can help to understand on how to organise a strategy combining different risk reduction, mitigation, or avoidance actions.

4. Cross-border multi-risk comparison and ranking

4.1 Guidelines for the comparison and ranking of natural hazard risks

The multi-risk assessment can be performed in different ways. In the BORIS project, the framework of a multi-layer single-risk assessment was used. The guidelines for this approach are presented in this section.

The steps taken in a multi-layer single-risk assessment are (adapted from Marzocchi et al., 2012):

1. Definition of the study area, the time window for the risk assessment and the indicator (metric) for evaluating the risks.
2. Identification of the types of risks impending in the selected area.
3. Hazard assessment for the study area covering all possible intensities (separately for each risk).
4. Vulnerability and exposure assessment for relevant assets at risk in the study area (separately for each risk).
5. Calculation of losses for each point (return period) on the hazard curve (separately for each risk).
6. The assemblage of risk curves and the calculation of EAL for each point of analysis in the study area (separately for each risk), and the comparison of EALs calculated for different risks.

The study area, time window and risk indicator have to be chosen consistently with end-users needs. Within the preparation of Civil Protection plans at the level of local communities aimed at increasing prevention and preparedness, the study area may comprise an assemblage of municipalities. A reasonable time window for such analysis is one year or more. In the BORIS project, both a 1-year and a 50-year window were selected. This means that the risk assessment results were expressed as the expected (average) consequences in 1 year and 50 years. Concerning the metric, different types of losses can be considered. The direct economic losses were selected as the indicator within the multi-risk assessment performed in the BORIS project.

The risks considered in the multi-risk assessment depend on the study area. Floods and earthquakes, considered in the BORIS project, can be replaced or supplemented with other risks relevant for specific study area.

The hazard, vulnerability and exposure assessments, and the calculation of losses are foreseen to be performed for each risk separately. Sections 2 and 3 of this document provide the guidelines for performing these steps. It is worth noting that all single-risk assessments included in the multi-risk assessment should focus on the same risk elements (e.g., assets at risk) to obtain comparable results. For example, residential buildings were the main element considered in the BORIS project. However, some considerations within the single-risk assessments can vary. For example, different damage scales can be used, as the type of damage caused by different hazards varies. Moreover, spatial scales used in the single-risk assessments can differ, as some hazards have shorter spatial correlation lengths than others. However, such differences should not prevent calculating the same risk indicator or aggregating the losses to the same spatial units. For example, the flood hazard assessment in the BORIS project used a different damage scale and was performed at a more refined spatial level than the seismic hazard assessment. This is because floods cause a different type of damage than earthquakes, and their hazard varies spatially (e.g., inundated area extension) much more significantly than the seismic hazard within a given municipality. However, in the final step of single-risk assessments, the same risk indicator (i.e. direct economic losses) was evaluated for both floods and earthquakes, and that indicator was aggregated at the municipality level in order to provide a common basis for the multi-risk comparison and ranking.

By calculating losses for different levels of hazard intensities, risk curves can be assembled. Each point on a risk curve connects the probability of exceedance of an event (e.g., a flood or an earthquake) with the expected losses from that event. A separate risk curve is generated for each considered risk and each point of the analysis (e.g. each municipality). By comparing the risk curves for different risks and the same municipality, it is possible to compare the economic losses expected at events with the same return periods. Further, by calculating the area under a risk curve, the corresponding EAL (expected annual loss) can be obtained. The EAL represents the losses expected on average each year. It accounts for all return periods and is, therefore, a better point of comparison between different risks than losses at an arbitrarily selected return period. For this reason, it is recommended that the ranking of risks in a municipality is performed based on comparing EALs evaluated for different risks within that municipality. Specifically, the criticality of one risk over another can be assessed based on the ratio between the EALs. However, another useful piece of information is the total EAL, which communicates the loss expected yearly due to the combined effect of all considered risks. By neglecting the potential complex interdependencies between different risks (e.g. domino effects), the total EAL can be calculated as the sum of all single-risk EALs.

The EAL should be evaluated considering the risk curve defined at all possible probabilities of exceedance (all possible return periods). Therefore, care should be taken when evaluating the losses for the return periods where the hazard assessment results are unavailable or highly uncertain. Usually, this includes very short and very long return periods, where some form of extrapolation is required. One option to deal with this challenge is to extrapolate the available hazard assessment results, while another includes the extrapolation of the risk curve obtained based on the available hazard assessment results. In the BORIS project, both types of extrapolation were used. In the seismic risk assessment, the hazard curve was extrapolated, while the flood risk assessment utilized the extrapolation of the risk curve. More information can be found in Sections 2 and 3 of this document.

5. Transferability of the methodology to other regions

5.1 Transferability to cross-border areas in Montenegro

5.1.1 Transferability of the methodology for seismic risk assessment

The exportability of harmonized procedures for cross-border risk assessment is tested for a Montenegro-Serbia cross-border site. This area was selected since it is both earthquakes and floods prone, with some significant events recorded recently (an earthquake in Plav 2018, floods caused by Lim river in 2010 and floods caused by river Ibar in 2016). On the Montenegrin side, the affected municipalities are Andrijevica, Berane, Bijelo Polje, Petnjica, Plav and Rozaje. The affected territory that should be considered on the Serbian side has a similar surface area and consists of municipalities Novi Pazar, Tutin, Sjenica and Prijepolje (Figure 5.1).

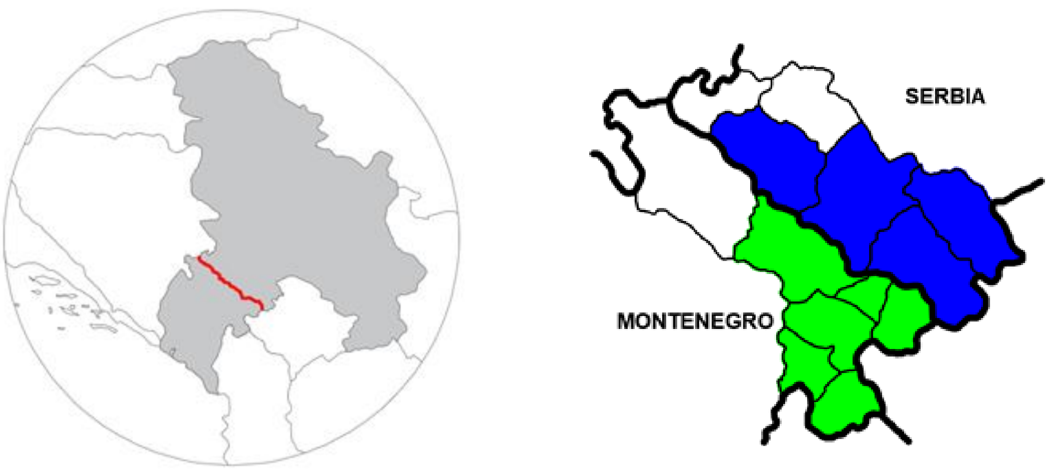

Figure 5.1: Montenegro-Serbia cross-border site.

According to the guidelines for modelling seismic hazard, the European hazard model (ESHM2020) (Figure 5.2) can be used for modelling the seismic hazard at Montenegro cross-border sites since the range of yearly exceedance probabilities covered by the existing national seismic hazard model are insufficient. In Table 5.1, the PGA values for the 476-year return period for municipalities at Montenegro cross-border sites obtained from the ESHM2020 model are presented. However, the PGA values were also obtained for other return periods covered by the ESHM2020 model.

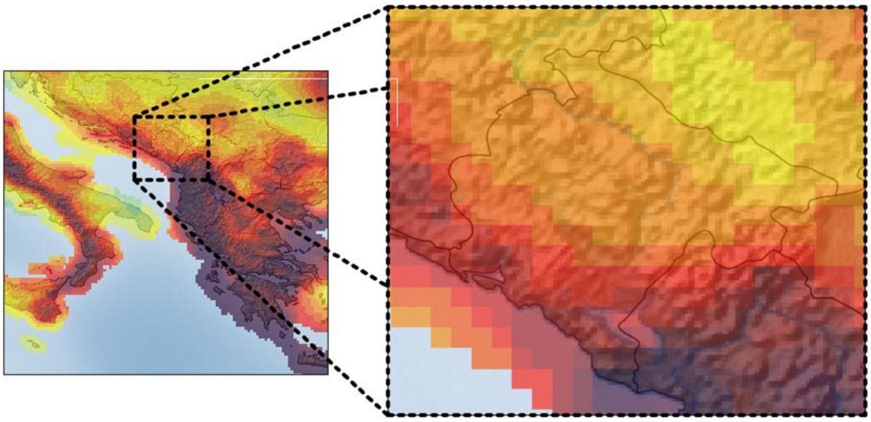

Figure 5.2: ESHM2020 seismic hazard model: Montenegro.

Table 5.1: PGA values for municipalities at Montenegro cross-border sites (476 return period).

Municipality	Andrijevica	Berane	Bijelo Polje	Plav	Rozaje
PGA (g)	0.127	0.104	0.086	0.143	0.096

Considering that the obtained PGA values are valid only for rock sites, the effects of local soil should be considered by a supplement model. For this purpose, the global Vs30 map proposed by Worden and Heath (2019) was used, since local Vs30 maps are not publicly available. Based on the initial hazard model and supplemental soil amplification model, by following the six steps in the guidelines given in Section 2.2, it is possible to derive a hazard curve for every municipality. Hazard curves for individual soil classes and their weighted average curve for the municipality of Rozaje are presented in Figure 5.3.

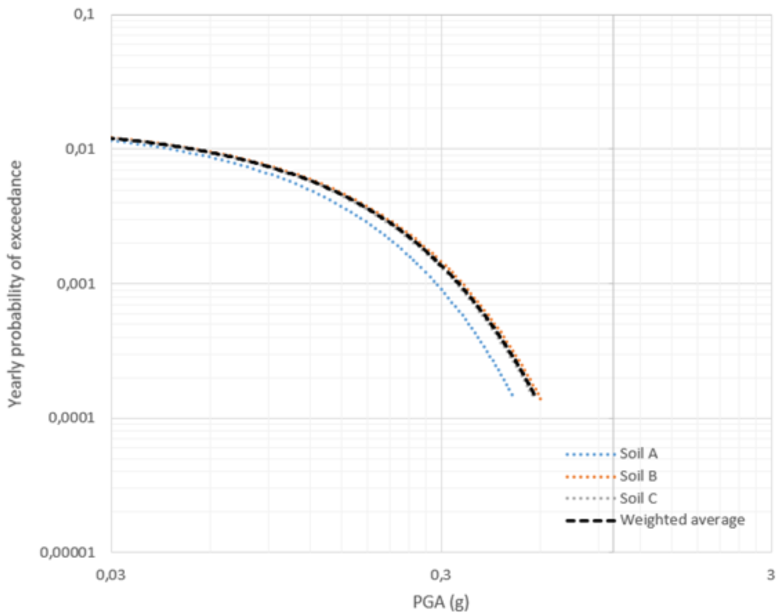

Figure 5.3: Hazard curves for individual soil classes and the weighted average curve for the municipality of Rozaje.

In Montenegro, the exposure data are produced by Monstat (National Institute for Statistics), which provides information on dwellings, population and construction periods. SERA exposure model should be used since it is the only available model currently based on Monstat census data. Having the basic knowledge of the building inventory and exposure model for Serbia, it is reasonable to assume that nine building typology classes, both for masonry and RC buildings, should be considered in the vulnerability analysis. These classes are defined by a combination of the construction period and the number of stories (Table 5.2). It is reasonable to assume that the same building classification can be used in both sub-areas, considering that the two countries have similar historical and cultural backgrounds. Building inventory for the Montenegro cross-border site is given in Figure 5.4.

Table 5.2: Harmonized building classes identified for vulnerability analysis

Material	masonry
	reinforced concrete
Stories	1 - 2, 3 - 5, >=6
Period	< 1964
	1965-1981
	> 1981

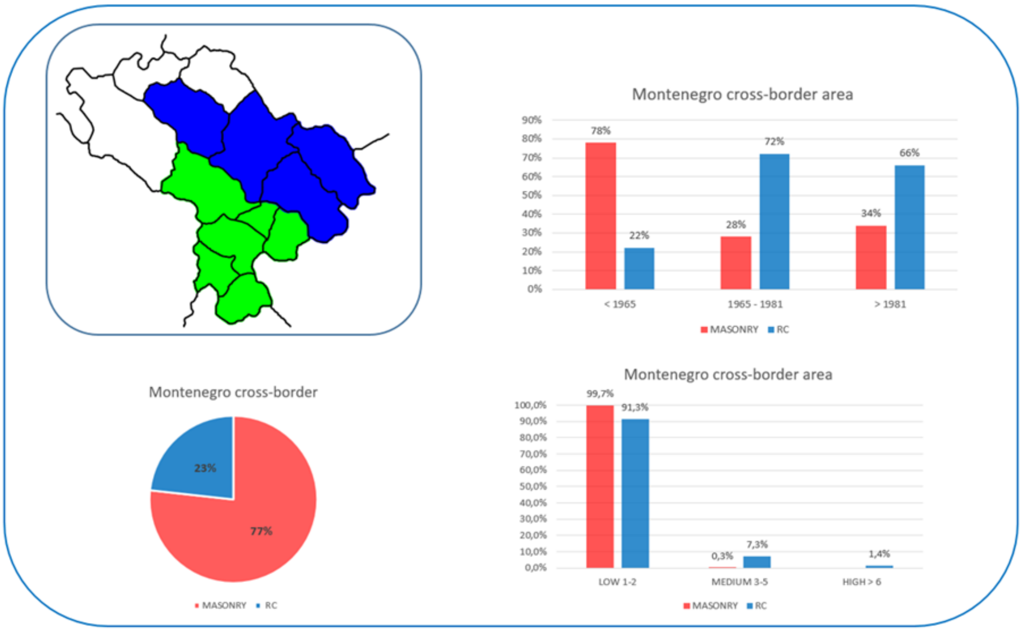

Figure 5.4: Building inventory for the Montenegro cross-border site.

Since the participating countries do not use different damage scales, the conversion between the damage scale is unnecessary, and the EMS98 damage scale can be used to obtain comparable damage analysis results. Furthermore, according to the guidelines, the available Montenegro vulnerability model can be applied on both sides of the considered border since there is no available information on the vulnerability model at the Serbian cross-border site (similar situation as in the Pilot 2 area).

For illustration purposes, the fragility curves for masonry buildings (building class: construction period 1965–1981, number of storeys 1–2) are shown in Figure 5.5. The fragility curves are presented for the macroseismic intensity and the PGA.

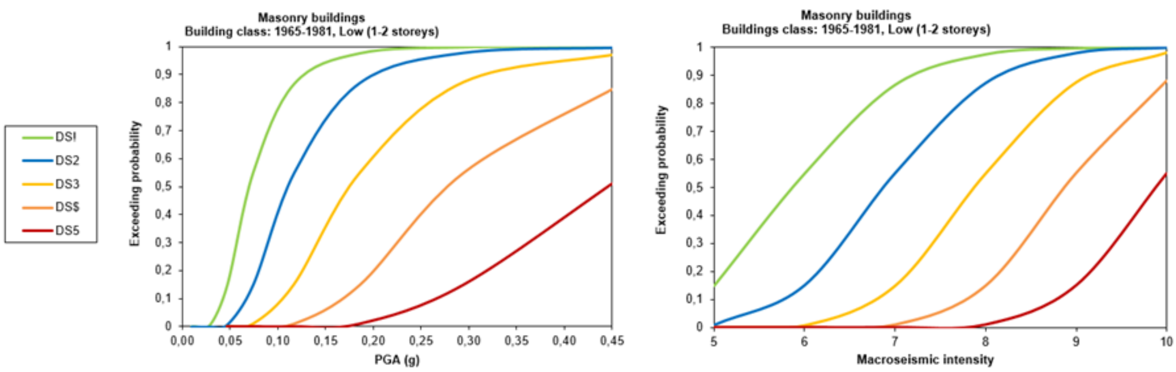

Figure 5.5: Fragility curves for masonry building (building class: construction period 1965–1981, number of storeys 1–2) defined based on the PGA (left) and the macroseismic intensity (right).

The existing consequence model in Montenegro (number of collapsed buildings, fatalities and injured people) is in line with the guidelines for harmonized consequences functions. However, the evaluation of unusable buildings is not performed in Montenegro. Since this is a fundamental step to calculate the number of dislocated people, the proposed model in the guidelines (Section 2.5) can be applied to Montenegro. For the considered Montenegro cross-border site, the number of dislocated people is calculated (for the return period of 476 years) and shown in Figure 5.6.

The proposed model for direct economic losses is in line with the existing model in Montenegro with the difference in the value of reconstruction cost (CR_{MNE}=720€/m^2 based on the data from MONSTAT). The direct economic losses calculated according to the guidelines are presented in Figure 5.6. The presented losses are obtained for the return period of 476 years and expressed as a percentage of the municipality budget (%m.b).

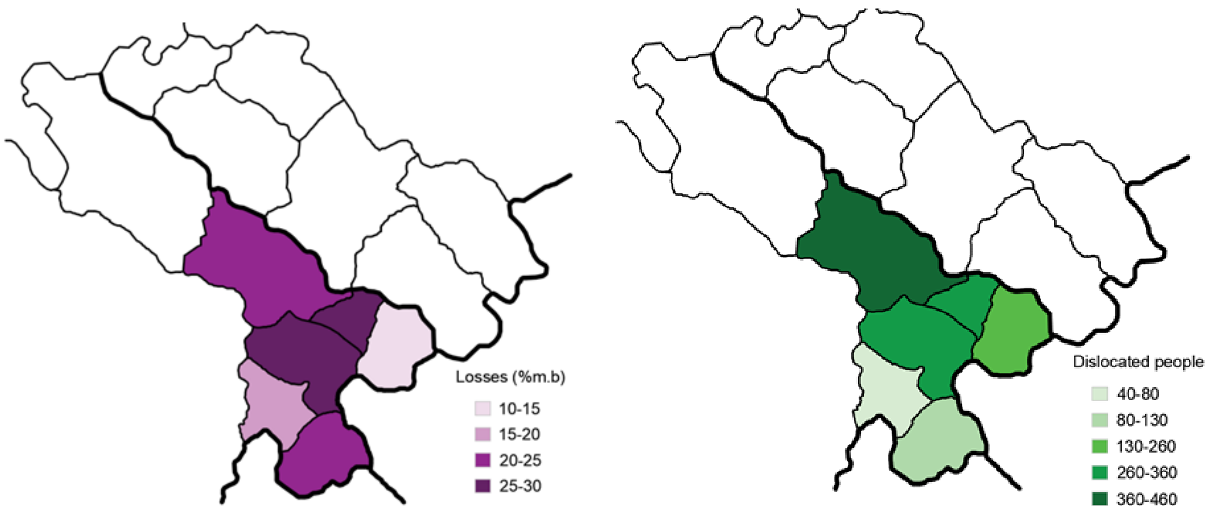

Figure 5.6: The direct economic losses (left) and the number of dislocated people (right).

5.1.2 Transferability of the methodology for flood risk assessment

In Montenegro, flood-prone areas (Areas of Potential Significant Flood Risk – APSFRs) in 5 municipalities are analysed to test the applicability of guidelines developed in the BORIS project. These municipalities are Bijelo Polje (river Lim), Berane (river Lim), Plav (river Brezojevica), Rozaje (river Ibar) and Andrijevica (river Prljanija). The hazard maps constructed for these APSFRs could serve as a basis for cross-border flood risk assessment following the guidelines. To create these hazard maps, two-dimensional hydraulic models in HEC-RAS were developed for each of the APSFRs in Montenegro. Flood hazard in Montenegro is depicted through its probability and the intensity of flooding (for a given return period).

The relevant return periods for hazard map production are T = 10 years (flood with a high probability of occurrence), T = 100 years (medium probability of occurrence) and T = 500 years (low probability of event). The flood hazard intensity is expressed by intensity classes (ranging from 1 to 4), which are assigned according to the flood depth values calculated in the model, as shown in Table 5.3. This means that corresponding flood depths are already available – they can be directly exported from the previously formed hydraulic model. Figure 5.7 depicts the available hazard data (intensity classes) for one APSFR (river Ibar) located in Rozaje, one of the cross-border municipalities that are used to examine the exportability of harmonised risk assessment methods. The water depths could also be obtained using the suggested FwDET algorithm as stated in the guidelines since the DEMs (5m x 5m) are available for the entire county's territory. In this case, only the flood extent from the hazard maps (created for the three mentioned return periods) would be used for the process. For the cross-border flood-prone areas in Montenegro, it would be necessary to harmonise the hazard maps with the neighbouring countries, i.e. the information on the return periods used for their hazard maps production would be required. Suppose the analysed return periods were different between the countries. In that case, the interpolation procedure proposed by guidelines could be applied to obtain a set of flood hazard maps with a specific return-time step. Another possible approach could be to interpolate the hydrological input, i.e. to determine the boundary conditions and hydrographs that correspond to the harmonised values of return periods and then run the model with this new input (since the hydraulic models have already been developed). The calculated flood extent could be exported from the model for future use for cross-border risk assessment following the guidelines.

Table 5.3: Hazard intensity definition

Water depth	Intensity class
0.0-0.5m	1
0.5-1.0m	2
1.0-5.0m	3
> 5.0m	4

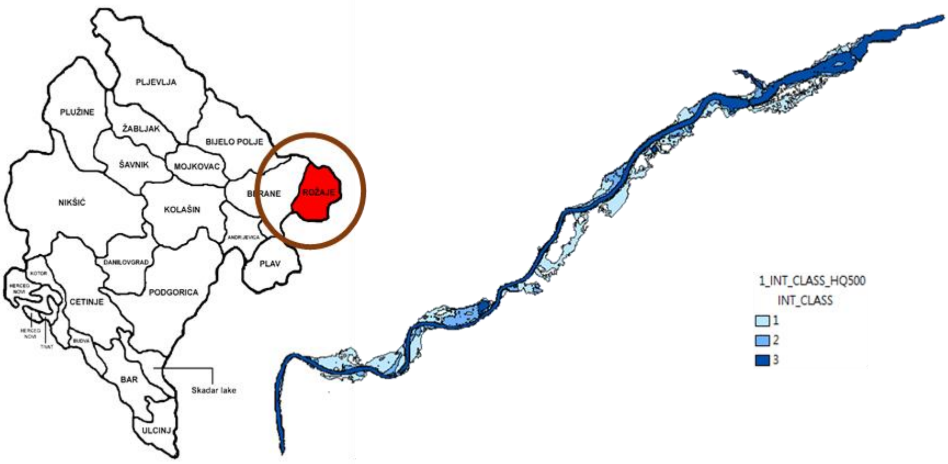

Figure 5.7: Location of Rozaje municipality (left) and Hazard intensity for river Ibar in Rozaje for T = 500 years (right)

Concerning the exposure model, in the BORIS guidelines, considered elements include population and residential buildings. It is worth mentioning that in the identified APSFRs in Montenegro, high waters endanger settlements, agricultural lands, and industrial plants. Agricultural areas located in river valleys, although relatively humble in size, are essential for agricultural production because the total resources of agricultural land in Montenegro are minimal. Due to such a concentration of goods in the valleys, the damage caused by floods, even on a relatively small spatial scale, can be significant.

As for the raster representation of the buildings located in the designated APSFRs, there is a high-resolution Orthophoto footage dating from 2018. available for the entire country (Figure 5.8a). This footage would make a good base layer for the visualisation of the results – for showing the flood extent and other relevant calculated data concerning the risk. One of the critical inputs for building the exposure model according to the guidelines is the population datasets. There are no ready-made population maps in Montenegro, but there is census data (the last census dating from 2011.). This data provides the total number of inhabitants for each settlement (a spatial scale smaller than a municipality – each municipality consists of a certain number of settlements, as shown in Figure 5.8b). Table 5.4 shows available population data for settlements that comprise the analysed APSFR in the municipality of Rozaje. A possible way to create continuous population distribution data would be to downscale the population numbers using the settlement area. The vector file containing the boundaries of settlements is available, so when the total number of inhabitants is divided by the settlement area – the average population density is obtained for each settlement. If the settlement boundaries are intersected with the flood extents (for each return period) – the flooded area of each settlement is obtained, and when multiplied by the average population density (for that settlement) – the affected population is obtained for each settlement. This method would not yield the most precise results since there are settlements in Montenegro which are very sparsely inhabited. The method delineated in the guidelines would be more accurate in estimating the affected population. Still, it would be necessary to acquire information about the building usage and the number of storeys currently unavailable.

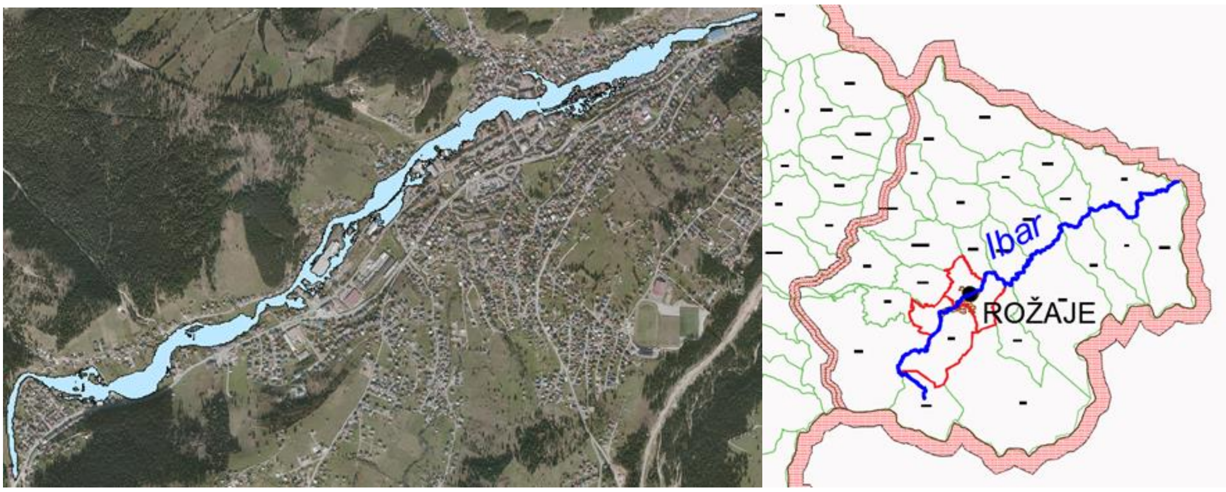

Figure 5.8: a) Orthophoto footage that could be used as a base for exposure model (example of river Ibar in Rozaje municipality) and b) Division of Rozaje municipality into settlements

Table 5.4: The number of inhabitants per settlement for settlements that belong to APSFR located in the basin of river Ibar, Rozaje municipality (red border in Figure 5.8b)

Municipality	Settlement	Total number of inhabitants
Rozaje	Rozaje	9422
Rozaje	Ibarac	3135

As for vulnerability modelling – mesoscale models would be easier to apply in Montenegro since they work at more aggregated scales. The land use data available online (such as Corine land cover, for example) is inappropriate due to its rough scale, which would be insufficient for relatively small areas with different land uses in Montenegro. Therefore, land use shape files (containing polygons with other land use assigned as attributes) are formed based on valid urban planning documents (Figure 5.9). Currently, there are no damage models developed, neither relative nor absolute. To perform any damage assessment, it would be necessary to rely on some of the methodologies for estimating damage functions or previously established catalogues of functions that may be found in the technical and scientific literature. To apply the HAZUS functions (recommended in the BORIS project), which describe the relationship between the flood depth and the damage suffered, it would be required to build a microscale exposure model (containing information on building occupancy and number of floors).

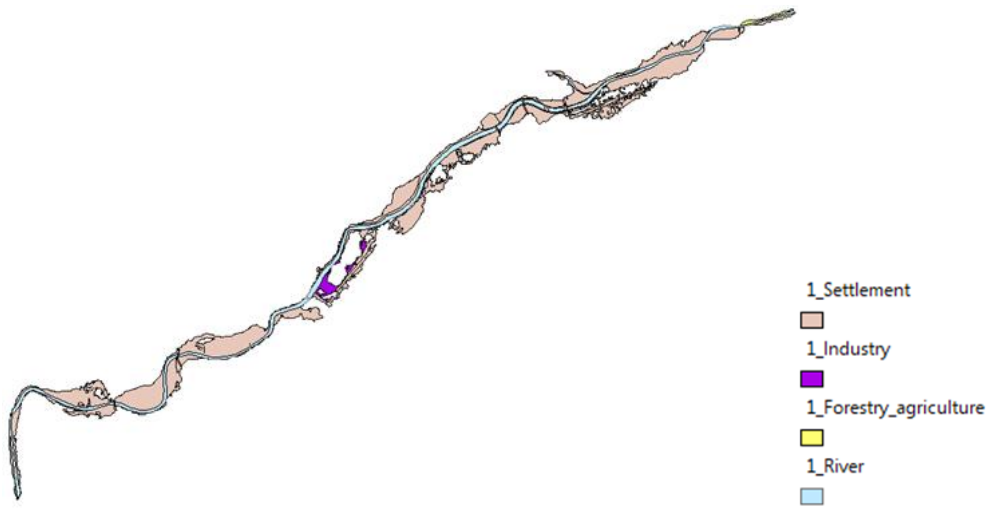

Figure 5.9: Land use classes for APSFR in Rozaje municipality

The consequences, in terms of the affected population, have been defined through the exposure model. The consequences, in terms of economic damages, could be calculated based on the previously formed vulnerability model for each flooded building. The damage ratio could be determined based on the vulnerability function and then multiplied by the economic value of that building type.

5.1.3 Transferability of the methodology for multi-risk comparison and ranking

As previously shown, the shared methodology is applicable at the borders of Montenegro, considering each risk separately. Also, the proposed framework of a multi-layer single-risk assessment is acceptable considering the end-user needs in Montenegro. The steps (1 to 5) given in the guidelines (Section 4) and their exportability to the Montenegro cross-border sites are proven and commented (Sections 5.1 and 5.2). Ranking risks through deriving risk curves and calculating corresponding EAL is possible for each municipality of the considered Montenegrin cross-border site and presents additional computation effort after a time-based single risk assessment is conducted.

5.2 Transferability to cross-border areas in Türkiye

5.2.1 Transferability of the methodology for seismic risk assessment

The approach for cross-border seismic risk assessment described in this report requires four models, i.e. the seismic hazard model, vulnerability model, exposure model and consequence model. Below, we present the discussion on cross-border seismic risk assessment procedure defined in this report with an emphasis on the limitations for the application to Turkish cross-border areas.

As mentioned in Section 2.2, the results of the seismic hazard assessment performed for the entire investigated cross-border area can be employed as the hazard model. However, if no hazard assessment has been performed specifically for the cross-border area, then a hazard model developed for a wider area can be used. The hazard model adopted in the BORIS project, the European hazard model (ESHM2020), does not cover the neighbouring countries of Türkiye to the east and south-east. Thus, the 2014 Earthquake Model of the Middle East (EMME14) might be included as mentioned in BORIS (2022a). But, the differences in the ESHM and EMME hazard models should be analysed and they should be harmonized if necessary to obtain comparable seismic risk assessment results at different cross-border regions involving Türkiye. In addition, they should be compared with the Earthquake Hazard Map of Türkiye (AFAD, 2018) especially in the Turkish side of cross-border areas. In Section 2.2, it is suggested that one or more local maps with Vs30 values are used to account for the local soil effects in the cross-border area analysed. In this regard, there is an ongoing study on the determination of the Vs30 values for the AFAD earthquake observation stations distributed throughout Türkiye. Besides, there is an ongoing project, supported by the National Earthquake Research Program of AFAD, for the development of empirical relationships between the geological units, topographic elevation data and Vs30 in Türkiye using a digital geological map, digital topographic height data and a Vs30 sample with certain coordinates. These relationships can be used to produce digital estimated Vs30 maps in grid and raster formats, which can be used in GIS applications.

As for the exposure model, the nationwide data used by AFAD in scenario-based seismic risk assessment studies by utilizing AFAD-RED (Rapid Earthquake Damage and Loss Estimation System) includes only the number of buildings and population in each neighbourhood/village. In other words, the data does not contain any other information that could be used in the classification of buildings useful in the vulnerability assessment, such as the material of the load-bearing structure, the number of storeys, the construction period, etc. On the other hand, there are studies on building inventory in Türkiye. The most comprehensive study carried out on a national scale is the MAKS "Spatial Address Registration System Program". Another source of the data is the KAYES-Public buildings inventory system. In this system, as of 2020, earthquake risk inventory information of public buildings from 81 provinces was collected by the Ministry of Environment, Urbanization and Climate Change. There is also another study related to the determination of the building inventory on a provincial basis, which is being performed within the scope of "Provincial Risk Reduction Plans" (IRAP) carried out by AFAD.

Developing the vulnerability model for cross-border seismic risk assessment procedure defined in the BORIS project requires the classification of buildings based on their typology, unifying the damage scales used by participating countries, definition of vulnerability models for the building stock in the cross-border area or harmonization of the available national models. As mentioned above, the nationwide data used by AFAD-RED includes only the number of buildings. Therefore, fragility curves, which are average for all buildings, are utilized in current analyses. As for damage scale, four damage states (i.e., slight, moderate, extensive and complete) are defined in AFAD-RED. If the other countries participating in the cross-border risk assessment, including Türkiye, use different damage scales, a conversion to a common damage scale can be needed. In this deliverable, the PGA is considered as the intensity measure. On the other hand, spectral displacement and seismic intensity-based fragility curves are utilized in current analyses by AFAD-RED. As a result, the implementation of the methodology explained in Section 2.4 for the definition or harmonization of the vulnerability models might require a literature survey on the available vulnerability models that could be applied to the building stock in the Turkish side of the cross-border areas.

The assessment of seismic risk in terms of consequences is crucial to understand the potential impact of earthquakes, set up seismic risk management strategies and enhance preparedness measures and emergency planning. Regarding outputs of AFAD-RED, the following impact indicators are used to express the consequences of an earthquake: numbers of slightly, moderately, extensively and completely damaged buildings; numbers of outpatients, slightly injured people, severely injured people and life loss; the number of people who need temporary shelter as well as serviceability of critical facilities, transportation systems and lifeline systems. So, the number of collapsed buildings, deaths and injured people are common with the impact indicators used in the BORIS project. Since the proposed method for estimating the number of unusable buildings in short term and in long term is based on the number of buildings in each damage level, it can be adopted in cross-border seismic risk assessments, including Türkiye. The harmonized consequence function for the estimation of direct economic losses due to buildings requires a percentage cost of repair or replacement for each designated damage state, the built area and the reconstruction cost of the buildings. As mentioned above, the nationwide data does not contain this information. So, some further studies may be required to obtain it. It should also be noted that considering the potential regional differences in construction practices, validation and calibration/modification of the adopted harmonized consequence functions can be required.

The neighbouring countries of Türkiye do not participate in BORIS project. There might be differences in the data and models used in seismic risk assessments in Türkiye and the neighbouring countries. Therefore, the procedure described for cross-border seismic risk assessment in this deliverable might not be directly applicable to seismic risk assessments in the Turkish cross-border areas. But, the main framework of it might be adopted through similar international projects and collaborations. As one of the "beneficiary" countries in the BORIS project, Türkiye can utilize the experiences learned from the BORIS project in such projects. As a result, dissemination of this kind of projects, like BORIS, can be provided through increasing awareness of decision-makers.

5.2.2 Transferability of the methodology for seismic risk assessment

Because, in Türkiye, the flood risk management plans are being prepared in line with the EU Floods Directive (2007/60/EC), the methodology for flood hazard and risk assessment suggested in the BORIS project is highly resemble.

Two types of flood events, fluvial floods (riverine floods) and flash floods, are taken into consideration in the scope of flood risk management. Flood hazard assessment in Türkiye has a certain approach that follows the general probabilistic approach where the flood hazard classes are defined based on the hydrologic and hydraulic modelling with return periods of 50-, 100-, 500- and 1000-years. Flood frequency analysis is used to calculate relevant return periods for hazard map production. Therefore, calculation of specific return-time intervals would not be an issue.

Concerning the exposure model in the BORIS guidelines, population and residential buildings are considered elements included in the calculation. In Türkiye, there are census data from 2021. These data provide the total number of inhabitants for each settlement, each municipality, and each district.

Concerning to mapping, a new approach called Photogrammetric Texture Mapping has been using in Türkiye to obtain digital terrain through stereo images which provides up-to-date data. As a result of this new methodology, stock information is also more detailed.

As mentioned previously, the neighboring countries of Türkiye do not participate in the BORIS project. Because the flood risk management in Türkiye is in line with EU Floods Directive (2007/60/EC), differences in the data and models used in flood risk assessments between Türkiye and the neighboring countries are not expected. Therefore, the procedure described for cross-border flood risk assessment in this deliverable could be harmonized to apply in the Turkish cross-border areas. But, the main framework of it might be adopted through similar international projects and collaborations. In case of a cooperation, this cross-border flood risk assessment methodology facilitates to implement in trans-boundary river basins between Türkiye and neighboring countries. As a result, dissemination of this kind of projects, like BORIS, can be provided through increasing awareness of decision-makers.

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