BORIS

Cross **BO**rder **RIS**k assessment for increased prevention and preparedness in Europe

D4.1

Guidelines for cross-border risk assessment: Shared framework for single and multi-risk assessment at cross-border sites

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1. SUMMARY

Transboundary risk assessment cannot be based directly on national risk assessment because the neighbouring countries use different risk assessment methodologies and levels of detail. To address this issue the harmonisation process was carried out with the aim to establish the use of shared approaches, employ common data type and analysis models, which allow to represent the impact of the flood and seismic hazards in a shared framework established among the countries. Moreover, in areas that are threatened by different hazards, their relative importance can be suitably evaluated and a proper methodology for risk comparability in a multi-risk framework should be put in place.

Therefore, building on the results of the needs and gaps analyses performed in the WP2 "Analysis of the context and needs assessment", the first two tasks of WP4 aimed at addressing and solving issues related to effective cross-border single risk harmonization with consideration of seismic risk (Task 4.1) and flood risk (Task 4.2). The objective of these tasks was achieved by introducing a shared methodology aiming to improve the knowledge and understanding of disaster risk towards the most effective prevention, mitigation, preparedness and response to flood and seismic events. Moreover, task 4.3 proposed a shared framework to compare and rank the single risks in multi-risk perspectives, evidencing the possible solutions to achieve such harmonized approach.

A common denominator to the approach employed for both the single risk analyses is the need to allow comparability of results towards multi-risk assessment. Therefore, a scenario-based approach is excluded because it could hardly be applicable due to the difficulty to find or simulate historic scenarios having comparable likelihoods for both the risks and because such an approach does not account for the relative difference between the consequences of flood and earthquake scenarios with varying mean annual return period. Conversely, the proposed shared methodologies for single risk assessment, either seismic risk or flood risk, are based on a probabilistic approach and on adopting the risk curves as a fundamental tool for effective risk representation in each unit area of analysis. While the spatial scale for single risk analysis remains different, namely the municipality scale for seismic risk and building footprint scale for flood risk, the final risk results expressed in the chosen metric are represented at the same scale, i.e. at the level of municipality.

Each considered risk, seismic and flood risk, is determined by coupling the hazard, vulnerability of the assets at risk and exposure in each unit of analysis. Therefore, the harmonization of each model of risk analysis is necessary. Moreover, the method to evaluate the consequences, e.g. economic losses depending on estimated damage, has to be harmonised among different types of natural hazards to achieve its unbiased prediction.

Concerning seismic hazard in the transboundary region (section 3.2.1), the shared methodology proposes to adopt the ESHM2013 or the newly available ESHM2020 model, covering the whole European territory, including Turkey. Indeed, such models were already developed with the aim to provide integration across national borders. The issues regarding homogenization of data type and methods to evaluate site amplification in confining countries are also discussed. Future needs for the seismic hazard model development are presented in section 3.3.

Concerning seismic vulnerability (section 3.2.3), it is proposed to define a harmonized vulnerability model for cross-border risk assessment based on existing vulnerability models. In particular, a heuristic approach

allowing to combine existing models in each one of the confining countries and suitably taking into account the differences in the relative vulnerability models as well as building typologies is proposed. However, the proposed harmonized vulnerability model is a compromise. The solution in the long term is to develop the EU standards for performing risk studies to natural hazards.

As for the exposure model(section 3.2.2), an approach to obtain homogeneous typological-based building classification is proposed. Moreover, in case of relevant data, which would allow assembling building inventory at the required scale of analysis, is missing, a possible solution allowing to exploit existing global exposure databases and to downscale relevant information based on speed interview-based survey is proposed.

The most challenging issue concerning flood risk assessment is the harmonization of flood hazard assessment. In particular, a simplified approach to assess flood harmonized hazard curves that can be applied in cross-border areas is proposed (section 4.2.1). It is based on the results of the EU Floods Directive in the different cross-border basins of the Countries considered in BORIS (Italy, Slovenia and Austria). The method represents a simple but effective procedure to generate flood hazard maps that are fully compliant with the results provided by each Member State within the EU floods Directive. Moreover, the method allows to further elaborate the flood hazard maps by defining flood scenarios (extension and depth) with return periods from 10/30 years to 300/500 years with a yearly timestep. In this way, a flood hazard curve can be easily defined for each point (5m resolution) of the cross-border catchments considered.

Concerning flood vulnerability (section 4.2.3), it is chosen to rely on existing consolidated models from literature, allowing to estimate the expected damage on building typologies based on the flood depth.

As for exposure (section 4.2.2), a methodology to build harmonize exposure database necessary to perform analyses at the building footprint level is proposed. Such methodology requires first the collection of built-up area and population from global databases. In the next step, the building footprints for the built-up and the census data for the population are identified. Finally, the downscaling of the global data is carried out by applying integrative GIS-based approach to determine a spatial distribution of the residential population (which can be used to evaluate affected people), the economic values of the built-up and the factors describing the vulnerability of the buildings.

The multi-risk assessment in BORIS is performed in the framework of a multilayer single risk assessment. In this context, the risk curves are the most appropriate tools for consistent quantitative assessment of the single risks towards their effective comparability. Therefore, no hazard interaction nor vulnerability interaction are considered, but the shared framework (section 5.2) is obtained by adopting the same boundary conditions for the analysis (common area, time frame of analysis and metric to represent the risk) as well as the same methodological approach to compute the probabilistic risk curves. To obtain an effective multi-risk harmonization, relevant issues are considered and solutions proposed (section 5.3). Concerning the spatial scale (section 5.3.1), even though the analyses for the single risks are performed at different scales, it is proposed to represent the risk results for risk comparison and ranking at the municipality scale. The assets at risk (section 5.3.2) considered in the analyses are residential buildings and the population. The metric to evaluate the impact (section 5.3.3) is measured in terms of direct economic losses and affected population and proposal for harmonization of the damage-to-loss functions is presented. Finally, cross-risk harmonization of vulnerability and exposure data is discussed (section 5.3.4), and future developments are discussed in Section 5.4 with a final objective to develop an EU standard for multi-hazard risk assessment.

2. INTRODUCTION

In line with the indications of (Decision No. 1313/2013/EU) of the European parliament on the objectives for the Union Civil Protection Mechanism and the relative updates (REGULATION (EU) 2021/836), particularly to fulfil and enhance prevention and the risk management process, as well as to improve resilience and planning for disaster prevention, preparedness and response, there is the need to perform regular risk assessments and analyses of disaster scenarios at the national and subnational level. Referring to cross-border disasters, comprehensive risk management approaches that underpin prevention and preparedness, taking into account a multi-hazard approach, are encouraged (REGULATION (EU) 2021/836), fostering close cooperation with the relevant scientific communities as well as with regional and local authorities that are key stakeholders in the risk management process.

In this framework, the BORIS project focuses particularly on the development of cross-border risk analyses having the aim to improve the understanding of the disaster risk, coherently with the first priority of action of the Sendai Framework for Disaster Risk Reduction 2015-2030 (United Nations, 2015). The activities devoted to improving knowledge and understanding of risk assessment are based on 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. In addition, risk analysis can also help to improve preparedness for dealing with disasters, as it can facilitate efforts such as exercises and training organized based on pre-determined scenarios. However, these features towards risk mitigation are not the main focus of BORIS. Indeed, a sound response planning would require a detailed scenario-based assessment of expected damage and impact distribution at a district or smaller scale, encompassing the evaluation of the impact on residential buildings as well the evaluation of critical and emergency facilities (e.g. hospitals, schools), of connection infrastructures and their post-earthquake functionality, and should consider the availability of means and resources for effective logistic planning of rescue intervention. While this kind of information would certainly be of interest also in the framework of transboundary risk assessment, the level of detail and amount of data required for a consistent evaluation would hamper the possibility of application to larger cross-border areas. In fact, generally, these types of studies perform response-oriented applications in focus areas limited to single towns or districts (Dolce et al., 2018; Giuliani et al., 2020) or with the aim to simulate the consequences of disastrous historical events (Dolšek et al., 2020). Therefore, with the aim to build a shared and harmonized framework for cross-border risk assessment, allowing to perform risk analyses for better prevention and preparedness at a regional scale and not limited to a single town or district, the BORIS project will focus mainly on (residential) buildings and population as exposed assets at risk. The analysis of the total costs of earthquakes in the last years has highlighted that about the 50% of these costs are due to direct losses to dwelling buildings, i.e., costs related to the repair or reconstruction of residential buildings (Dolce and Di Bucci, 2017). In the case of floods, damage to buildings is minor if compared to damage to other goods (e.g., vehicles, contents). However, despite the minor damage, direct economic losses mostly involve repair costs of such damage to buildings and replacement costs of existing household contents (Luino et al., 2009; Arrighi et al., 2018).

3. SHARED METHODOLOGY FOR SEISMIC RISK ASSESSMENT

3.1. Seismic risk assessment and the needs for transboundary harmonized approach

Seismic Risk depends on seismic hazard, on the vulnerability of the considered assets at risk and on their exposure. If deterministic scenario approach for seismic risk estimation is adopted, as is the case for example for the National Risk Assessment applied in Slovenia and Montenegro (BORIS, 2021b), the hazard is described by scenario earthquakes that are determined based on historic events or corresponding to most likely and/or worst possible consequence events. On the other hand, if the seismic risk has to be compared with other type of risks, induced by diverse hazardous events (e.g. floods), a scenario based approach is not the most appropriate way to proceed, since it would be difficult to find historic scenarios, or simulate them, having comparable likelihood. Moreover, the overall impact associated to different kind of hazards may be greatly variable for different return periods. Indeed, as shown in Grünthal et al. (2006), in areas of relatively low seismic hazard and prone to flood risk, as for example the city of Cologne, for higher exceedance probabilities the risk is clearly dominated by events such as floods, while at lower probability levels, e.g. $5 \cdot 10^{-3}$, corresponding to 200 years return period Tr, the risk associated to earthquakes is higher with respect to that for floods. Hence, comparing the effect of different hazards at the same return periods does not allow a comprehensive assessment of the effective risk in an area. On the other hand, by evaluating the entire risk curve it is possible to consider the impact that is associated to the different annual frequencies λ of a hazard. A risk curve is a curve relating the level of impact that will be surpassed in given time period with the actual probability of the hazard; the curve is developed for varying hazard levels from low to very high. The risk curve is also called the exceedance probability curve and it is the usual output of the full probabilistic approach (Poljanšek et al., 2019).

If the impact is expressed in terms of economic losses L, the area under the λ-L curve represents all the possible losses in the reference time frame considered for risk analysis, that is the mean expected annual loss EAL. As noted in (Poljanšek et al., 2019), the EAL has the advantage to accounting for cumulative damage of small impact and frequent events next to rare and big impact events.

Therefore, in viewpoint of multi-risk assessment and for having the possibility to compare and rank different risks in an area, it is preferable to employ a probabilistic-based risk analysis.

In this context, the seismic hazard, expressing the probability of exceedance of levels of ground motion in a certain interval of time at a site, is obtained by Probabilistic Seismic Hazard Analysis (PSHA).

Seismic vulnerability for assets at risk (e.g. building classes) represents their susceptibility to be damaged by earthquakes, as a function of the seismic intensity. The vulnerability can be described through fragility curves, expressing the probability of attaining different levels of damage by varying the seismic intensity, damage probability matrices (DPM), representing the conditional probability of obtaining different damage levels given the earthquake intensity or vulnerability curves, that represent the variation of a mean value of damage with the earthquake intensity (Dolce et al., 2021).

As for exposure, it describes the quality and quantity of the assets at risk in the region of interest. For example, referring to buildings as assets at risk, the building inventory gives number of buildings and percental distribution in the different vulnerability classes. This inventory is linked to the vulnerability model so that the assets at risk, based on their typological characteristics, are clustered in a certain number of vulnerability “classes” to which a specific vulnerability model is associated.

The probabilistic based calculation of seismic risk involves the convolution of the seismic hazard at the site with vulnerability and exposure of the assets at risk. As noted in (Tocchi et al., 2022), even when performing territorial based risk assessment, the calculation is point-wise, meaning that it is performed for each point (e.g. the geographical barycentre of a municipality) to which both hazard and exposure data are referred; global results for a larger area are obtained by summing up for all the points in a region.

Obviously, to obtain consistent results in a cross-border area, the same models for hazard, vulnerability and exposure should be employed. However, as also noted in (BORIS, 2021a), the models used in different nations to perform national risk assessment are different. As example, comparing the models for Italy and Slovenia (for Slovenia we refer here to model used for the Stress-Test, as introduced in D2.1), it can be noted that they employ not homogeneous hazard models, different criteria for buildings classification and methods to build fragility curves, variable granularity for building exposure assessment. Therefore, there is clearly the need to build a harmonized model for transboundary risk assessment, encompassing the adoption of harmonised hazard, vulnerability and exposure models.

In the next sub-sections the approaches for hazard, vulnerability and exposure modelling are resumed, evidencing the possible differences that may arise and solutions that could be adopted towards harmonization.

3.1.1. Seismic hazard

Seismic hazard is measured by the frequency of earthquakes with different levels of ground motion intensity. For the purpose of earthquake-resistant design, seismic hazard assessment is normally performed at a national level. Usually, countries develop their own official seismic hazard models. This is also the state of practice in the countries participating in the BORIS project (BORIS, 2021a). However, in some cases, additional seismic hazard models are employed or newly developed for the purpose of a risk assessment at a local or national level. For example, in Slovenia, the official national seismic hazard model (Lapajne et al., 2003) as well as a more recent European SHARE seismic hazard model (Giardini et al., 2014, Woessner et al. 2015) were used for the purpose of a seismic stress test (Dolšek et al., 2020). Therefore, many different seismic hazard models may exist for a given cross-border area. These hazard models may not be compatible, due to different approaches to the seismic hazard assessment. In the following, potential differences between the hazard models are pointed out and resumed in Table 3.1.

One potential point of difference between seismic hazard assessments performed for different parts of the same cross-border area is the intensity measure. Many types of intensity measures can be used in the seismic hazard assessment, e.g. peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), the European macroseismic intensity (EMS-98), spectral acceleration at a given vibration period and others. Although spectral acceleration at the fundamental building period or average acceleration in a given period interval may be a more efficient ground motion intensity measures for the seismic performance assessment of a building, the most common seismic intensity measure is still the PGA, which is also the intensity measure considered in the seismic hazard assessments performed in the countries participating in the

BORIS project. Thus, it is reasonable to expect that two neighbouring countries that would be involved in a cross-border risk assessment would have their own maps of the PGA related to the designated return periods. However, even if this is not the case, harmonization in terms of the seismic intensity measure can be achieved by applying conversion rules between different intensity measures. For example, the conversion between the PGA and spectral acceleration can be performed based on the shape of the acceleration spectrum. Moreover, conversion rules relating ground motion parameters such as the PGA, PGV or PGD, to the macroseismic intensity were proposed by several authors (e.g. see Fasan, 2019; Zanini et al., 2019; Masi et al., 2020). In general, such conversion rules consist of a linear relation between the macroseismic intensity and the logarithm of a ground motion parameter (e.g. PGA, PGV, PGD), differing in the type of correlation used and the type of macroseismic intensity considered (e.g. MSC, MSK, EMS-98).

Another potential difference between two seismic hazard assessments is the basis on which the assessments are performed. The seismic hazard can refer to a single scenario, which is defined, for example, by the magnitude and the hypocentre (e.g. Babič et al., 2021b) or by the macroseismic intensity and the epicentre (e.g. GRS, 2020). Such a hazard assessment is herein referred to as a scenario-based hazard assessment. A different approach is a hazard assessment that refers to the mean annual return period of an event characterized by the level of the ground motion intensity, which is herein referred to as a return period based hazard assessment and is common to all countries participating in the BORIS project (BORIS, 2021b). Therefore, it is a reasonable choice for a cross-border analysis, especially because it is necessary for a return period based or a time-based risk assessment. However, even with a return period based hazard assessment, a problem occurs if two neighbouring countries consider different return periods. This is also the case in the countries participating in the BORIS project. For example, the seismic hazard in Austria is assessed for one return period, the one in Italy considers nine return periods, and the one in Slovenia considers any given return period, although the validity of seismic hazard is limited to a certain return period. In order to harmonize the return periods, interpolation of the available results may be performed. Because the seismic hazards function is approximately linear in the logarithmic domain, such interpolation should also be linear in the logarithmic domain. However, the extrapolation of the results of seismic hazard assessment to intensity levels outside the intensity range directly considered in the hazard assessment is less reliable and can lead to significant error in the estimated risk, as observed by Bradley and Dhakal (2008).

Furthermore, microzonation for soil effects consideration may not be available or may not be expressed in the same way in all countries sharing the cross-border area. For example, in Italy, soil effects are considered via an amplification map containing Vs30 values, which allows soil effects to be estimated in each municipality or census point. Similarly, a Vs30 database is available in Turkey. However, in Slovenia, soil classes according to the Eurocode have been estimated at all locations of buildings based on the known geological characteristics and past studies. Such a soil class map can be a rough basis to define the Vs30 map itself. Similarly, only soil classes have been identified for some locations in Montenegro, while local soil classes have not been yet considered in detail in Austria earthquake hazard assesements. For cross-border seismic risk estimation, however, soil effects should be considered at least approximately. One option is to estimate the Vs30 values based on the geological characteristics or by using a global Vs30 map (e.g. Worden and Heath, 2019). More detailed Vs30 maps can, in the future, provide slightly more accurate results. However, other effects on site-specific ground motions intensities should also be systematically studied in the future.

Moreover, national seismic hazard models usually cover the entire territory of a country. It is common that the mesh of the grid for which the hazard values are calculated differs from country to country. For example, a

5×5 km mesh is used in Italy and Slovenia, while a spacing of 0.1°×0.1° in latitude and longitude is considered in Turkey. Some type of conversion rules would be needed in order to harmonize the results. However, even if the grid mesh is already harmonized, additional conversion may be needed in cases where the seismic risk assessment is performed at the level of single administrative units (e.g. at a municipality level) in order to obtain the hazard representative of the given administrative unit.

Due to the aforementioned differences in seismic hazard assessment for rock-equivalent outcrop motion, the simplest approach to cross-border harmonization would be the use of a seismic hazard model that encompasses all countries involved in the cross-border assessment. Fortunately, such models exist for the European territory, including Turkey. They include the 2013 and the 2020 Euro-Mediterranean Seismic Hazard Models (ESHM2013 and ESHM2020) (Woessner et al., 2015; Weatherill et al., 2020). It is recommended to use these models, which are described in more detail in Section 3.3.1. However, the national seismic hazard models can still be used to quantify the uncertainty in seismic hazard assessment.

Table 3.1: Possible differences in Seismic Hazard Modelling

Feature	Example 1	Example 2	Example 3
Ground motion intensity measure	Objective (measurable) peak quantities: PGA, PGV, PGD.	Objective (measurable) spectral quantities: spectral acceleration, spectral velocity, spectral displacement.	Subjective (observational) quantities: macroseismic intensity (e.g. MSC, MSK, EMS-98).
Assessment basis	Scenario-based assessment: for scenarios defined, e.g., by the magnitude and hypocentre or by the macroseismic intensity and epicentre.	Return period based assessment: for different designated return periods.	
Microzonation for soil effects consideration	Considered via an amplification map containing Vs30 values.	Considered via a map of soil classes that are based on the interval of Vs30 values.	Information on the local soil effects unavailable
Assessment scale	Hazard assessed performed for each administrative unit.	Hazard assessed for a grid of points: grid defined in terms of UTM coordinates (e.g. 5 × 5 km mesh).	Hazard assessed for a grid of points: grid defined in terms of latitude and longitude (e.g. 0.1° × 0.1° mesh).

3.1.2. Seismic vulnerability

Seismic vulnerability for buildings expresses their propensity to sustain a certain damage level given a specific ground motion intensity. Although there are several approaches to derive and represent the seismic vulnerability, there are some common logic steps that are needed in order to proceed, briefly listed below (Polese et al. 2019):

1. The first step is to provide a suitable classification of the exposed assets, i.e. identify the typological characteristics of those objects that define the seismic behaviour of a "class" and that are identifiable at the territorial scale of analysis;
2. Next, a damage scale has to be established;
3. The propensity of buildings 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 vulnerability functions.

Depending on the vulnerability model adopted, the building classification can be different. For example, it may be based on the sole construction material of the vertical structure as in EMS98 (Grünthal, 1998), or it can employ further information on the building features that are relevant for seismic behaviour, e.g. construction age or code design level, storey number or building height ranges etc. In general, consideration of a greater number of descriptive variables of buildings increases the precision of the vulnerability model. However, publicly available data is often limited, which can prevent one from adopting a highly sophisticated vulnerability model. In fact, the level of detail of the information at hand can be the governing factor in defining the building classification and selecting or developing the vulnerability model.

The building classification can be purely typological, if the information required by vulnerability model concern only construction material (e.g., masonry, reinforced concrete, steel, mixed structures), period of construction and number of storeys. However, the typology-based classification can also be combined with the exposure model to obtain the vulnerability-based classification, where buildings are assigned to pre-defined vulnerability classes. According to vulnerability-based classification, buildings are grouped in classes based on the construction material and load resisting system type (es. Unreinforced masonry buildings with rubble stone, unreinforced masonry buildings with simple stone,reinforced concrete frame with earthquake-resistant design, shear walls, etc.). Generally, for masonry structures also the types of slabs or the presence of horizontal connection are taken into account (Braga at al. 1982, Rota et al. 2008, Del Gaudio et al. 2019). Another possible classification of buildings can be obtained assigning suitable indices depending on relevant vulnerability factors. In index-based classification other vulnerability factors for buildings could be considered in addition to the factors already considered in other classification schemes, such as, e.g., the presence of irregularity in plan or in elevation or the building position in the block. With index-based classification scheme, a vulnerability index is calculated assigning a weight for all relevant buildings vulnerability factors and finally the vulnerability class which buildings belong to is defined based on the vulnerability index value. Examples of index-based vulnerability classification can be found in Lagomarsino et al. (2006) and Zuccaro et al. (2015). It is possible that two neighbouring countries use different types of building classification in their risk assessment. In such cases, it makes sense to use the typology-based classification, which is the more basic one allowing to compile building inventory using data easily available in both countries.

Concerning damage, different scales may be adopted to describe its severity depending on the building typology. The reference scale for empirical methods in Europe is defined in EMS98 (Grünthal, 1998). It identifies five damage grades D_k (k = 1/5), that are defined based on the observed damage for both structural and non-structural components; also the absence of damage D_0 (no damage) is introduced. On the other hand, other proposals are widely employed, as for example the HAZUS damage scale (FEMA, 2015), which includes four damage states (slight, moderate, extensive, complete). If the countries participating in the cross-border risk assessment use different damage scales, a conversion to a common damage scale is needed, as further discussed in Section 3.2.3.

Table 3.2: Possible differences in Seismic Vulnerability Modelling

feature	Example 1	Example 2	Example 3
Building classification	Typology-based classification: classes are distinguished based on construction material and age or code-class (e.g. FEMA , 2015; Babič et al., 2021b)	Vulnerability-based classification: building classification is performed combining the typological based classification and the exposure model; the latter assigns the percentage belonging of each typology to few pre-defined vulnerability classes (e.g. Di Pasquale et al., 2005; Rosti et al. 2021a,b; Borzi et al., 2021; Lagomarsino et al., 2021; Zuccaro et al., 2021; Donà et al., 2021)	Index-based classification for which preliminary classification is based on the material of vertical structures, as in EMS98, and then more detailed classification is possible considering additional vulnerability factors (e.g. type of masonry or type of horizontal structure for masonry buildings) (e.g. RISKUE - Lagomarsino et al., 2006; SAVE - Zuccaro et al., 2015a)
Damage Scale	HAZUS (FEMA, 2015) Four structural and nonstructural damage states are considered: DS1 Slight, DS2 Moderate, DS3 Extensive, and DS4 Complete. Descriptions of these damage states are provided for all model building types with reference to observable damage incurred by structural and nonstructural building components	EMS98 (Grünthal, 1998) Five damage grades are considered Dk (k = 1/5), that are defined based on the observed damage for both structural and non-structural components for masonry and reinforced concrete constructions. Also, the absence of damage D0 (no damage) is introduced.	
Vulnerability modelling	Lognormal fragility curves (HAZUS (FEMA, 2015; Da Porto et al., 2021; Babič et al., 2021b)	DPM depending on macroseismic intensity I (Braga, et al., 1982; SAVE - Zuccaro et al., 2015a)	
Intensity measure	Objective (measurable) peak quantities: PGA, PGV, PGD.	Objective (measurable) spectral quantities: spectral acceleration, spectral velocity, spectral displacement.	Subjective (observational) quantities: macroseismic intensity (e.g. MSC, MSK, EMS-98).

The seismic vulnerability can be expressed with suitable matrices, functions or curves, representing the propensity of a building class to sustain different levels of damage varying the seismic intensity. In the last decades, several vulnerability models were developed to estimate damage likelihood for ordinary building types, realized, e.g. by masonry (M) or reinforced concrete (RC) structure. Different approaches can be used to develop vulnerability models, including (1) analytical approaches, (2) empirical approaches and (3) heuristic or hybrid approaches. Another relevant source of possible inhomogeneity of different models is the intensity parameter used to represent seismic input, e.g. macroseismic intensity, peak ground acceleration PGA, peak ground velocity PGV, spectral ordinates in terms of acceleration Sa(T) or displacement Sd(T), Housner Intensity etc.

Table 3.2 resumes the main possible sources of inhomogeneity for vulnerability modelling, reporting some examples from the literature. A synthetic gap analysis, encompassing the three factors of hazard, vulnerability and exposure as well as consequence functions, towards harmonized seismic risk assessment, is performed with reference to the models adopted in Italy and Slovenia as reported in Section 3.2.

3.1.3. Exposure

Exposure expresses a quantitative and qualitative estimation of elements at risk in a given system and geographic area. Having defined a proper classification of the exposed assets with the purpose of performing vulnerability analysis, exposure analysis starts from the "counting" or quantification of the number of elements within each vulnerability class. For example, referring to buildings as assets at risk, exposure models generally give information on building inventory, that is related to the type of constructions and on their distribution at the territorial scale. Occupancy data need to be added to building inventory when, in addition to physical impact, intended as damage distribution, the economic and social impact has to be evaluated (Polese et al., 2019).

According to van Westen et al. (2011) the elements at risk can be grouped considering different categories, including physical elements (buildings, monuments and cultural heritage), essential facilities (emergency shelters, schools, hospitals, police, etc.), transportation facilities (roads, railways etc.), lifelines (Water supply, electricity supply, gas supply etc.) environmental elements (Ecosystems, protected areas, natural parks etc.), population as well as economic activities and socio-economic aspects. The accounting of all the above mentioned elements, together with the adoption of suitable vulnerability models, that can be different for each category of assets, would allow a comprehensive risk estimation in a region. However, as observed before, the level of detail and amount of data required for consistent evaluation would hamper the possibility of application to larger cross-border areas.

Therefore, in BORIS, mainly (residential) buildings and population will be considered as exposed assets at risk.

Various data sources and related approaches can be used to assemble building inventory; indeed, depending on data availability and scale of analysis different methods can be adopted.

For large scale assessments, the inventory is frequently based on census data, which are cheap sources of information available over a large scale and dispatched in aggregated form. For European countries, the information on buildings from census returns is often limited to construction age and storey number (Polese et al., 2020), while more informative census surveys were conducted in Portugal, Greece, Turkey and Italy, where data on construction age, building material and number of storeys are available (Crowley et al., 2014). Unfortunately, for privacy reasons the data, when disseminated, are often provided in aggregated form at the census tract level. The basic information contained in census data can be integrated with more detailed data allowing to use more refined vulnerability models, requiring the use of additional vulnerability factors (e.g.

index-based methods as RISKUE and SAVE, reported in Table 3.2); to this end rapid in situ surveys (e.g. by external visual screening) can be adopted at the town level.

Table 3.3: Data sources and related approaches for building inventory (adapted from Polese et al., 2019)

Source	Building features	Applicability scale	Advantage	Disadvantage	Example applications for inventory
Census data	storey number; construction age; construction material - RC/Masonry/Other; state of preservation	from town districts to regional or national scale	complete database for all the nation; information on both population and buildings; free or low-cost database	Some countries have limited info by census returns; variable size of census unit; data are available in aggregated form at the census tract level for privacy reason; census forms compiled by non-experts	Crowley et al., 2014; Dolce et al. 2021
Remote sensing (HR or VHR imagery)	building shape, position and height	from town districts to regional, national or even larger scale	automatic and semi-automatic detection algorithms are being developed; geo-referenced spread data on potentially very large building stock; can be easily updated	requires processing massive data volumes; necessary the combination with other data sources (e.g. urban context information and/or local surveys on benchmark buildings) to derive attribute type building features (e.g. construction age, roof type)	Miura et al., 2006; Polli et al., 2009
Interview based survey	Detailed spatial and attribute type building features for building typologies and %incidence of building typologies in a district	from town districts to regional or national scale	detailed info for building typologies; speed economic approach	data reliability depends on interviewed experience/knowledge of the built environment	Dolce et al., 2002; Guéguen et al., 2007
Real Estate Register or Cadastral Maps	storey number; construction age; construction material - RC/Masonry/Other; Building location	from town districts to regional or national scale	complete database for all the nation; information on both population and buildings;	Available in few countries; in some cases not free of charge; info on population is available in aggregated form at the census tract level for privacy reason;	Babič et al., 2021b
Building by building	Detailed spatial and attribute type building features	town districts	detailed info for single buildings in a district;	costly and time consuming; difficulty of access to information for not visible features (e.g. horizontal system; strengthening interventions etc.)	Del Gaudio et al., 2015; Polese et al., 2018

However, for larger scale assessments, e.g. at regional or even national scale, other integrative approaches to increase the information available in building inventory could be used. Innovative image-processing based techniques, using high resolution (HR) optical satellite imagery or from airborne radar sensors, are attractive due to their rapidity and automation and the potential spread over large regions of interest; however, these methods allow mainly to determine “spatial type” building features, such as footprint shape and size, number of floors, height of floors etc..

Building-by-building surveys, providing detailed data for both spatial and “attribute type” features (e.g. building materials, e.g. masonry/reinforced concrete, or the building age) for single buildings in an investigated area, are generally the most complete source towards vulnerability classification. Being costly and time demanding, this kind of detailed survey is generally applied during post-earthquake vulnerability and damage survey campaigns (Braga et al., 1982; Del Gaudio et al. 2015). However, there are some examples of databases encompassing building by building data assembled starting from Real Estate Register (GRS, 2008) or from the address register and the building and apartment register - cadastral data available from the Federal Office of Metrology and Surveying (BEV) as is the case of Slovenia and Austria, respectively.

A recent advancement towards compilation of regional scale inventories is provided by the Cartis approach. The interview-based CARTIS form, aimed at the typological and structural characterization of urban settlements (Zuccaro et al., 2015b), was implemented in Italy by ReLUIS, under the coordination of the Italian Civil Protection Department. This approach allows to gather rapidly relevant data on building typologies, which could enhance the relatively poor information available at census level. However, as noted in (Dolce et al., 2021), although the method represents a promising tool to integrate the census inventory, it had not yet been implemented exhaustively at national level and could not be employed for the national risk assessment.

A systematic review of possible approaches to assemble building inventory, encompassing the data sources that could be used as well as the scale of applicability is reported in (Polese et al., 2019).

Table 3.3, adapted from (Polese et al., 2019), resumes the various data sources and related approaches for building inventory. Observing the Table, it is evident that inhomogeneity of kind of data, as well as applicability scales, could hamper the harmonised evaluation of exposure in transboundary regions. Therefore, it is necessary to adopt a common approach for cross-border inventory assemblage and representation.

3.1.4. Consequence functions

The evaluation of seismic risk in terms of consequences is crucial to understand potential impact due to earthquake, to set up mitigation strategies for reducing earthquake losses and to enhance preparedness measures and emergency planning. To express negative consequences due to a seismic event, commonly used impact indicators for civil protection purposes are the expected number of collapsed and unusable buildings or dwellings, the expected number of homeless, casualties and injured people as well as the direct and indirect economic losses (JRC 2015, FEMA 2015). Generally, consequence functions are expressed as a function of buildings’ damage, meaning that the above-mentioned indicators are determined as a function of the expected numbers of buildings (or dwellings) affected by the different damage levels, obtained according to the adopted damage model.
According to HAZUS approach, the number of collapsed buildings could be determined as a portion of buildings reaching the complete damage state (DS4). Collapse fractions are based on judgment and limited earthquake data and they are dependent on the material of the load-bearing structure and number of storeys. For example, considering reinforced concrete moment resisting frame structures, the 13%, 10% or 5% of the total area of these type of buildings with 1-3 storeys, 4-7 storeys and more than 7 storeys respectively, that attained complete damage state DS4, is expected to be collapsed. If EMS-98 damage scale is adopted, a simpler

model can be used, considering that all buildings that reached damage grade D5 (i.e. Destruction) may intrinsically considered as collapsed (Dolce et al. 2021).

Together with the expected number of collapsed buildings, the evaluation of the expected number of unusable buildings and, in turn, of the number of homeless allow the estimation of indirect costs related to temporary shelters and other kinds of temporary arrangements for homeless. The HAZUS model evaluates the uninhabitable or unusable dwelling units as all dwelling units located in buildings that are in the complete damage state (i.e. DS4 for HAZUS damage scale) while for dwelling units that are in moderately and extensively damaged buildings the number of uninhabitable ones also depend on the residential occupancy, i.e. multi-family or single-family homes. Displaced households, intended as people needing provisional shelters, that are the equivalent of the number of homeless according to other models, are calculated as a function of the occupants in uninhabitable homes: the 90% of all occupants in severely damaged multi-family homes and 100% of all occupants in extensively and completely damaged multi-family and single-family home. In Khazai et al. (2012) three different usability classes (non-usable, partially usable and fully usable) are considered and empirically-derived usability ratios for each usability class are defined as a function of the damage level. To determine the number of homeless, the model defines the building habitability by a combination of the functionality of buildings (building usability), the level of residual service in the utilities and the prevailing weather conditions at the time of impact. Therefore, the number of homeless are determined as sum of number of occupants in non-usable buildings and number of occupants in non-habitable buildings, defined as percentages of fully usable and partially unusable buildings, then detracting the number of dead persons.

The number of injuries or deaths can be computed as a function of the damage level of the building, as well. As proposed in Coburn at al. (1992) casualties can be estimated as a percentage of the number of collapsed buildings, determined by factors that take into account several aspect concerning the occupancy of the buildings, such as the number of people effectively accommodated in buildings depending on the time of the event, the percentage of population trapped in collapsed buildings as well as the outright mortality when collapse occurs and the mortality of trapped victims after collapse. These modifiers depend on the building typologies (e.g. masonry or reinforced concrete structure), as well. Several updates of the above-mentioned casualty model, that consider studies by various authors based on local context and observed data after significant earthquakes worldwide, are presented in Spence et al. (2011). According to the proposal from Zuccaro and Cacace (2011), the rates of injury or deaths, i.e. the probability of injury or death of the building occupants, are expressed by a function of the EMS-98 damage grades and the vertical structure type of the building. These factors are calibrated on the basis of previous earthquake surveys and they assume significant values only for damage grades D4 and D5. Moreover, many factors that can affect the number of casualties during an earthquake, such as the variation of the exposure over the day and over the week, are also taken into account.

The economic losses model provides costs for the repair or replacement of damaged or collapsed buildings. Generally, the computation of economic losses caused by direct structural damage requires the definition of the building replacement cost, defined based on the building type, and a damage ratio, that expresses for each damage state the percentage of the building replacement value (FEMA 2003, Chang et al., 2008, Karaman et al. 2008, Molina et al. 2010). Following the methodology adopted in FEMA (2003), the building replacement cost is defined as a function of the type of occupancy (i.e. residential, commercial, industrial, etc) and the damage ratio is assigned for each damage state and each type of occupancy; the expected losses for each damage state and each occupancy type is calculated multiplying the built area of the considered occupancy type and the relative probability to experience the considered damage state for the relative damage ratio and

the building replacement cost. A similar calculation is performed for losses due to non-structural damage. The differences between existing models usually concern calibration of damage ratios and definition of the building replacement cost, that obviously can vary for different geographic areas.
Indirect seismic economic losses are a systematic manifestation of losses in the chain of economic activities, that may be affected to by interruptions and general disruption in their normal operations. Several studies are carried out by researches to estimate indirect losses (Boisvert, 1992, Chang et al. 2000, An et al. 2004, Enke et al. 2008), but the most used computation approach is the HAZUS one (FEMA 2003). This model is based on dividing the economy into a number of industrial sectors and on the conversion of expected damages in buildings and infrastructure into a loss of functionality measurement for each industrial sector, used as the input for the indirect loss calculation. Contrary to the direct losses, indirect losses are naturally characterized with more ambiguous causes and the uncertain amount of losses. Indirect economic losses could be affected by various disruptions, for example, transportation difficulty due to damaged highway and transportation systems, water pipe damage, and electricity disruption, among others. Moreover, there is still a lack of systematic data collection in the aftermath of a seismic event, thus it is very difficult and often not possible to develop forecast model for their estimation based on survey data. These reasons make the evaluation of indirect economic losses a complicated task and available studies are affected by high uncertainties.

3.2. Shared framework for seismic risk assessment

The brief model description reported in previous sections for hazard, vulnerability, exposure and consequence functions highlights potential differences that can be found in the available models to be employed for risk assessment. With the aim to build a harmonized approach towards cross-border risk assessment, such differences should be analysed specifically for the transboundary regions of confining countries, evidencing the relative discrepancies and gaps to be filled to build a consistent risk assessment. Starting from the results reported in the Deliverable D2.1 “Comparison of National Risk Assessments” (BORIS, 2021a) and on the gaps analysis performed in section 4.1 of the Deliverable D2.2 “Data availability and needs for large scale and cross-border risk assessment, obstacles and solutions” (BORIS, 2021b), a comprehensive synthetic Gaps Analysis Table (see Table 3.4) could be compiled referring to Italy and Slovenia, two of the countries for which cross-border pilot applications will be performed in WP5. For each of the factors involved in the risk assessment, Table 3.4 reports the Harmonization Goal, the Current State and the Identified Gap.

In the following sections the approach for harmonization of each one of the factors composing seismic risk is described. Although the methodology is developed adopting as reference the confining countries Italy and Slovenia, indications for exportability of the methodology to other countries are reported in section 3.3.5 and duly considered in the harmonization process.

Table 3.4: Gaps Analysis for transboundary Seismic Risk Harmonization

Factor	Harmonization Goal	Current State	Identified gap	Action plan
Hazard	Harmonize hazard evaluation for different return periods	Official seismic hazard model: - Italian Model (MPS04) - Slovenian Model	Differences in seismic hazard models - different return periods - different mesh grid for hazard values - considered soil effects	Use the same hazard model ESHM 2013: - for selected return periods - Time-based assessment
Exposure	- Homogenization of input data - Same scale of analysis	Available exposure data: - Italy: Census data at municipality level - Slovenia: Building by Building data	Inventory differences - different building typologies - different levels of detail considered - different scale adopted	Aggregation/de-aggregation rules; Consider similar typologies based on: - construction material - relevant age ranges - storey number
Vulnerability	Develop a uniform methodology for fragility analysis or propose a consistent transboundary vulnerability evaluation approach	Country specific fragility functions - Italy: Masonry and RC vulnerability models defined for 5 building classes - Slovenia: fragility functions simulated at the building level for 20 building typologies	Differences in vulnerability models and related fragility curves - Different vulnerability class definition - Different damage scale adopted - Different methodology used to build fragility curves	Combination of vulnerability models A Heuristic approach is proposed to combine the model by the definition of parameter w (representing model uncertainty)
Consequence functions	Definition of the same damage-to-impact conversion criteria	Impact indicator at national level - Italy: collapsed buildings/dwellings, unusable buildings/dwellings in short term and in long term, Homeless, victims, injured, direct economic losses. - Slovenia: Permanently and temporarily unusable buildings, fatalities, direct economic losses.	Differences in damage to impact modelling - different indicators considered - different formulation for the conversion	Definition of uniform approach for impact assessment - Economic model - Casualty model'- Building usability

3.2.1 Harmonised hazard

Seismic hazard assessment is usually performed at a national level using official seismic hazard models. Due to several differences in hazard assessment methods, a harmonized approach is needed to allow cross-border coordination of results. The most obvious solution is the use of the 2013 Euro-Mediterranean Seismic Hazard Model (ESHM2013) (Woessner et al., 2015), which covers the whole European territory, including Turkey. It was developed within the SHARE (Seismic Hazard Harmonization in Europe) project, a collaborative project aimed to provide integration across national borders without the burden of political constraints and administrative boundaries. The ESHM2013 model provides a complete assessment of seismic hazard and associated uncertainties and was computed using the OpenQuake hazard engine (Pagani et al., 2014). It consists of more than sixty time-independent ground motion hazard maps for various ground motion intensities, from PGA to spectral acceleration at periods up to 4 seconds. The model uses harmonized and homogenized data from national, regional and site-specific PSHAs from across Europe.

The ESHM2013 model is based on three time-independent earthquake source models to describe the expected future earthquake activity in different regions; an area source model, smoothed background seismicity and a fault source model based on active faults. The ESHM2013 model includes all events with magnitudes of 4.5 and higher in the computation of hazard values, which are referenced to a rock velocity of Vs30=800 m/s. To capture the epistemic uncertainty in ground-motion prediction, a logic tree for the selection of best suited ground motion prediction equations (GMPEs) with associated weights was prepared for different tectonic regimes based on input data and expert judgment. Fourteen GMPEs were included in the logic tree based on a pre-selection from over 250 published GMPEs. For example, for stable continental regions, five GMPEs with even weights of 0.2 are proposed to be used for ground motion prediction.

Recently, an updated hazard model, the 2020 Euro-Mediterranean Seismic Hazard Model (ESHM2020), was proposed within the European Union's Horizon 2020 research and innovation programme. Its development was motivated by an increase in ground motion data and innovations in ground motion modelling and epistemic uncertainty consideration (Weatherill et al., 2020). The ESHM2020 uses a different approach to characterize ground motions for probabilistic seismic hazard analysis than ESHM2013. In the latter, the epistemic uncertainty is represented by using a logic tree with multiple ground motion models assigned to each tectonic region type. In ESHM2020, however, a scalable ground-motion logic tree is used, where a single core ground motion model for each seismic environment is considered and then modified to capture epistemic uncertainties (Weatherill et al., 2020). The ground motion model for active shallow crustal seismicity was developed using 786 events with magnitudes between 3.1 and 7.6, for stable craton regions the core ground motion model was obtained from a generated synthetic set, whereas for subduction and deep source seismicity a ground motion model was selected from literature, which best suited the available data.

Both ESHM2013 and ESHM2020 are publicly accessible on the European Facilities for Earthquake Hazard and Risk (EFEHR) web platform hazard.EFEHR.org. Hazard spectra, maps and curves can be obtained from the platform for any site coordinates in Europe, including Turkey, and both hazard models (ESHM13, ESHM2020) on rock or rock-equivalent sites (Vs30=800 m/s). Additional locations are available through the inclusion of the 2014 Earthquake Model of the Middle East (EMME14) (Giardini et al., 2016). Six return periods are available for hazard spectra and hazard map computation, i.e. 73, 102, 475, 975, 2475 and 4975 years for ESHM2013, corresponding to probabilities of exceedance of 1, 2, 5, 10, 39 and 50 % in 50 years. These values vary slightly for ESHM2020. Twelve intensity measure types are available for hazard map and hazard curve computation (i.e. PGA and Sa at T = 0.1, 0.15, 0.2, 0.25, 0.3, 0.5, 0.75, 1, 2, 3 and 4 s) for ESHM2013, whereas five additional intensity measures are available for ESHM2020 (i.e. Sa at T = 0.05, 0.35, 0.4, 0.6 and 5 s).

Because the ESHM2013 and ESHM2020 models provide a seismic hazard for rock-equivalent outcrop motion, the effects of local soil and other effects on ground motion intensity have to 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 cross-border area analysed. Based on the Vs30 values, the amplification factors can then be determined by considering, e.g., the guidelines from wdEN 1998-1-1 (CEN, 2019). 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. However, the accurate prediction of Vs30 cannot improve the seismic risk assessment significantly because of a relatively large scale used in the cross-border assessment and because other phenomena affect the ground motion intensity at the site of interest.

3.2.2 Harmonised exposure

For exposure modelling harmonization, the first step is the analysis of the available exposure data. Concerning buildings, in Slovenia building by building data are available, that include information on predominant material of the load-bearing structure, the number of storeys, the year of construction and the net usable surface area. These building specific information are provided by Real Estate Register (REN) for the entire country and they are publicly available. Concerning population, the average number of people per housing unit in each municipality is provided by Central Population Register, but it is not publicly accessible. In Italy exposure data are produced by ISTAT (National Institute of Statistics) that provides publicly accessible information on buildings, dwellings and population at census tract level. Last available census database (ISTAT 2011) includes buildings' information on construction material (masonry, reinforced concrete or other), number of storeys (1, 2, 3, 4 or more) and construction period (>1919, 1919–1945, 1946–1960, 1961–1970, 1971–1980, 1981–1990, 1991-2000, 2001-2005, >2005). However, for privacy reason, disaggregated data on buildings and population are available only at municipality level. Thus, the number of buildings identified by the combination of material, construction period and number of storeys, are available only for the entire municipality, as for the living area, the number of dwellings and the population.

Therefore, for harmonization purposes, the exposure is evaluated at municipality level and Slovenian building by building data are grouped for construction material type into age ranges and classes of height, coincident with the ranges identified in Italy wherever possible. Table 3.5 shows the criteria for building typologies identification adopted in Italy and in Slovenia respectively, after the exposure harmonization procedure. It can be noted that 10 age ranges are identified in Slovenia, one more than in Italy. In particular, two different periods are identified between 1960 and 1970 (i.e. 1961-1964 and 1965-1970) in order to take into account the evolution of the seismic codes and to be coherent with the definition of vulnerability classes adopted by the model.

In order to compile building inventories, harmonized vulnerability classes should be also defined. Although the vulnerability model for Italy refers to (5) building classes, an exposure model is required to associate building typologies derived by ISTAT to the vulnerability classes identified by the model. As a suitable exposure model may be not available in all countries while typological information are easier to detect, for cross-border harmonization purposes the typological-based classification is selected.

Therefore, for vulnerability analysis six building typological classes for masonry buildings and six typological classes for RC are considered, defined by a combination of period of construction and number of storeys (see Table 3.6).

Table 3.5: Criteria for building typologies identification. The possible grouping of age ranges for building classification are highlighted with different colours.

	ITALY	SLOVENIA
Material	masonry	masonry
	reinforced concrete	reinforced concrete
	other	other
Stories	1, 2, 3, >=4	1, 2, 3, >=4
Period	< 1919	< 1919
	1919 - 1945	1919 - 1945
	1946 - 1960	1946 - 1960
	1961 - 1970	1961 - 1964
		1965 - 1970
	1971 - 1980	1971 - 1981
	1981 - 1990	1982 - 1990
	1991 - 2000	1991 - 2000
	2001 - 2005	2001 - 2007
	> 2005	> 2007

It is worth noting that buildings categorized as "other" material are not included. As a matter of fact, in Italy no vulnerability model is officially included in NRA for these kinds of structures, as they are not very widespread in the country. However, if in some country this typology is relevant, it can be taken into account and added to the classification.

Table 3.6: Harmonized building classes identified for vulnerability analysis.

Material	masonry
	reinforced concrete
Stories	1 - 3, >=4
Period	< 1965
	1965-1982
	> 1982

In countries where census data do not provide the needed information for building classification, such as the construction material or the period of construction, and no building by building database are available, alternative sources of information could be adopted. For example, in Austria, the GWR data available from Statistik Austria should theoretically provide data needed for building typology identification relative to construction material (masonry, RC and other), period of construction (the same periods adopted in Italy except for period from 2000 onwards) and number of storeys. However, because the filling of information about construction material is not mandatory in the questionnaire used to compile the database, for up to 80 % of the buildings within the Austrian pilot municipalities there is no data regarding the construction material. For cases like this, the GEM's Global Exposure Database (GED), implemented within GED4GEM project (Gamba, 2014) can be used as an alternative source to compile large scale building inventory. This database is a multi-scale database focused on people and residential buildings with global coverage at national and sub-national (province, municipality) level. The distribution of building types for urban areas is estimated combining remote sensing with local expertise and field observations. The 2020 European Seismic Risk Model (ESRM20) includes the residential exposure models for 44 European countries, developed using existing GED4GEM data, local expert processed census data and available public census data (Crowley et al. 2021). The scale at which the exposure data are provided could change based on the geographic area considered: for Austria these data are available at federal state level, for Malta at regional administrative level, for Hungary they are provided at provincial level, for Germany and Montenegro at municipality level and for Czech Republic and Luxemburg at local level, corresponding to a grid of about 1km x 1 km. Thus, for example, for the federal state of Styria in Austria the ESRM20 exposure model provides the number of buildings, dwellings and population in each building class identified by the combination of construction material (e.g., reinforced concrete, unreinforced masonry, wood, steel, etc.), lateral load resisting system (e.g., wall, moment frame, dual frame-wall system, braced frame, etc.), number of storeys (e.g., 1-2, 3-5, 6-10) and design code level (e.g., no code, low code, high code depending on the age of construction), according to GEM Building Taxonomy v3.1 (https://github.com/gem/gem_taxonomy). In the ESRM20 framework, the fragility functions of these European vulnerability classes are provided, as well.

It is worth noting that if a lower scale of analysis is required, as is the case for the pilot application in Austria (e.g., municipality scale), the distribution of GEM building classes at the selected territorial scale may be defined integrating GED data with field surveys or, as the latter may require much time and efforts, with interviewed-based ones. As a matter of fact, as already mentioned in section 3.1.3, the interview-based form Cartis (Zuccaro et al. 2015) implemented in Italy by ReLUIS, under the coordination of the Italian Civil Protection Department, allows to rapidly collect information on relevant buildings features at urban level. The survey of ordinary building typologies is carried out in sub-areas of the town denominated Town Compartments (TC), characterized by homogeneity of the building stock in terms of construction age and construction techniques and/or structural types, through an interview with a technician belonging to the local Public authority (Region, Province, Municipality) and / or a technician who carries out a private profession in the area that has proved experience on local building typologies. With this interview-based approach, for each investigated municipality, the percentages occurrence of the prevailing typologies in each TC can be defined, and the main constructive and structural characteristics of each typology, such as the number of storeys, the age of construction, the vertical and horizontal structure types (for masonry buildings), the type of reinforced concrete structures and infill types, the roof types and, if any, presence of structural interventions, can be detected. Applications adopting the Cartis database as a support for compiling building inventory at regional or at municipality scale can be found in Tocchi et al. (2022) and Polese at al. (2019, 2020, 2021).

3.2.3 Harmonised vulnerability

There are several potential issues in harmonizing the seismic vulnerability model for a cross-border seismic risk assessment, as described in Section 3.1.2. In order to tackle those issues, the preferred strategy would be to develop a uniform methodology for vulnerability analysis at the European level, analogously to the approach taken in the development of the European seismic hazard model (see Section 3.1.1). However, such an effort significantly exceeds the scope of the BORIS project and should probably be the goal of another research project dedicated solely to this topic. Another possible strategy, which is also taken in the BORIS project, is to define a harmonized vulnerability model for cross-border risk assessment based on existing vulnerability models. This strategy is described in the following.

The first step in developing a harmonized vulnerability model is to define a building classification for each country involved in the cross-border risk assessment. In general, the building classifications of neighbouring countries can differ significantly. However, in this section, it is assumed that two countries sharing a border have a similar historical and cultural background and that, consequently, their building stocks are also similar enough to use the same building classification. This is also the case for the cross-border areas at the Slovenia-Italy border and at the Slovenia-Austria border, where the communities on both sides of the border have had close connections throughout history. Please note that this does not imply that the vulnerability models for the countries sharing a border are the same. In spite of a similar historical and cultural background, the differences in the building stocks may still exist for politico-economic reasons, resulting in different fragility functions assigned in different countries to the same building class. Please also note that, as explained in Section 3.1.2, the building classifications of neighbouring countries can have different bases (typology- or vulnerability-based classification). In such cases, it is suggested to use a typology-based building classification, which is more basic than the vulnerability-based classification in that it does not require coupling with the exposure model.

The second step is to harmonize the damage scale. In general, two neighbouring countries can use quite different damage scales that have not been yet compared to one another in the literature. In such cases, it is suggested to connect the damage states from both scales based on their corresponding consequence functions. However, it is reasonable to assume that a country is using either the EMS-98 damage scale or the HAZUS damage scale, which are both widely used in Europe. This also applies to the countries involved in the BORIS project, with the exception of Austria, where no vulnerability model is available (please note that this issue is addressed at the end of this section).

For the pilot studies in the BORIS project, the EMS-98 damage scale was selected. Therefore, the HAZUS damage scale, which is used in Slovenia, needs to be converted to the EMS-98 damage scale, which is used, for example, in Italy. This conversion can be performed based on recommendations from Lagomarsino and Giovinazzi (2006) presented in Table 3.7. The table shows that the HAZUS and EMS-98 damage scales are very similar. However, some differences exist in the case of the most severe damage states. It is especially an issue how to convert D5 ("destruction") from the EMS-98 damage scale to the HAZUS damage scale. This issue can be tackled by considering that HAZUS specifies, for each designated building class, a percentage of buildings that are expected to collapse if reaching the DS4 damage state. Thus, if assuming that "destruction" and "collapse" indicate the same damage state, an additional damage state (DS5) can be defined for the HAZUS damage scale equivalent to D5 from the EMS-98 damage scale. The probability of DS5 given the value of IM can be calculated as follows:

$$P(DS5|IM)_c = P(DS4|IM)_c \cdot \lambda(C|DS4)_c \quad (3.1)$$

Where:

- c indicates the c-th building class;

- $P(DS4|IM)$ is the probability of damage state DS4 (from HAZUS) given the value of IM;

- $P(DS5|IM)$ is the probability of damage state DS5 (equivalent to D5 from EMS-98) given the value of IM;

- $\lambda(C|DS4)$ is the rate of collapse given that a building has reached damage state DS4 (from HAZUS).

Table 3.7: Conversion from the HAZUS damage scale to the EMS-98 damage scale (proposed by Lagomarsino and Giovinazzi, 2006).

HAZUS damage scale	EMS-98 damage scale
DS1 (slight damage)	D1 (slight damage)
DS2 (moderate damage)	D2 (moderate damage)
DS3 (extensive damage)	D3 (heavy damage)
DS4 (complete damage)	D4 (very heavy damage)
/	D5 (destruction)

In the third step, the propensity of buildings to suffer damage given the value of the IM needs to be defined. Mathematically, this can be described by the conditional probability of reaching designated damage states given the value of the IM. $P(DS4|IM)$ and $P(DS5|IM)$, which were introduced in Eq. (3.1), are an example of such conditional probabilities. It is proposed that these conditional probabilities be described with lognormal fragility curves. Both HAZUS and EMS-98 damage scales allow such vulnerability characterization. Further, it is proposed that the PGA be selected as the intensity measure. Such a selection has several advantages. In contrast to the macroseismic intensity measures, the PGA is measurable and thus an objective quantity. Moreover, unlike the spectral quantities (e.g. spectral acceleration), it is independent of the building class, which is beneficial when the risk assessment is performed for many different building classes. Another advantage of the PGA is that it is commonly used in the literature (e.g., FEMA, 2003; Dolšek et al., 2020; Borzi et al., 2021; Babič et al., 2021b), which makes it easier to find and obtain fragility curves applicable to the building stock under investigation.

The definition of fragility curves is straightforward if exactly one set of the curves has been developed specifically for the analysed building stock. However, this is rarely the case. For example, no fragility assessment has ever been performed specifically for the building stock in the Slovenia-Italy cross-border area. Nevertheless, there are several vulnerability models available in the literature that could be applied in the risk assessment of that area. Among the available vulnerability models, there are two obvious choices, i.e. the aggregated vulnerability model developed for the Italian territory that consists of five sets of fragility curves (Zuccaro et al., 2021; Lagomarsino et al., 2021; Donà et al., 2021; Rosti et al., 2021a; Rosti et al., 2021b; Borzi et al., 2021) and the vulnerability model developed for the Slovenian territory (Dolšek et al., 2020; Babič et al., 2021b). Even adopting simplifying hypotheses for damage scale harmonization and for building classification, the inherent modelling differences for vulnerability may lead to significant discrepancies in the damage assessment and consequent impact scenario. To have a better understanding of the differences of the models in transboundary regions and what are the possible solutions for accounting them in a harmonization framework, in the next sections a comparison of Italian and Slovenian fragility curves is first carried out, and finally the proposed approach for cross-border vulnerability harmonization is presented.

3.2.3.1 Comparison of Italian and Slovenian fragility curves

The models adopted in Italy and in Slovenia describe vulnerability through fragility curves, expressing the probability of attaining different levels of damage as a function of PGA by a cumulative lognormal distribution. According to the Slovenian approach (Babič et al., 2021b), fragility curves are defined at the level of building typologies for the four damage states of the HAZUS scale. In Italy fragility curves are defined for vulnerability classes and the five-grade EMS-98 damage scale is adopted (Dolce et al. 2021). Therefore, the main issues for fragility curves comparison concerns the differences in in the damage scales used and in vulnerability classes definition.

Concerning the former one, the conversion rules to convert the HAZUS damage scale into EMS-98 one presented previously are adopted (see table 3.7). Therefore, EMS-98 scale can be adopted without any modification to Slovenian fragility curves for damage grades D1 – D4, while for the heaviest damage grade D5 (i.e. Destruction) the fragility curves can be derived given the probability of damage state DS4 for each value of the intensity measure (i.e. PGA) and the rate of collapse given that a building has reached damage state DS4.

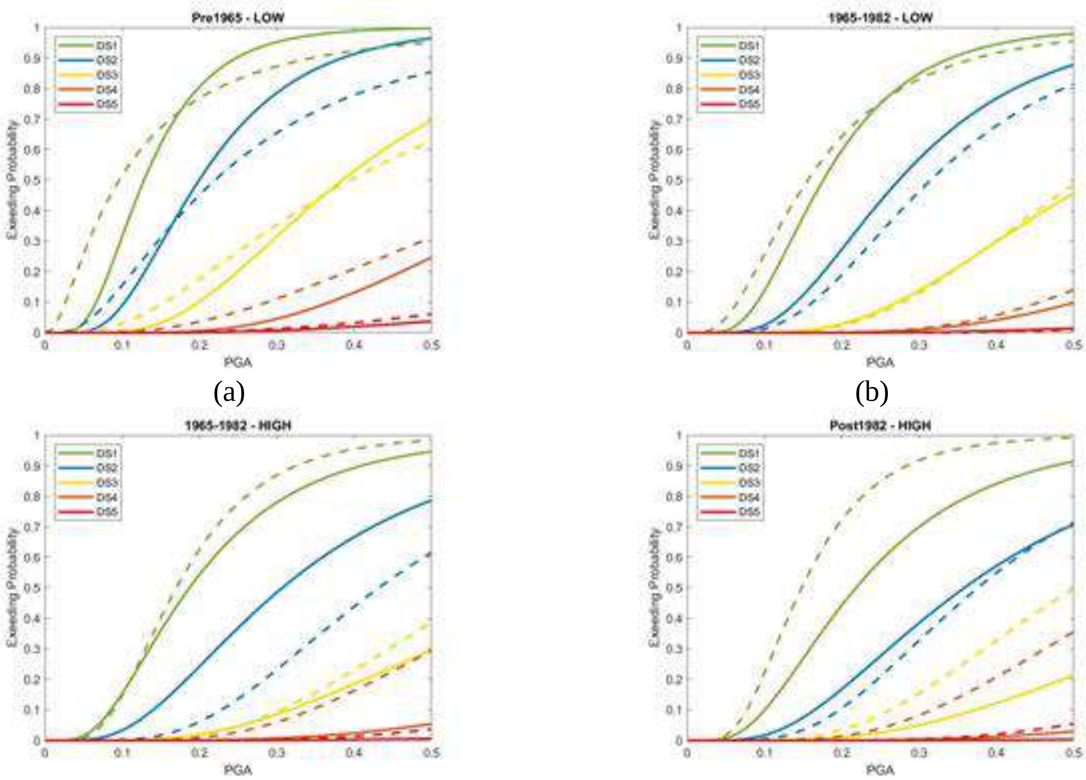
Concerning the vulnerability classes definition, the Slovenian vulnerability model identifies 20 building classes based on the material of load-bearing structure (masonry, reinforced concrete and other), construction period (before 1965, 1965–1981, after 1982) and the number of storeys (1–3, 4 or more for masonry and other structure types and 1-3, 4-6 and 7 or more for reinforced concrete structures). For each of these building classes, a different set of fragility curves is defined. The Italian vulnerability model provides fragility curves sets for 5 vulnerability classes, named A, B, C1, C2 and D, ranked according to decreasing vulnerability level. Buildings are generally grouped into vulnerability classes based on the construction material and code design level, that intrinsically should take into account the similar behaviour expected during a seismic event. For example, class A may represent traditional irregular masonry buildings with low quality structural details, class B and C1 regular masonry buildings and modern masonry buildings with rigid horizontal diaphragms respectively, while C2 and D classes may represent reinforced concrete buildings without and with ERD (earthquake resistant design). However, this is just a preliminary qualitative classification, while the need to express the inventory through vulnerability classes requires the definition of an exposure model, to properly associate building typologies identified by census data to these classes. Considering construction material (masonry, reinforced concrete), age of construction period (<1919, 1919-1945, 1946-1960, 1961-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2005, >2005) and number of storeys (1-2, 3, 4 or more for masonry; 1,2,3, 4 or more for reinforced concrete), 27 typological building classes are identified for masonry buildings and 36 for the reinforced concrete ones. These typological classes are defined according to the most recent national census database available in Italy (ISTAT 2011). Therefore, the exposure model defines the percental attribution of each vulnerability class to each typological building class.

As the fragility curves of the two countries should be defined at the same level (i.e. at building typology level or at vulnerability class level) to allow their comparison, and since the adoption of vulnerability classes requires an exposure model (not available for Slovenia), it is preferred to use typological fragility curves also for Italy.

The procedure adopted to obtain the typological fragility curves is based on the linear combination of the fragility curves for vulnerability classes (A, B, C1, C2, D), using the relative percentages of the exposure model as linear combination coefficient. Thus, a set of fragility curves (from D1 to D5) for each building class can be obtained. It is worth noting that Italian exposure model is not uniquely defined. As a matter of fact, the methodology adopted in Italy for National Risk Assessment (NRA) is a multi-model approach, as also described in Deliverable 2.1 (BORIS, 2021a). Different research units are involved in the definition of national vulnerability model, and each of them provides a different exposure model and relative sets of fragility curves. Therefore, each model leads to a different set of typological fragility curves. Moreover, the models implemented for NRA refers only to masonry and reinforced concrete buildings, so the comparison is possible only for these two categories of buildings. Considering that, however different, the various models generally provide predictions of damage and consequently of risk reasonably comparable, as also shown in da Porto et al. 2021, for this application a single model for masonry buildings and one for reinforced concrete are considered, namely the one proposed in (Lagomarsino et al. 2021) and (Borzi et al. 2021), respectively.

In order to derive typological fragility curves referring to the Italian vulnerability model, we should consider the same building typologies as those used in the Slovenian model. For example, to the Slovenian class of masonry buildings built before 1965 with 1 to 3 storeys, for which a unique set of fragility curves is employed, correspond six different building classes according to Italian classification (<1919 with 1-2 storeys; <1919 with 3 storeys; 1919-1945 with 1-2 storeys; 1919-1945 with 3 storeys; 1946-1960 with 1-2 storeys; 1946-1960 with 3 storeys) and six different sets of fragility curves. Therefore, a further combination of the Italian curves is performed, considering as combination coefficient the occurrence percentages, throughout the Italian territory, of such single age-height classes in the macro-class age (< 1965) - height (1-3 storeys).

Figure 3.1 shows the comparison between Italian and Slovenian fragility curves for the following building classes: masonry buildings with 1-3 storeys (low) built before 1960 in Italy and before 1965 in Slovenia (a); masonry buildings with 1-3 storeys (low) built between 1960-1980 in Italy and between 1965-1982 in Slovenia (b); reinforced concrete buildings built between 1960 and 1980 with more than 4 storeys in Italy and reinforced concrete buildings built between 1960 and 1982 with 4 to 6 storeys in Slovenia (c); reinforced concrete buildings built after 1980 with more of 4 storeys in Italy and reinforced concrete buildings built after 1982 with 4 to 6 storeys in Slovenia (d). It can be noted that for older masonry buildings (built before 1960 in Italy and 1965 in Slovenia) the probability of damage is higher according to Italian curves mostly for PGA values lower than 0.2, while for greater PGA values Slovenian curves are higher. The observed differences in the curves may depend on intrinsic differences of construction features or material for one building typology rather than another one in the two countries; for example, depending on the diffusion of rubble stone or rounded stone rather than brick masonry.



(a) (b) (c) (d)

Figure 3.1: Comparison between the weighted sum of Italian fragility curves (dashed lines) and the Slovenian fragility curves (continuous lines).

A more similar trend between the curves can be observed for 1965-1982 low masonry buildings (1-3 storeys) class, probably due to the large diffusion of modern masonry building types (e.g., regular masonry building with rigid diaphragms) in both countries. The greatest differences can be observed for reinforced concrete buildings: for high buildings (with 4 or more storeys in Italy and with 4 to 6 storeys in Slovenia) built between 1965 and 1982 the main differences can be observed for DS2 and DS4, while for modern buildings (>1982) the differences are significant for all damage states, except DS2. This considerable gap may be explained by the possible differences in the reinforced concrete typologies adopted in the two countries, considering that in Italy frame structure types are mostly present, while a larger diffusion of wall types can be observed in Slovenia.

It is worth noting that the differences in the typologies that may affect fragility curves correspond to the differences detected at national level, because the vulnerability models are derived for respectively NRAs and, therefore, they depend on the typological characterization of the built environment at the national level. In cross-border areas, typologies may be less different, mostly considering masonry buildings. Moreover, the differences in the fragilities are probably due also to differences in the methodology used for their derivation. The proposal for accounting these kinds of differences in vulnerability models in a harmonized framework will be presented in the following section.

3.2.3.2 Heuristic approach for vulnerability models' harmonization

The comparison exercise carried out in the previous section between Italian and Slovenian vulnerability models has shown that these models are different, which may present an issue when defining a harmonized vulnerability model for the Slovenia-Italy cross-border area. It is proposed to tackle this issue by using a heuristic approach in which a linear combination of both vulnerability models is defined for each site of the border in the cross-border area and each building class. Such a linear combination of the vulnerability models may be expressed as:

$$M_{c,A}^{comb} = w_{c,A,A} \cdot M_{c,A} + w_{c,A,B} \cdot M_{c,B} \quad (3.2)$$

$$M_{c,B}^{comb} = w_{c,B,A} \cdot M_{c,A} + w_{c,B,B} \cdot M_{c,B} \quad (3.3)$$

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 (in this case, sub-areas A and B present the Slovenian and Italian parts of the cross-border area);

- $M_{c,A}$ 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 ($w_{c,B,A} + w_{c,B,B} = 1$).

The harmonization of the vulnerability models for the Slovenia-Italy cross-border area can thus be achieved by defining, for each building class, weights $w_{c,A,A}$, $w_{c,A,B}$, $w_{c,B,A}$ and $w_{c,B,B}$. However, because the weights used in the same combination should sum up to unity, it is sufficient to determine only two different weights per building class (e.g. $w_{c,A,A}$ and $w_{c,B,B}$). In determining these weights, it should be considered that the differences between the vulnerability models $M_{c,A}$ and $M_{c,B}$ arise both from the typological and the methodological differences. It is proposed that the typological differences are addressed by assessing the typological weights: $w_{c,A,A}^T$, $w_{c,A,B}^T$, $w_{c,B,A}^T$ and $w_{c,B,B}^T$ (ranging from 0 to 1). Each of these 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 assessed based on advanced building data from the census that also includes parameters not yet considered in the definition of the building classes. For example, for the Slovenia-Italy pilot application, it is foreseen that masonry buildings will be treated together without distinguishing between the different types of masonry (e.g. stone or brick). However, if there are advanced building data allowing to inspect which type of masonry is prevalent at the cross-border area and which at the national level, it is possible to identify the degree of similarity between the building classes defined at both levels. On the other hand, if such advanced building data are not available (as is the case in Slovenia), engineering judgement could be applied to assess the typological weights. Further, it is proposed to address the methodological differences by assessing the methodological weights: $w_{c,A}^M$ and $w_{c,B}^M$, which sum up to unity ($w_{c,A}^M + w_{c,B}^M = 1$). These weights indicate the integrity of vulnerability assessments methodologies used in countries A and B, respectively. They can be assessed by using the multiple-expert interaction and integration (MEI[3]) protocol developed within the

STREST project (Selva et al., 2015; Esposito et al., 2020). Based on the typological and methodological weights, weights $w_{c,A,A}$ and $w_{c,B,B}$ can be calculated as:

$$w_{c,A,A} = \frac{w^T_{c,A,A} \cdot w^M_{c,A}}{w^T_{c,A,A} \cdot w^M_{c,A} + w^T_{c,A,B} \cdot w^M_{c,B}} \tag{3.4}$$

$$w_{c,B,B} = \frac{w^T_{c,B,B} \cdot w^M_{c,B}}{w^T_{c,B,B} \cdot w^M_{c,B} + w^T_{c,B,A} \cdot w^M_{c,A}} \tag{3.5}$$

From Eqs. (3.4) and (3.5) it follows that when one vulnerability model is significantly superior, only that vulnerability model is used for buildings on both sites of the border. For example, if $w^M_{c,A} \approx 1$ and $w^M_{c,B} \approx 0$, then $w_{c,A,A} \approx 1$ and $w_{c,B,B} \approx 0$, which means that $M^{comb}_{c,A} \approx M^{comb}_{c,B} \approx M_{c,A}$. In another extreme situation, where the building typologies on both sites of the border are similar only to the building typology in one of the two countries, the vulnerability model from that country is used for both sites of the border. For example, if $w^T_{c,A,B} \approx w^T_{c,B,B} \approx 0$, then $w_{c,A,A} \approx 1$ and $w_{c,B,B} \approx 0$, which means that $M^{comb}_{c,A} \approx M^{comb}_{c,B} \approx M_{c,A}$.

It is also possible that the resources to conduct the MEI[3] protocol or a procedure equivalent to it are not available. In such cases, it is proposed to use equal methodological weights ($w^M_{c,A} = w^M_{c,B} = 0.5$). This approach is also foreseen for the pilot application at the Slovenia-Italy cross-border area. By using equal methodological weights, Eqs. (3.4) and (3.5) reduce to:

$$w_{c,A,A} = \frac{w^T_{c,A,A}}{w^T_{c,A,A} + w^T_{c,A,B}} \tag{3.6}$$

$$w_{c,B,B} = \frac{w^T_{c,B,B}}{w^T_{c,B,A} + w^T_{c,B,B}} \tag{3.7}$$

From Eqs. (3.6) and (3.7), it follows that when the buildings at the cross-border area are equally similar to buildings in both neighbouring countries (i.e. when $w^T_{c,A,A} = w^T_{c,A,B}$ and $w^T_{c,B,A} = w^T_{c,B,B}$), then weights $w_{c,A,A}$ and $w_{c,B,B}$ are equal to 0.5. In this scenario, the differences between the vulnerability models come solely from the methodological differences. However, in another extreme scenario, where the buildings in sub-area A are similar only to the buildings in country A, and the buildings in sub-area B are similar only to the buildings in country B, then weights $w_{c,A,A}$ and $w_{c,B,B}$ are equal to 1. In this scenario, the sole source of the differences between the vulnerability models are the typological differences, which means that despite being in the same building class and located close to each other, buildings on each site of the border were designed and constructed differently.

The above procedure can be generalized to combine any number of vulnerability models:

$$M^{comb}_{c,A} = \sum_i w_{c,A,i} \cdot M_{c,i} \tag{3.8}$$

$$w_{c,A,i} = \frac{w^T_{c,A,i} \cdot w^M_{c,i}}{\sum_i w^T_{c,A,i} \cdot w^M_{c,i}} \tag{3.9}$$

Where:

- $M_{c,i}$ is the *i*-th vulnerability model for the *c*-th building class;

- $w_{c,A,i}$ is the weight of the *i*-th vulnerability model for sub-area A and the *c*-th building class ($\sum_i w_{c,A,i} = 1$);

- $w^T_{c,A,i}$ is the typological weight of the *i*-th vulnerability model for sub-area A and the *c*-th building class;

- $w^M_{c,i}$ is the methodological weight of the *i*-th vulnerability model for the *c*-th building class ($\sum_i w^M_{c,i} = 1$).

The procedure for defining a linear combination of any number of vulnerability models may be interesting in the case of the pilot application at the Slovenia-Austria cross-border area. This is because there is no available vulnerability model developed for the Austrian territory. Therefore, for the Austrian site of the border, it makes sense to consider not only the vulnerability model originally developed for Slovenia but also other vulnerability models developed for building classes similar to those on the Austrian site of the cross-border area (e.g., the vulnerability model proposed in Crowley et al. 2021). Further development of this vulnerability model is foreseen in the pilot application, which is to be performed within Work package 5.

3.2.4 Harmonised consequence functions

As shown in paragraph 3.1.4, several indicators can be used to express possible negative consequences of a seismic event. For their evaluation, different consequence functions, that convert structural damage into impacts, can be adopted. As for hazard, vulnerability and exposure, the starting point for a sound harmonization of consequence functions in transboundary areas is the comparison of the ones adopted in confining regions. Therefore, in view of pilot application at Italy-Slovenia border the damage to impact modelling used in Italy and in Slovenia are compared for relevant impact indicators.

Concerning collapsed buildings, in Slovenia their number is determined as a portion of buildings reaching the complete damage state (DS4 of HAZUS scale), according to procedure described in FEMA (2003). In Italy, they are determined as the 100% of buildings in the heaviest damage level of the EMS-98 scale, level that corresponds to collapse or near total collapse of buildings. As noted in 3.3.3, the shared framework adopts the EMS-98 damage scale, therefore a consistent solution would be to directly use the latter approach for estimation of collapsed buildings.

Fatalities are assumed as a ratio of the occupants in buildings that reached the most severe damage levels. In Slovenia, the number of fatalities is first determined at the building level as follows:

$$F_{k,l} = O_{k,l} \cdot \lambda_{f,k} \cdot N_{P,k} \tag{3.10}$$

Where:

- k indicates the *k*-th building;

- l indicates the l-th damage simulation;

- $O_{k,l}$ is a variable that takes the value of 1 in case of building's collapse, 0 otherwise;

- λ_f is the fatality rate, assumed equal to 0.10;

- $N_{p,k}$ is the number of people inside building *k*.

Then the total number of fatalities is calculated as the sum over the entire building stock.

In Italy, the following equation is adopted to calculate the expected number of deaths N_d:

$$N_d = \sum_{j=1}^{n_t} [(O_{j,D4} \cdot p_{d,D4} + O_{j,D5} \cdot p_{d,D5})] \tag{3.11}$$

In the equation (3.11) n_t is the number of building typologies; $O_{j,D4/D5}$ is the number of occupants in building typology j which experienced a damage level D4 or D5 of the EMS-98 scale; ; $p_{d,D4}$ and $p_{d,D5}$ are the percentage of deaths with respect to the occupants in buildings with damage levels D4 and D5, assumed, independently of the building typologies,, equal to 1% and 10% respectively. Similarly, the number injured people is evaluated as:

$$N_i = \sum_{j=1}^{n_t} [(O_{j,D4} \cdot p_{i,D4} + O_{j,D5} \cdot p_{i,D5})] \tag{3.12}$$

Where the percentages of injured with respect to the occupants in buildings with damage levels D4 and D5 are $p_{i,D4}$=5% and $p_{i,D5}$=30%.

The comparison of the models for victims' evaluation shows that the methodology used is quite similar. The fatality rate in case of collapse of the buildings (D5 for the EMS-98 scale) assumes the same value (0.10) while according to Italian model buildings in damage state D4 also affect the calculation, even if very lightly ($p_{d,D4}$=1%). Therefore, the fatalities calculation can be performed using Eq (3.11) and adopting $p_{d,D4}$ =1% and $p_{d,D4}$ =10% .

On the contrary, as no function is proposed in Slovenia for their evaluation, the expected number of injured people can be calculated according to Eq. (3.12).

The evaluation of unusable buildings is not performed in Slovenia. However, as also highlighted in paragraph 3.1.4, the estimation of the expected number of unusable buildings is a fundamental step for homeless calculation, that is a very important indicator for civil protection purposes. Therefore, the models proposed in Italy for determining unusable buildings in short term UB_{st} and in long term UB_{lt} can be adopted for cross-border assessment:

$$UB_{st} = \sum_{k=1}^{5} (N_k \cdot u_{stk}) \tag{3.13}$$

$$UB_{lt} = \sum_{k=1}^{5} (N_k \cdot u_{ltk}) \tag{3.14}$$

Where N_k is the number of buildings that experience structural damage level Dk and u_{stk} (u_{ltk}) are the percentage of unsafe buildings in the short (long) term for each structural damage level Dk.

The number of homeless can be estimated as the number of inhabitants in unusable buildings (in the short and long term) and next subtracting the estimated number of victims.

Finally, the models adopted for direct economic losses are analysed. In Slovenia, the direct economic losses for *k*-th building and *l*-th damage simulation were modelled as:

$$L_{k,l} = c_{k,l} \cdot A_k \cdot C_R \quad (3.15)$$

Where A_k is the net floor area of the *k*-th building and $c_{k,l}$ is the ratio between the repair/reconstruction cost and CU the estimated reconstruction cost per m^2 of the net floor area of a building (Table 3.9). The ratio $c_{k,l}$ is dependent on damage state and is equal to 0.02, 0.1, 0.4 and 1 for damage states from DS1 to DS4 (HAZUS scale). As for fatalities, economic losses are first calculated at building level and then they are summed up over the building stock.

Similar approach is adopted in Italy, where direct economic losses are calculated as follows:

$$L = CU\left(\sum_{j=1}^{n_t}\sum_{k=1}^{5} A_j \cdot p_{j,k} \cdot c_k\right) \quad (3.16)$$

Where n_t has the same meaning as in the Eq (3.11), CU is the Unit cost (Euro/m^2) of a building (i.e. the reconstruction cost, estimated taking into account the demolition and the reconstruction cost, including technical expenses and VAT), A_j is the built area of the j^{th} building typology; $p_{j,k}$ is the probability for the j^{th} building typology to experience structural damage state Dk (EMS-98 scale) c_k is the percentage cost of repair or replacement (with respect to CU) for each structural damage state Dk, assumed equal to 0.02, 0.1, 0.3, 0.6 and 1 from damage level from D1 to D5.

In order to be able to harmonize the consequence functions a suitable conversion of the EMS98 and Hazus damage scales should be firstly adopted, as proposed in 3.2.3.

Table 3.9 summarize the values adopted for ratios c_k and the reconstruction cost CU (or C_R) for both countries. Note that a direct correspondence of the first three damage levels with the HAZUS damage states is assumed, while the DS4 in HAZUS is considered to represent both very serious damage D4 and destruction D5 grades of EMS98.

Table 3.9: Values adopted in Italy and in Slovenia for the reconstruction cost CU and for the percentage cost of repair or replacement (with respect to CU) for each structural damage state, according to the considered damage scale.

ITALY			**EMS-98 scale**		
CU (€/m²)	D1	D2	D3	D4	D5
1350	0.02	0.1	0.3	0.6	1
SLOVENIA			**HAZUS scale**		
CU (€/m²)	DS1	DS2	DS3	DS4	
1250	0.02	0.1	0.4	1	

Observing the table it can be noted that the key to harmonize the consequence models is the definition of c_k for each damage grade Dk, while a unique value cannot be defined for the reconstruction cost, that is obviously country-dependent. The values assumed by damage-dependent ratios for damage grades D1 and D2 are the same according to both models; for D3 an intermediate value between those adopted in Italy and Slovenia for D3 and DS3 could be used. Finally, while for D5 a cost ratio equal to 1 could be reasonably employed, assuming that buildings in D5 are effectively collapsed and should be substituted, for D4 the harmonized model should assume an intermediate value between 0.6 and 1.

Table 3.10 resumes values adopted in the BORIS project for the reconstruction cost for Italy (CU_{IT}) and for Slovenia (CU_{SL}) and for the percentage cost of repair or replacement (with respect to CU) for each structural damage state. The latter is uniquely defined for both countries and it is expressed for each grade of the EMS-98 scale, the damage scale adopted in the projet.

Table 3.10: Cost ratios adopted in BORIS for transboundary loss assessment.

BORIS		EMS-98 scale				
CR_{IT} (€/m^2)	CR_{SL} (€/m^2)	D1	D2	D3	D4	D5
1350	1250	0.02	0.1	0.35	0.6	1

3.2.5 Indications for exportability to other countries

The methodology proposed in previous sections for cross-border seismic risk harmonization was defined considering the confining countries of Italy and Slovenia, posing some observations for Austria, as well. As a matter of fact, these countries are directly involved in the cross-border pilot application of BORIS project, that will be performed in WP5. However, the possible exportability of the harmonization procedure to other countries was also considered. Following are reported some indications for its applicability in Montenegro and in Turkey.

<u>Harmonized Hazard model</u>

As mentioned in Section 3.1.1, the 2013 Euro-Mediterranean Seismic Hazard Model (ESHM2013) and the updated 2020 one (ESHM2020) are proposed as harmonized hazard model in the BORIS project as they encompass all countries involved in the cross-border assessment, including Turkey. Therefore, they are applicable in local context in Montenegro and Turkey, as well. The proposed hazard models are in line with Seismic Hazard Map of Montenegro given in MEST EN 1998-1:2015/NA:2015 (ISME, 2015). However, these models do not cover the neighbouring countries of Turkey to the east and south-east. Thus, the 2014 Earthquake Model of the Middle East (EMME14) might be included as mentioned in Section 3.2.1. 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 Turkey. In addition, they should be compared with the Earthquake Hazard Map of Turkey (AFAD, 2018) especially in the Turkish parts of cross-border areas.

Since ESHM2013 and ESHM2020 hazard models do not consider local soil effects, in section 3.2.1 it is stated that additional supplement model is needed, i.e. local maps with Vs30 values used to account for the local soil effects on the cross-border area analysed. These local maps are not publicly available in Montenegro, but the values of Vs30 can be derived from local studies at border areas, or database of global slope-based Vs30 map can be used. Concerning Turkey, there is an ongoing study on the determination of Vs30 values for the AFAD earthquake observation stations distributed throughout the country. Within the scope of this study, the Vs30 values of 676 out of 1143 stations have been determined so far. This data can be accessed through Turkish Accelerometric Database and Analysis System (tadas.afad.gov.tr). 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 Turkey 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.

Harmonized Exposure model

For exposure modelling harmonization, described in Section 3.2.2, the municipality scale is selected for building inventory compilation, as exposure data about buildings, dwellings and population is available at such level for most partner countries, and the typological-based classification is adopted. The proposed harmonized building classification in shared methodology are applicable in Montenegro, since exposure model currently in use is in line with proposed typologies. As a matter of fact, SERA exposure model is used (Crowley et al., 2020a), since there are no other available data in Montenegro. This model is based on census data (construction period, dwellings and population) from 2011 provided by Monstat (National Institute for Statistics). The information derived by the model about buildings are available at municipality level and concern the number of buildings identified by two material types (masonry and reinforced concrete), five construction periods (<1945, 1946-1960, 1961-1980, 1981-2000, >2001) and three ranges of number of stories (1-2, 3-5, >6). In addition, regarding the available data, another story range can be recognized (1-2, 3-5, >6). The adopted period of construction for defining building typologies in harmonized exposure are in line with development of seismic codes in Montenegro and construction period ranges in exposure model, so it would be applicable in cross-border Montenegrin municipality areas. Regarding the similar seismic code development and building typologies in most of the border countries with Montenegro, it could be assumed that proposed methodology is applicable also for neighbour municipalities. The situation at the Montenegro-Albania border could require additional survey on building typologies specifically related to period of construction.

In Turkey, the available 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 building classification such as construction material, number of stories, year of construction, etc. It should also be noted that the available data are not publicly accessible.

In Turkey there are studies on building inventory at the provincial level, and each one containing information at a different standard. The most comprehensive study carried out on a national scale in recent years is the MAKS "Spatial Address Registration System Program". With the aforementioned project, studies are also carried out on the building inventory. Some of the information needed for buildings can be obtained from building documents. In addition, the renovation works have been completed with the Turkish Standards Institute (TSE) regarding the building permit documents. However, the building documents before 2007 are not available in the digital environment. Considering the buildings that do not have a building permit and the buildings in the villages where it is not necessary to obtain a building permit, a lack of scope will arise. Another study is the KAYES-Public buildings inventory system. In order to ensure the sustainable use of public buildings after a possible earthquake, to ensure the use of public buildings for sheltering, when necessary, without disrupting public services, to prioritize public buildings and to make accurate and fast strategic planning of earthquake performance-based studies (budget, construction period, etc.) is important. In this context, 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, continue within the scope of "Provincial Risk Reduction Plans" (IRAP) carried out by AFAD.

Harmonized vulnerability model

For the harmonized vulnerability model, the methodology defined in Section 3.2.3 for cross-border risk assessment is based on existing vulnerability models. It requires the definition of a common building classifications for countries involved in the cross-border risk assessment, harmonization of damage scales used by these countries, selection of intensity measure (IM) based on which the propensity of buildings to suffer damage is to be defined and harmonization of the available vulnerability models developed for both sites of the border in the cross-border area by using a heuristic approach, where a linear combination of both vulnerability models is defined for each site. The proposed methodology for harmonization of vulnerability models in cross-border areas can be applied in Montenegro. However, in Montenegro vulnerability-based building classification and EMS-98 damage scale is in use. Since it is suggested to use a typological-based classification, in order to linear combine vulnerability models according to heuristic approach, an additional survey should be conducted in Montenegro to obtain adequate building typology vulnerability models what can be done using historical data and literature review.

As mentioned above, in Turkey the available exposure 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. For the pilot studies in the BORIS project, the EMS-98 damage scale was selected. Similar to damage scale used in Slovenia, 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 Turkey use different damage scales, a conversion to a common damage scale will be needed as explained in Section 3.2.3. In the BORIS project, PGA is proposed to be selected 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, defined in Section 3.2.3, for harmonization of vulnerability models for the cross-border risk assessments involving Turkey might require a literature survey on the available vulnerability models that could be applied for the building stock in Turkish parts of the cross-border areas.

Harmonized consequence functions

The assessment of seismic risk in terms of consequences is crucial to understand potential impact due to earthquake, to set up seismic risk management strategies and to enhance preparedness measures and emergency planning. In Montenegro for expressing negative consequences of an earthquake event several indicators are in use: number of deaths, number of injured, number of temporary dislocated people, direct economic losses related to repair/reconstruction costs of damage buildings and direct economic losses related to repair/reconstruction costs of damaged road infrastructure. The adopted consequence functions in harmonized approach for the expected number of death and the number of injured people are completely in line with assessment practice in Montenegro. The harmonized consequence functions for long term and short term unusable buildings as well as number of homeless also can be applied for Montenegro since they are based on damage analysis results. In Montenegro, EMS-98 damage scale is in use, so the proposed percentage costs of repair/replacement for each structural damage are acceptable and applicable in local context. The reconstruction cost (EUR/m^2) in Montenegro can be estimated based on costs of unit price per square meter for new construction (available from National Institute for Statistic for every municipality).

In Turkey, 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; 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 impact indicators with those in the shared framework for cross-border seismic risk assessment in BORIS project. Since the proposed method for the estimation of number of unusable buildings in short term and in long term is based on the number of buildings in each damage levels, it can be adopted in cross-border seismic risk assessments including Turkey. The harmonized consequence function for the estimation of direct economic losses due to buildings requires percentage cost of repair or replacement for each damage state, built area and reconstruction cost of the buildings. As mentioned above, the available 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.

3.3. Future needs

As discussed in previous sections, an effective harmonization of the models for consistent seismic-risk assessment at cross-border sites requires the harmonization of all the models entailed in risk calculation, namely seismic hazard, vulnerability and exposure models.

Regarding the seismic hazard, there is a fortunate situation in which the ESHM2013 and the newly developed ESHM2020 model, covering the whole European territory, including Turkey, could be used in the absence of national models. The ESHM models were already developed with the aim to provide integration across national borders without the burden of political constraints and administrative boundaries. Therefore it could seem that the issue of harmonization of the seismic hazard is solved to some extent. However, there are some possibilities for improvement of the European hazard model. Firstly, the model could be further refined, e.g. to the level of detail used at the national level. Secondly, the ESHM models could be extended to enable prediction of additional ground motion parameters, e.g. spectral accelerations for very long return periods, which are currently not included in the model. Thirdly, the ESHM models provide seismic hazard for rock-equivalent outcrop motion. Therefore, seismic hazard assessment should be extended to different soil conditions or, even better, to geographical locations. This can be achieved in different ways and levels of detail. Namely, it is well known that ground motions are affected by soil conditions, topographical and basin effects, as well as many other parameters that are location dependent. These effects could be addressed by developing new non-ergodic ground-motion models that account for these effects based on the ground motion measurements at the site of interest. However, more commonly, these effects are related to shear wave velocity at the top 30 m of soil, vs30, although the uncertainty in the ground motion prediction based on knowing only this parameter cannot be very significantly improved. Nevertheless, it makes sense to develop approximate Vs30 maps, as already done in many countries. However, it is also suggested to focus on the development of non-ergodic ground-motion models that provide a location-dependent prediction of ground motions that account for all ground motion phenomena and not only for vs30.

Concerning building exposure, a suitable inventory encompassing the same building classification and providing data for each unit scale of analysis of the transboundary area should be provided. As noted in 3.2.2, a typological based classification (see Example 1 in Table 3.2) is the most indicated since it can be more easily adapted for use with different vulnerability models. As for the scale of analysis, with the aim to perform risk analyses adopting as basic territorial unit of analysis the municipality, the available inventories should be reported to this scale. While this can be performed by simple aggregation of data and without relevant problems if data at a smaller scale are available (e.g. at the building level, or at census tract level), the same is not true if the inventory is initially provided at a larger scale. Indeed, in countries for which the available inventory databases do not provide enough data needed for typological based classification, existing global databases such as the GEM's Global Exposure Database (GED) can be used as alternatives. However, in such kinds of databases, the scale at which the exposure data are provided could change based on the geographic area considered, as in the case of Austria, where these data are available at the federal state level. Therefore, suitable downscaling of such global databases to the required scale of analysis, i.e. to the municipality level, is required. While the integration of available data with a field survey would be a good approach to gathering additional building information, this does not represent a viable solution for inventories encompassing several municipalities. Therefore, the assemblage of urban level inventories based on interviews, as proposed with Cartis approach, briefly described in 3.2.2, could be promoted for a faster filling of exposure gaps.

In the case of the seismic vulnerability, extensive effort is required to develop a standardised European methodology, analogously to the one addressing the seismic hazard. Such a methodology should not attempt only to combine the existing vulnerability models, as done in the BORIS project (Section 3.2.3), but to develop new vulnerability models for buildings as well as infrastructures based on harmonized constraints and assumptions. In this effort, different approaches to vulnerability modelling (e.g. analytical, empirical, heuristic) should be reviewed and their limitations should be outlined. In order to harmonize the different approaches, they should be made consistent in how they consider the seismic capacity of building structures/infrastructures as well as the seismic demand (both in terms of the average and the dispersion). The spatial scale of the common vulnerability model should be harmonized. A multi-level approach could also be developed allowing to consider different spatial scales but in a consistent manner. Such a multi-level approach could be useful because the available data on the building stock and the infrastructures can vary between countries. Moreover, a standardised European vulnerability model would need to consider a standardised damage scale regardless of the hazard type. Presumably, it should not be difficult to reach a consensus on this issue because there is already a damage scale that is widely used, also in the BORIS project, i.e. the EMS-98 damage scale. However, damage scales should in the future be more precisely defined. Furthermore, it is advisable to select common intensity measures within the harmonized vulnerability model. However, it is also possible that different intensity measures are used. In that case, the models for the conversion between the intensity measures should be reviewed and their uncertainty should be taken into account.

4. SHARED METHODOLOGY FOR FLOOD RISK ASSESSMENT

4.1 Flood risk assessment and the needs for transboundary harmonized approach

In the field of natural hazards, the concept of disaster risk introduces a series of different elements, which together contribute to determine it: hazard, exposure and vulnerability. Risk is given by the 'product' of a certain hazard and a human dimension, characterized in terms of vulnerability and exposure. Therefore risk assessment involves the following steps (Douglas, 2007; van Westen et al., 2011): hazard assessment; identification and characterization of exposed elements; vulnerability assessment; combination of previous steps and determination of the risk. This procedure is not standardized all over the world and different methods to determine each of these steps exist in literature and have been implemented in tools and platforms for risk management.

As mentioned in section 3.1, in viewpoint of multi-risk assessment it is preferable to employ a probabilistic-based risk analysis, where the risk is a product between a frequency and a certain loss/consequences. The link between these two quantities is represented by the return period-magnitude relationship that allows to associate a certain magnitude of the hazard to a certain frequency and, through the knowledge of the damage (expected annual damage) related to a certain magnitude, allows finally to know the link between the probability and the related loss. The probabilistic risk can be seen as the evaluation of the damage caused by all possible flood scenarios, taking into account their associated likelihood. Each scenario, which represents one of all the possible realizations of the risk, is obtained through an event-based scenario modelling (Boni, 2010; Boni and Siccardi, 2011). In particular, the modelling approach is needed to best predict possible present and future scenarios, taking into consideration the spatial and temporal uncertainties involved in the analysed process. A realistic set of all possible hazardous events (scenarios) that may occur in a given region, including very rare, catastrophic events, is simulated. For each event, potential impacts are computed in terms of economic losses or number of people and assets affected, considering available information on hazard, exposure, and vulnerability. Finally, statistics of losses are computed and summarized through proper quantitative economic risk metrics, such as: Annual Average Loss (AAL) and Probable Maximum Loss (PML).

In computing the final metrics (PML, AAL) the uncertainties that permeate the different steps of the computations are explicitly quantified and taken into account: uncertainties in the hazard forcing, uncertainties in the exposure values and their vulnerabilities. Average Annual Loss (AAL), often also indicated as Expected Annual Loss (EAL) is the expected loss per year, averaged over many years. While there may actually be little or no loss over a short period of time, the AAL also accounts for much larger losses that occur less frequently. As such, AAL represents the funds that would be required annually in order to cumulatively cover the average disaster loss over time. Probable Maximum Loss (PML) describes the maximum loss that could be expected corresponding to a given likelihood, expressed in terms of annual probability of exceedance or its reciprocal, the return period. Typically, PML is relevant to define the size of reserves that, for instance, insurance companies or a government should have available to manage losses.

In this framework the hazard entails a modelling chain composed of climate, hydrological and hydraulic models using all the available information, in terms of rainfall, temperature, humidity, wind, and solar radiation, to best predict possible flood scenario. A set of mutually exclusive and collectively exhaustive possible hazard scenarios that may occur in a given region or country, including the most catastrophic ones, are generated and expressed in terms of frequency, extension of the affected area and intensity at different locations. For the probabilistic approach, the distinction between flood map and flood scenario is fundamental (UNDRR ROA 2019 and 2021): a flood event or flood scenario usually affects only a portion of the country, therefore flood risk estimates based on flood maps are reliable only if the area of interest is relatively small but, if the area is wide (e.g. country or regional level), it is necessary to generate all possible flood scenarios that can affect the area of interest with their probability of occurrence. In a probabilistic framework, it is therefore advisable to go through the generation of all possible flood events that can affect the area of interest with different intensities. For this theme, a more detailed description is provided at section 4.1.1.

The vulnerability and consequences are composed by the definition of the direct and indirect losses for the different elements at risk evaluated by applying vulnerability functions, which link the hazard intensity to the expected loss (economic loss or number of affected people) or damage, considering also the associated uncertainty. Vulnerability functions are differentiated for each typology of exposed element and take into account local factors, such as typical constructive typologies. In this context, within BORIS vulnerability curves that relate intensity to damage are considered (described in section 4.1.2) and direct losses related to buildings and population are taken into account (see section 4.1.4). In terms of exposure (illustrated in section 4.1.3), it is in general based on various assets, population, Gross Domestic Product GDP and a series of critical sectors (education, health, transport, housing, and productive and agricultural sectors). In particular, the BORIS project considers buildings and population as assets at risk.

4.1.1. Flood hazard

The deterministic flood hazard zoning is based on the deterministic flood hazard maps for selected return periods – these are basically inundation maps prepared across EU generally excluding any uncertainty in the models used for its production. According to European Flood Directive, different countries are applying different return periods (Tr), from 10-year to 500-year return period, the most common return period used overall is the classical 100-year return period (Table 4.1). Table 4.1 shows methodology used in Austria, Italy, and Slovenia. More specifically, return periods (Qx) are shown together with the methodology used to define the flood hazard map classes. Hence, it can be seen that three neighbouring countries use different return periods for the definition of the low, medium and high probability events. Hence, a possible solution would be to select three most frequently used return periods for the definition of the low, medium and high probability classes at the European level. Thus, in such a way we could do some steps towards harmonization of selection of the return period. Moreover, differences in flood hazard mapping are even bigger with the consideration of the flood hazard classes. In this case, the harmonization at EU level probably cannot be easily achieved, since there are significant differences among European countries in topographical, climatological, hydrological, etc. characteristics. Thus, selection of a specific water level (i. e. flow depth) and flow velocity thresholds depends on national specific hydrological and hydraulic conditions (e.g., water velocity and depth both depend on the slope-topography; it is not meaningful to harmonize specific thresholds in countries such as Austria (mountainous) or Netherlands (lowland)).

Moreover, differences among countries are even more significant if one compares methodology used for the definition of topography and bathymetry, hydrological input and hydraulic simulation approaches (e.g. 1D, combined 1D/2D, full 2D hydrodynamical simulations) used in the process of the flood hazard map preparation (see the BORIS project Deliverable 2.2 (BORIS, 2021b) for more detailed comparison among Austria, Slovenia, Italy as EU members and Turkey and Montenegro as non-EU member states). Additionally, the probabilistic flood hazard maps are taking different uncertainties into account, even though defined for a fixed return period (i. e. 30-year or 300-year return period). These uncertainties that need to be accounted for, are related to hydrological modelling (rainfall-runoff mechanisms) and hydraulic modelling. Apel et al. (2004) mentioned the variability (aleatory uncertainty) and incomplete knowledge (epistemic uncertainty) that affect inundation simulation results: i. e. extreme value statistics, runoff routing, stage-discharge relationships, topographic data, roughness distribution properties.

Table 4.1: Comparison between return periods and flood hazard maps classes used in Slovenia, Italy and Austria for the EU Flood Directive.

Country	Return periods (Q_x) in years	Flood hazard maps classes
Slovenia	10, 100, 500	**High**: At discharge Q100 or water level G100, water depth ≥ 1.5 m OR water depth water velocity ≥ 1.5m/s. **Medium**: At discharge Q_{100} or water level G_{100}, 1.5m > water depth ≥ 0.5 m OR 1.5m/s > water depth· water velocity ≥ 0.5 m/s OR where at discharge Q_{10} or water level G_{10}, water depth > 0 m. **Low**: at discharge Q_{100} or water level G_{100}, water depth < 0.5 m OR water depth · water velocity < 0.5m/s. **Other**: at discharge Q500 water depth ≥ 0 m OR where flooding occurs due to extraordinary natural or man-made events
Italy	30, 100, 300	For every scenario (30, 100 and 300 years as return period) water height layers: 0–0.5 m; 0.50–1.00 m; 1.00–2.00 m; > 2.00 m water velocity layer: 0–0.5 m/s; 0.5–1 m/s; > 1 m/s
Austria	30, 100, 300	For every scenario (30,100,300) three separate intensity classes (low, medium, high) of the process characteristics of water depth and flow velocity are defined: **low intensity** (water depth < 0.6m; flow velocity < 0.6 m/s). **medium intensity** (water depth between 0.6; 1.5 m, flow velocity between 0.6 and 2 m/s). **high intensity** (water depth > 1.5m and flow velocity > 2 m/s).

The European Flood Directive (2007) defines deterministic flood hazard maps (showing the flood extent, inundation/flow depth and flow velocities) for fixed (selected) return periods (10/100/500 years or 30/100/300 years) using single design hydrographs neglecting any aforementioned uncertainties. The harmonization across borders for transboundary cases needs at least harmonization in the selected return periods and hazard classes related to inundation/flow depths and flow velocities used to classify inundation maps for a given return periods into a flood hazard map using zonation into 3 or more classes. Starting from this point three possible approaches can be followed.

4.1.1.1. Generation of flood hazard maps starting from the results of the EU Floods Directive

The approach presented here, albeit simple, is based on the results of the EU Floods Directive in the different cross-border basins of the Countries considered in BORIS (Italy, Slovenia and Austria). It represents a simple but effective procedure to generate flood hazard maps in cross-border catchments that generate flood hazard maps that are fully compliant with the results provided by each Member State within the EU floods Directive.

This approach allows for further elaborate the flood hazard maps provided by Italy, Slovenia and Austria to comply with the EU Floods directive by defining flood scenarios (extension and depth) with return periods from 10/30 years to 300/500 years with a yearly timestep. In this way a flood hazard curve can be easily defined for each point (5m resolution) of the cross-border catchments considered in this study. The advantage of this methodology is that it can be applied also in similar cross-border rivers in different EU Countries. This approach is detailed in section 4.2.1.

4.1.1.2. Probabilistic flood hazard assessment

From a theoretical point of view, a step forward towards multi-risk assessment in the field of flood risk would be to go from the deterministic flood hazard assessment to the probabilistic flood hazard assessment. However this cannot be easily achieved without performing a well-organized campaign of flood simulations at regional level.

In the following is described the probabilistic approach for flood hazard definition, able to account for all the sources of uncertainty related to the physical processes that lead to floods in different areas.

Quantification of uncertainties related to the hydrological-hydraulic modelling in the process of flood hazard map definition are essential for effective flood risk assessments (Merz and Thieken 2005; Apel et al. 2008). An overview of hydraulic and hydrological uncertainty in flood risk assessment is given by e. g. Annis et al. (2020).

A possible framework (algorithm) for a probabilistic flood hazard assessment in three steps is briefly described below. Harmonization would need to be achieved in relation to the selection of the hydrological model, methods to estimate hydrological model parameters, selection of the stochastic rainfall models, selection of hydraulic model and its parameters, etc.

HYDROLOGICAL MODELLING

Set up hydrological model (estimate the parameters), calibrate and evaluate it using measured (historical) flood events (e.g., discharge data). If there are no historical data available, use the procedure suitable for ungauged catchments (e.g., Blöschl et al., 2013).

Set up stochastic rainfall model (e.g., Haberlandt and Radtke, 2014) (estimate model parameters based on the historical rainfall data), evaluate it based on the measured precipitation data. If there are not station-based rainfall data available, one can also test the suitability of the satellite-based data or reanalysis data that are covering the whole continent at uniform spatial resolution without any gaps in the data.

Using fitted stochastic rainfall model, simulate long time series of rainfall events (multiple times), for example generate 1000 (n) times 100 years of precipitation data (k).

If needed generate air temperature data using weather simulators and if needed estimate evapotranspiration.

Based on the size of the catchment, consider spatial rainfall distribution, for example use the synchrony scale concept (e.g., Berghuijs et al., 2019), or areal reduction factors in case that large catchments are considered.

Based on the selected hydrological model type vary hydrological model parameters within a pre-selected range or vary initial parameters related to initial conditions (e.g., catchment wetness) in order to account for the possible hydrological variability during different rainfall (and air temperature) time series.

Based on the simulated discharge time-series (e. g., 1000 (n) times simulated 100 (k) years of data), extract relevant data (e.g., annual maximum peak discharge values and the corresponding flood hydrograph), based on the k floods define the design hydrograph.

For each of the n simulation results a design hydrograph with a specific return period is available as input for the hydraulic model.

Flood frequency analysis can be used to define the design discharge-return period relationship with the consideration of uncertainty.

HYDRAULIC MODELLING

Select an appropriate 1D hydraulic model for the main river channel (in usual case where river channel cross sections are available) if not a 2D, and combine it with an appropriate 2D hydraulic model for the floodplains. Building a full 2D hydraulic model where river channel bathymetry data and floodplain DTM data are available and the simulations are feasible from the computational point of view.

Set up the hydraulic model (determine the parameters such as hydraulic roughness, initial conditions, boundary conditions, hydraulic structures etc.), calibrate and evaluate it using measured (historical) flood events (e.g., floodplain extent). If there are no historical flood maps available use some other indirect estimates of flood depth (e.g., flood marks on old buildings, etc.).

Optimize run time of the hydraulic model (e.g., Neal et al., 2013; Neal et al., 2018) in order to achieve manageable run times.

Run the hydraulic modelling using several different input hydrographs (or optimized block bootstrapping as described by Neal et al., 2013) that were defined in the scope of the hydrological modelling (unsteady flow simulations).

During each simulation, randomly vary roughness characteristics of floodplains and cross-section depending on the seasonal roughness changes in the investigated area.

FINAL PRE-PROCESSING

Depending on the hydraulic modelling results (1000 model runs or optimized block bootstrapping runs), generate a probabilistic flood hazard map for a given return period.

A 3D representation of such maps is to be envisaged, a possible solution is using 3D printer or virtual reality presentation.

4.1.1.3. Flood scenario generation with a probabilistic approach

Another approach was suggested from UNDRR and the content of this chapter is taken from report UNDRR ROA 2019 and 2021.

For describing this approach it is necessary to refer to the hazard maps and scenarios generation with the hydrological data used as input information for the hazard maps.

The flood events generation process needs to have a higher discretization of hazard maps: this because the flood generator can simulate events with all possible return periods. So the hazard map available has to be interpolated. The interpolation method starts with the computation of the total volume of water for each of the original maps. These values are then interpolated through Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) method for all return periods of interest, in order to maintain monotonicity of the curve and avoid spurious oscillation. In order to obtain the maps at intermediate return periods, for each couple of consecutive original maps (e.g. 10-20, 20-50, etc.), the filling of a virtual reservoir can be simulated, in which it can be imposed that the minimum filling corresponds to the lower return period map (for example 10 years) and the maximum filling corresponds to the higher return period (for example 20 years). Then, the Return Period – Total Volume curve, previously interpolated, is imposed in order to keep the correspondence. In this way, the maps can be interpolated between the original ones, the curve of total volume (always increasing with return period) is respected, and the monotonicity of the water depth at each return period can be guaranteed for every single cell of the maps.

The next step in the risk profiling chain is the generation of all possible flood events that can affect the area of interest: the hazard maps provide water levels in flood prone areas for different return periods but they do not represent flood events. A flood event or flood scenario usually affects only a portion of the country. The distinction between flood map and flood scenario is fundamental: flood risk estimates only based on flood maps are reliable if the area of interest is relatively small but, if the area is wide (e.g. country or regional level), it is necessary to generate all possible flood scenarios that can affect the area of interest with their probability of occurrence. Aim of the flood scenarios generation is the simulation of all the possible events that can affect different areas of the region with different intensities. To simulate possible flood scenarios the output of the GloFAS-Reanalysis v3.0 (Harrigan et al. 2020) (discharges in different locations of the river network) was analyzed to select independent flood events. The methodology that can be employed for the events generation relies on a multivariate statistical approach that takes in input the selected events and, by preserving their spatial correlation, it is able to simulate events not yet observed both in terms of intensities as well as geographical distribution. The approach used for the events generation covers all the possible range of intensities and spatial dependencies and assures that:

- the spatial correlation of small- and large-scale events is preserved in the simulated event set;
- the statistical properties of the observed events at each location are preserved in the simulated event set.

The scenario generation process consists of two components: the first one is the event definition and selection and the second one is the probabilistic events generation. The event selection is based on a consolidated approach already applied and tested in some countries that balances the need of capturing small scale events and the limited computational resources during the flood generations process.

The entire area is divided in hydrological units: the event selection process allows to identify localized events affecting only one unit and more distributed ones affecting several units contemporary. These events, characterized by their maximum discharge over the event duration for each hydrological unit, are the basis for the probabilistic scenarios' generation. The probabilistic approach proposed is the one already successfully applied for fluvial flooding in several other projects: in Angola, Zambia and Tanzania under the Programme "Building Disaster Resilience to Natural Hazards in Sub-Saharan African Regions, Countries and Communities" (CIMA, UNDRR (2019)); in the IGAD region for the "Horn of Africa Partnership for Early Warning for Early Action: increasing the availability and use of disaster risk information for decision-making in the IGAD region" (2021) and in the Volta Basin for the assignment "Integrating Flood and Drought Management and Early Warning for Climate Change Adaptation in the Volta Basin" (2019 – 2023).

The approach is based on a probability domain perturbation of the selected flood events via a multivariate gaussian distribution and uses a gaussian transformation in the probability domain to improve the representation of the tail dependencies and overcome boundary issues.

The algorithm consists of multiple steps:

1. each event is expressed in terms of maximum discharge during the event window: each hydrological unit has its own probability distribution of the selected events. Aim of this first step is the selection of the probability distribution that best fits the discharge sample of each hydrological unit: this is obtained by applying a best-fit algorithm able to identity the best distribution between different families (e.g. log-normal, GEV, Gamma, Gumbel, Exponential, Weibull, Pareto and Log Pearson). The best fit distribution is then applied to the discharges to convert them in probabilities: as a result, each event is characterized by the probability assigned to each discharge for all the hydrological unit.
2. The simulated flood event should be generated by a multivariate gaussian distribution with mean equal to the probability assigned to each discharge for all the hydrological unit (the ones calculated at step 1). In order to overcome some boundaries issues (e.g. probability should be limited between 0 and 1) the simulation of possible flood scenarios is not done in the probability domain, as it usually the case for simple copula application, but in a transformed space. A normal inverse cumulative distribution function is therefore applied to each probability value.
3. Each transformed event trough the inverse of the normal CDF becomes the centroid (mean) of a multivariate gaussian distribution that will be used to generate possible flood events. The covariance matrix of the multivariate gaussian is a function of the number of events and of the hydrological units.
4. The simulated samples will be anti-transformed by applying a normal cumulative distribution and then transformed back in discharges through the inverse function of each specific marginal distribution (the ones fitted in step 1).
5. Each event, expressed in terms of discharge in each hydrological unit, will be converted in return period to link the discharge to the corresponding hazard map in order to identify the flooded areas and the corresponding water levels.

The scenarios generation allows to simulate events not observed yet. The simulated event set is tested to assure that the marginal distributions (the distribution of the discharges of the selected flood events for each hydrological unit) are preserved during the simulation process.

The output of the scenario generation process is a flood event catalogue covering approximately 300 years. Each event will be characterized by its intensity expressed in terms of return period. This event catalogue, together with the hazard maps for different return periods are the input data for the risk calculation.

4.1.2. Flood vulnerability

Physical vulnerability measures the propensity of an element to suffer damage when subject to an external natural stress. Physical damages are directly linked to hazard intensity and the characteristics of the element at risk. For this reason, physical vulnerability is always hazard-dependent and element-dependent.

The physical damages are related to the intensity of the hazard through the vulnerability curves or fragility curves. These curves can be generated using both empirical, analytical and expert elicitation models. Furthermore, in literature a lot of heterogeneous approaches have been applied to determine damage curves from natural hazards. Some damage functions are called "relative damage functions": they show the damage as a percentage. Other curves are "absolute damage functions", indicating absolute damage amounts in monetary terms. Focusing on the nature of loss, and paying attention particularly to residential buildings, there are two main causes for loss: external/structural loss and internal loss (related to the content). Also, for this aspect in literature we have a quite heterogeneous approach: some functions are built to measure the physical structural damage while other functions take into account the content of the exposed element; in many studies the damage content is expressed as a percentage of the damage to the structure.

Physical vulnerability curves can be developed at different spatial scales. In general, three main classes of curves can be identified: curves associated to land use classes; curves associated to specific building types; micro-vulnerability curves, built for a specific exposed element. Each specific hazard has a certain preferable scale of action. In flood risk assessment sometimes it is necessary to start from areal information and only successively investigate the point scale.

Generally, the analysis of the flood physical vulnerability is performed by means of damage functions or vulnerability curves that relate flood intensity with vulnerability/damage data (Apel et al., 2009; Van Westen and Kingma, 2009). Two types of flood damage functions can be found on literature, historical or empirical and synthetic or analytical curves. Historical curves are developed from historical loss data from actual flood events. Synthetic curves rely on the analysis of expected damage under certain hypothetical flooding conditions and are used when sufficient past events are not available.

Most flood damage functions are based on the relationship between the type/use of the element at risk and the flood depth. The assumption that is implied is that a large hydrostatic pressure differential between the inside and outside of a building does not occur and the dominant effect of the flood is the slow-moving water that is at contact with buildings and objects. (Kelman and Spence, 2004; Mertz et al., 2010). Nevertheless it should be noticed that analyses of empirical damage data showed that the variability of damages can only be explained to a rather small extent by the depth of flooding experienced. But often other flood characteristics than depth are not recorded, so that it is difficult to quantify their influence (FLOODsite, 2007). However, for all the types of flood and for all the categories of exposed elements the most significant parameter is water depth. The second parameter that is very important in particular for flash floods and flood from infrastructure failure is water velocity.

White (1964) was believed to be the first to create flood depth-damage curves. Based on several flood depth and associated damage data, he established an analytical relationship between these two parameters. Flood depth was measured in cm and flood damages were transferred into monetary values, for different classes of buildings. Flood depths were measured from three occurrences of flood: 1959 flood, regional flood and maximum probable flood (Sagala, 2006). A few years later Penning-Rowsell and Chatterton (1977) determined depth-damage curves for flood in UK. Their method, later known as Blue manual, divided elements at risk into several detailed sub-classes, i.e. classification of houses was divided in detached, semi-detached, industry, commercial shop etc. For each element at risk, they developed questionnaires and they asked directly to households to record flood damages (Sagala, 2006). In the United States, the U.S. Corps of Engineering

(USACE, 1992) created a catalogue of depth damage functions for residential buildings, specifically for damage to structure or to content. Various depth-damage curves have been developed, considering specific structural assets of residential buildings. These curves were obtained with both post-flood analysis and by modifying existing curves for different locations in USA.

The duration of flooding is another parameter that can influence physical damage to buildings. Penning-Rowsell et al. (2003) assume increased damages from longer duration of flooding due to components that can deteriorate progressively at contact to water (mortar, drains, timbers, plasterwork and tiles). In their manual for damage evaluation in UK short (< 12 hours) and long duration of flooding (> 12 hours) are considered in damage function construction. These curves are extracted from a synthetically generated database of absolute damage functions - the Multi Coloured Manual - provided by the Flood Hazard Research Centre (FHRC) from Middlesex University, as well as its predecessors (Penning-Rowsell and Chatterton 1977; Parker et al. 1987; Penning-Rowsell et al. 1992). The database provides depth-damage functions for 100 residential and more than ten non-residential property types. Both residential and non-residential damage functions do not solely consider inundation depth but also durations of flooding (as already explained) and for non-residential damage function it is furthermore taken into account if a coastal flood is considered or not (salt or fresh water) (FLOODsite, 2007). The presence of salt water can increase flood damage repair costs to building fabric of the 10% (Penning-Rowsell et al., 2003).

The velocity of inundation can also contribute on damage generation, especially considering flash flood areas or areas close to potential dike breaches. Nevertheless velocity has rarely been taken into account in flood damage evaluation (FLOODsite, 2007).

As introduced in section 4.1, the subject of the risk analysis in the BORIS project are buildings. Their structural behaviour towards water depth and velocity depends on several elements: building construction material, building usage, number of storeys, presence of basement, position of the main openings (doors and windows), doors and windows construction material; position of valuable assets within the building; position of building internal systems, characteristics of the internal plumbing and sewage systems, etc. All these characteristics make each building almost unique, but in a vulnerability analysis of a large-scale building block it is necessary to group buildings for homogeneous behavior, according to a specific taxonomy, and introduce vulnerability model suitable for specific building types, since they use different combinations of characteristics in order to identify specific curves to be associated. For this reason, it is necessary to introduce the different spatial scales that are used to perform the flood damage assessments (Merz et al., 2010):

- Micro-scale: the assessment is based on single elements at risk. For instance, in order to estimate the damage to a community in case of a certain flood scenario, damages are calculated for each affected object (building, infrastructure object, etc.).
- Meso-scale: the assessment is based on spatial aggregations. Typical aggregation units are land use units, e.g. residential areas, or administrative units, e.g. zip code areas.
- Macro-scale: large-scale spatial units are the basis for damage estimation. Typically, administrative units are used, e.g. municipalities, regions, countries. Macro-scale analyses consider areas of national or international scale and should provide decision support for national flood mitigation policies.

The approaches previously described are applied at the micro-scale, considering in some cases a high level of detail for building description. Sometimes this high level of knowledge of exposed elements is not available or is not required by the spatial scale of the study. In these cases meso-scale and macro-scale vulnerability studies are carried out. Manciola (2003) divided the territory into classes and associated a pair of curves of vulnerability, relative to the structure and to content, to each class. The data used for the construction of vulnerability curves and the interpolation of their analytical expressions are derived from a compendium of different sources of literature.

Another meso-scale approach that estimates potential flood damage in The Netherlands is the Damage Scanner approach, which is extensively discussed in several studies (Klijn et al., 2007; Aerts et al., 2008b; Bouwer et al., 2009; Van der Hoeven et al., 2009). The Damage Scanner calculates potential flood damages in Euro based on 15 land-use classes, that are classes particularly important for flood damage because of their high potential damage, such as residential (differentiated into three types) and commercial land-use types, as well as greenhouses and infrastructure (Moel, 2012). The land use classification of the Damage Scanner corresponds well to the CORINE system. Similar to CORINE, the Damage Scanner recognises a high density and a medium density class for urban areas, plus an additional low density class for rural areas. Also, the Damage Scanner has a single land use class for "Labour", including both commercial and industrial properties, and one class for infrastructure. (Jongman et al., 2012). For the meso-scale approach, it is necessary to recall the following vulnerability curves: the HAZUS Multi-Hazard software (FEMA, US Federal Emergency Management Agency, 2009; Scawthorn, 2006), which will be described in detail at section 4.2.3; the technical report published by JRC (Huizinga et al., 2017) on global flood depth-damage functions; the CAPRA (Cardona et al. 2012) flood functions collection.

Huizinga et al. (2017) have developed a methodology to construct flood depth damage functions and a globally consistent database of depth damage curves. This dataset contains damage curves representing damage as a function of water depth and the corresponding maximum damage values for a variety of assets and land use classes. The damage curves have been produced per damage class: residential, commerce, industry, agriculture, infrastructure, transport for each continent separately (Africa, Asia, North-America, South/Central-America, Oceania and Europe). The two main components are: 1) Fractional depth-damage functions: defined for water depth level between 0 and 6 meters, for 6 continents plus an optional 'Global' function, and for six impact categories; 2) Maximum damage values: provided for each impact category and defined at a country level. The maximum damage values for residential, commercial and industrial buildings can be further refined to suit the location. Details can be added to calculate the depreciation value as a proportion of the construction cost; calculate the value of the contents; size of the building footprint; proportion of the undamaged part; adjustment for the material used. The damage functions indicate the proportion of the asset that is damaged at a given flood depth, while the maximum damage values indicate the associated maximum damage value for that asset and together give the monetary value of the damage. Further details on the individual classes are given in the report. For example, flood damage includes damage to building contents; Huizinga et al. (2017) use the following percentages for maximum damage to contents/inventory: 50% for residential contents, ~100% for commercial contents, and ~150% for industrial contents.

On the other hand, the CAPRA library contains functions for buildings (public, private or part of the critical infrastructures); region-specific vulnerability functions are defined for different construction materials (earth, concrete, masonry, wood) and for different number of stories of the considered building. The CAPRA functions, which report the percent damage for different water levels, are different when the number of stories of the building varies.

It is important to note that, coastal floods, riverine floods, flash floods and generic urban floods have been considered by these studies. Inside the "Generic urban flood" definition we can find any flood that can affect urban areas, independently from the source.

4.1.3. 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). Furthermore, an explanation on how to quantify this risk component states that "measures of exposure can include the number of people or types of assets in an area". This definition highlights two elements, which are both important for defining a suitable approach for exposure mapping. They refer, from one side, to the interaction with hazard in the area of interest, and, on the other side, to the quantification and characterization of exposure. The latter is usually done by describing the amount of exposed assets, or their value. The value can be expressed in monetary terms, or other units of measure.

The asset typologies which can be considered in an exposed model depends on several factors, that can be function of the specific objectives of the Risk Assessment subject of study. For instance, working in the framework of disaster risk reduction, three main objectives are often defined, namely: 1) reducing the loss of lives; 2) reducing the economic losses; 3) reducing the impacts on the environment. Associated potential exposure elements are for the first: number of residents (for administrative unit, or block, or building); presence of people in different time windows (e.g., summer/winter, day/night); population density; number or percentage of children, women, old people; number or percentage of minorities or other vulnerable groups. For the second purposes as well as the number of buildings (for administrative unit, or block, or building) it is necessary to introduce the economic value of each building, or the cost/m^2 of built-up area (of suitably associated with information on the area), the number and/or economic value of industrial facilities, the number and/or economic value of commercial areas, the GDP distribution, the Crop production. For the third the m^2 of forested area, the economic value of woods, the m^2 of protected area are exposure elements that can be used.

When representing the spatial distribution of the exposure model, the typical formats of the Geographical Information Systems G.I.S are adopted. These systems typically allow for two different methods to represent and store spatial features of the real world in a digital manner, namely raster and vector (as schematized in Figure 4.1 and 4.2). A georeferenced vector might be associated with a so-called attribute table, where information can be added and stored for each element. Some of them can be directly used as exposure information, others can be useful for the following vulnerability assessment, while the remaining can be useful for the representation of the results. In the vector representation, the points are preferred to display facilities like hospitals or schools. This type of representation is simpler than the polygon one, as it doesn’t take into account the footprint of the asset. Anyway, as an attribute table can be added also to this type of vector, in this case too we can add as much information as we want for each asset. The vector linear format is usually adopted for mapping linear infrastructures, like roads, railways, electricity distribution grid, and so on, but they are not covered in this deliverable. Raster representation is instead adopted when the single assets and the characteristics for each element may not be identified, but we rather prefer to map a unique variable over the whole area under analysis. Some typical examples of raster representation of stock information are: the population distribution, the Gross Domestic Product distribution, the settlement maps, or the maps representing the presence of cropland or grazing lands. Raster format has some advantages when we define stock for impact or risk assessment, such as the homogeneity of the representation and the easiness of combination with other raster information, like hazard maps, which are usually represented as rasters. On the other end, this type of representation is limited when the description of the assets potentially at stake requires more than a variable.

After going through the different possible options available for representing the exposure model in our area of interest, the best one should be selected. The first element to take into account for this choice is the availability of data and information which are used as a base for developing stock information. In fact, it is quite common to start from already existing data, even if they couldn’t be directly organized for risk assessment purposes. It could be more efficient to adapt their structure to our needs, rather than start again the process from scratch. From a general point of view, globally available products can be used, datasets developed at national level, or information collected at local level. It is expected that, going from the global level to the local one, the accuracy of the stock information improves (as schematized in Figure 4.1 and 4.2). If only global products are used, stock information that is good for an evaluation covering homogenously the national territory can be obtained. But if locally-available data are used, the evaluation can be significantly refined; this goal sometimes can be reached also by integrating the different types of information. When adopting an approach that explicitly takes into account local data, or even detailed-information coming from the stakeholders, we can reach a two-fold objective: to increase the level of detail of the stock representation (and thus of the following risk assessment) and to improve the ownership and the understanding of the results by the final users.

As above-mentioned, another element that should be taken into account in choosing the best representation of exposure is the relationship with the other components of the risk equation. Relationships among exposure, which is based on the stock representation, and other risk components can be spatial, or they can refer to the structure of the information. For example, referring to the spatial relationship, a very detailed mapping of buildings as stock layer can be available, but the hazard may be represented through a very coarse raster file. This situation is not optimal, as it could require a great effort for characterizing each element of the stock layer, without the hoped benefits in terms of results of the exposure and risk assessment. Of course, if the stock information is already available and there is not the need to add much work for its refinement and validation, this type of disaggregation can be kept, but it should be remembered that the resolution of the final results will be driven by the spatial resolution of the hazard. Unfortunately, the same thing cannot be assessed in the opposite situation. Let's assume that a very detailed hazard mapping is available, like for example the output of a high-resolution hydraulic model. If some coarse layer is adopted as stock information, as for instance a Land Use Land Cover map at national level, all the advantages of the high-resolution hazard are lost. It can thus be assumed that the spatial resolution of the exposure assessment and of the risk assessment results is driven by the coarser information among hazard and stock.

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 damage of the building. Let's assume that for a region 3 vulnerability functions at building level are available, and that each of them is suitable for describing 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 of 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.

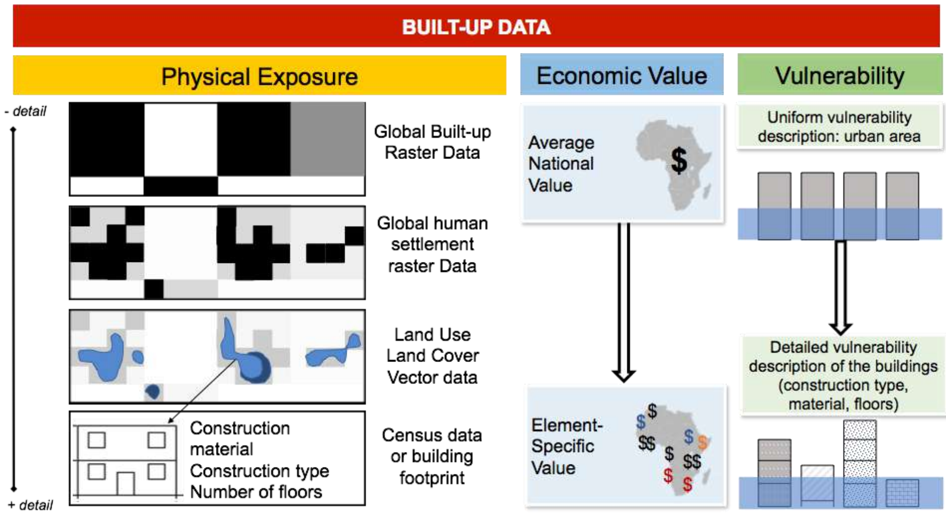


Figure 4.1: Potential improvements in the level of accuracy of the built-up data related to: the description of the physical exposure in terms of spatial representation and in terms of elements influencing the vulnerability; the economic value of the building stock (adapted from Rudari, 2019)

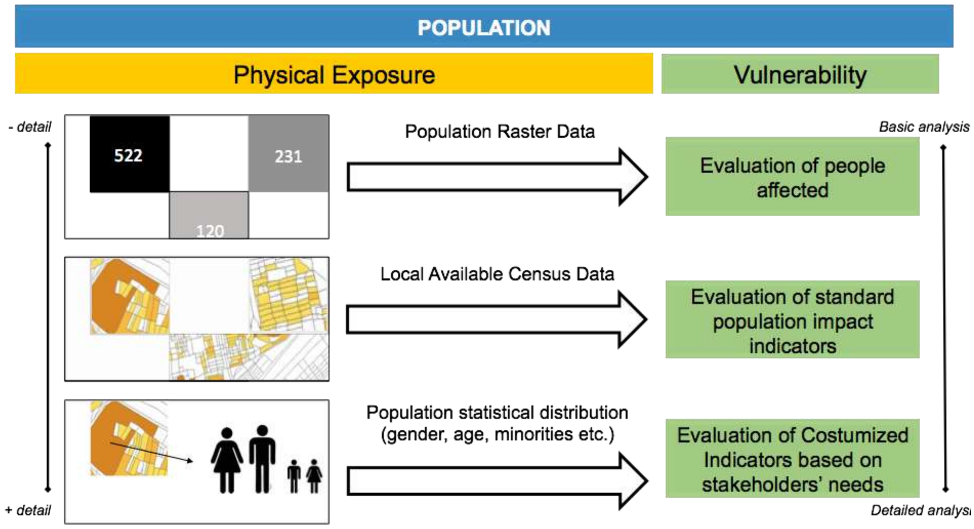


Figure 4.2: Potential improvements in the level of accuracy of the population thanks to: the description of the distribution of the population over the Country; the description of the population from the statistical point of view (e.g., age distribution, or sector of occupancy) (adapted from Rudari, 2019)

4.1.4. Consequence functions

When considering the consequences of floods, the literature often distinguishes between tangible/intangible and direct/indirect flood damage. Direct flood losses are economic losses, such as the destruction of property, but indirect losses can also occur inside and outside the affected area. In addition to direct tangible damage - i. e. damage to assets that can be monetised with a market price - such as buildings and their contents or vehicles, it must be taken into account that floods also cause direct intangible damage (deaths and injuries, environmental damage) as well as indirect consequences, some of which to some extent are tangible in the case of infrastructure and business interruptions, while indirect intangible consequences like psychological trauma or loss of trust in authorities cannot be easily monetised (Nicklin et al. 2019). In the present project the attention is focused on direct (tangible) flood damage.

Direct flood damage to buildings, per asset or per land-use class is usually considered using depth damage functions (described in section 4.1.2) to identify the economic impact. However, there are only a few depth-damage functions that describe flood damage in detail based on documented post disaster survey flood damage data / disaster loss data. Despite a large number of local and regional studies in Europe to establish local flood vulnerability functions or flood depth-damage functions, it is a highly debated question whether a site-specific depth damage function can be transferred to another region with similar climate and building conditions (Pistrinka et al. 2014, Fuchs et al. 2019, Thieken et al. 2008, Zhang et al. 2021). In the last decade there are ongoing activities on the international, European, as well as on the national level to standardise and harmonise disaster loss databases to generate more knowledge about damages and losses (e.g. EM-Dat, DRMKC – Risk Data Hub, https://drmkc.jrc.ec.europa.eu/risk-data-hub#/).

As introduced, the physical damage is used as an input to evaluate a series of impacts. Generally, the methodology for flood vulnerability assessment in EU partner countries is based on the classification of the impact indicators which are considered in the EU Flood Directive and should serve as a basis for further steps towards shared methodology for the flood vulnerability assessment. In particular flood risk maps shall show the potential adverse consequences associated with flood scenarios and, for the human parts, the indicative parameter is the number of inhabitants potentially affected. In addition to this aspect, also the impacts in economic terms are planned to be investigated in the present project.

The Economic impact can be evaluated multiplying the percent damage and the economic value of the considered asset: Damage [$] = Damage [%] X Economic Value [$]. The way in which this economic value is estimated changes according 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, on the other 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. A further detail allows to classify affected people in different hazard zones. Four hazard zones (very high, high, moderate, low flood hazard) can be defined based on the human instability in floodwaters, using available literature (Abt et al., 1989; Karvonen et al., 2000; Arrighi et al. 2017) together with expert judgments. When information on water velocity is not available, similar zoning classification is performed only on the basis of water depth information.

For the more in-depth evaluation of the population, it is essential to define which data to use; options that could be evaluated are EM-DAT international database for disaster losses, and DesInventar database at national levels (www.desinventar.org). It would need a study that gives an overview of used categories for after-flood studies in the world: fatalities, displaced, injured, affected (health and psychological problems) to estimate how the population is affected. These shares could be given as a percentage of the total affected population, as kind of a probability curve for a certain category within affected population (Ritchie et al. 2014). It is important to notice that these curves are a function of the type of a flood (flash flood, river flood, typhoon/hurricane flood, pluvial flood, tsunami-induced flooding).

Consequences information may be used to put in place a broad range of activities to reduce risk, from improving building codes and designing risk reduction measures, to carrying out macro-level assessments of the risks to prioritize investments. Risk metrics can help discern the contributions of different external factors (such as demographic growth, climate change, urbanization expansion, etc.) and provide a net measure of progress of disaster risk reduction policies implementation. Having detailed and more reliable assessments of direct losses from flood disasters is essential for civil protection and flood risk management.

Among the economic risk metric, Annual Average Loss (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. Economies can be severely disrupted if there is a high ratio of AAL to the value of capital stock. Similarly, future economic growth can be compromised if there is a high ratio of AAL to capital investment and reserves. Social development will be challenged if there is a high ratio of AAL to social expenditure. Moreover, limited ability to recover quickly may increase indirect disaster losses significantly. Countries that already have compensatory mechanisms such as effective insurance in place and that can rapidly compensate for losses will recover far more quickly than those that do not. Such mechanisms may include insurance and reinsurance, catastrophe funds, contingency financing arrangements with multilateral finance institutions, and market-based solutions such as catastrophe bonds (UNISDR, 2011 and 2013).

Also the Probable Maximum Loss (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 how to organise a strategy combining different risk reduction, mitigation, or avoidance actions. The PML curve can be subdivided into layers. Extensive Risk Layer: this layer is typically the one associated with risk reduction measures (e.g. flood defences, local vulnerability reduction interventions). Immediately after the extensive layer is the Mid Risk Layer that builds up cumulative losses from higher impact events. The losses of this layer are normally mitigated using financial funds, like contingency fund, that are normally put in place and managed by the country itself. The losses that compose the Intensive Risk Layer (severe, infrequent hazard events) are difficult to finance at the country level, and a mechanism of risk transfer has to be put in place (e.g. insurance and reinsurance measures). The remaining layer of the curve determines the Residual Risk (catastrophic events), which is the risk that is considered acceptable/tolerable due to the extreme rarity of the events able to determine such loss levels. Due to this rarity, there are no concrete actions to reduce risk beyond preparedness actions that tend to ease the conditions determined by the event (e.g. civil protection actions, humanitarian aid coordination).

As mentioned in the introduction of section 4.1 for the probabilistic approach and the evaluation of the AAL and PML, it is advisable to go through the generation of all possible flood events that can affect the area of interest and not exclusively adopt the hazard map. Since, in terms of these risk parameters the difference among these two approaches is significant (UNDRR ROA 2019 and 2021).

4.2. Shared framework for flood risk assessment

The harmonized approach for the cross-border flood risk analyses is based on the following steps:

- ***For the hazard component***: for each flood map with assigned return period the corresponding flood depth (if not already available) will be calculated and then interpolated for more flood hazard maps for different return periods. Needed Data are at least one flood extension map (from EU floods Directive) and high-resolution DTM (at least 5mx5m);
- ***For the exposure component***: the procedure for the definition of the harmonized spatial scale and exposure model consists of:
    1) Collection of the information on exposure (built-up area and population) at global level;
    2) Additional data described in a very precise and local way identifying the building footprints for the built-up area and the census data for the population;
    3) Downscaling methodology to implement the global information on the building footprints;
- ***For the vulnerability component:*** 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). They are function of occupancy and number of floors (and if it is available as information the presence of basement), and they are provided separately for structure and for content.
- ***For the consequence component:*** several indicators can be used to express possible negative consequences of a flood event; in the shared methodology the indicative number of inhabitants potentially affected and the economic consequences in terms of AAL and PML are considered.

4.2.1. Harmonised hazard

As briefly described in section 4.1.1.2, for defining harmonised flood hazard maps seamlessly available in the cross-border areas the starting point are the hazard maps provided in the framework of the EU Floods Directive (DIRECTIVE 2007/60/EC), from each European Member State.

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 idea is that through this quite simple procedure could be easily replied in other EU Member states when dealing with cross-border catchments.

The steps of the harmonization procedure are the following:

- STEP 1. Add to each flood hazard map provided by each Country the corresponding flood depths (if non already available). To add the flood depth the FwDET algorithms are used, as described in the following section.
- STEP 2. Starting from the flood hazard maps defined in STEP 1 a set of flood hazard maps with a specific return-time step is created, in this case we use 1 year. It is important to outline that these maps are based on statistical quantiles are reconstructed with an interpolation procedure with a 1-year step and are not calculated with hydraulic models/ simulations
- STEP 3. Cross-border post-processing and final harmonization

STEP 1 – FWDET application

The application FwDET (Cohen et al., 2019; Peter et al., 2020) calculates the water depth by subtracting the calculated flood water elevation (above mean sea level, asl) from the topographical elevation in each grid cell within the flooded domain. The flooded domain is provided as a polygonal layer to FwDET, making the tool agnostic with respect to the source and method used to derive the extent of the flood. The elevation of each cell of the grid and of the flood water is derived from a digital elevation model (DEM). While any DEM can be used, its horizontal and vertical resolutions can have a major impact on the accuracy of the instrument. The heart of the FwDET algorithm is the identification of the local polygon dividing flooded and not flooded area. The FwDET water depth calculation follows the procedure below:

- Conversion of the flood polygon to a line that represents the flood level
- Creation of a raster layer from the line layer that has the same size and alignment as the DEM grid cells
- Extraction of the DEM (elevation) value for these grid cells (called boundary grid cells)
- Assignment of the local tie value for each grid cell within the flooded domain from its closest boundary grid cell
- 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.

The figure 4.3 shows the theoretical cross-sections of floodplain (a) and coastal (b) illustrating a FwDET approach for calculating the depth of alluvial waters. The alluvial water boundary elevation (100m at the top and 3m at the bottom) is used to calculate the water depth (blue numbers) for each grid cell within the flooded domain (point A) . In river flooding (a) an underestimation of the water depth on the river is expected (point B) since DEMs typically capture the elevation of the water surface. In coastal flooding (bottom panel) the seaward flood limit can be on the coast (point B) or ocean (point C) and cannot be used to estimate the depth of the flood (elevation ≤0). In FwDET v2.0 these boundary positions are excluded, which means that only the internal flood boundary is used.

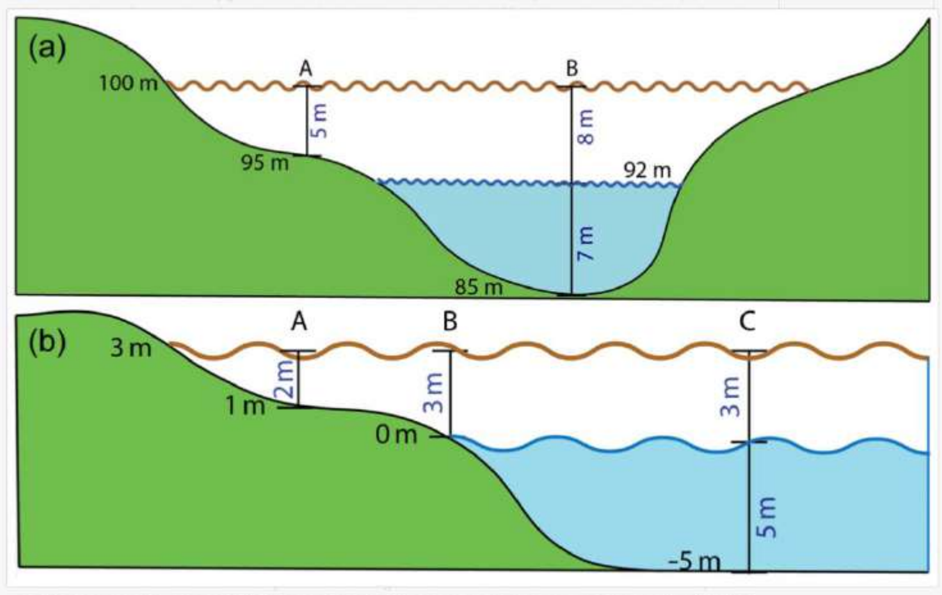


Figure 4.3: FwDet estimation of the tie in the case of flooding in the alluvial plain (panel a) and in the case of flooding in coastal areas (panel b) (Cohen et al., 2019)

In FwDET, the elevation allocation of the closest boundary grid cell is done using a cost function. Cost allocation changes the way in which the closest boundary grid cells are allocated thus eliminating an iterative approach to the benefit of a drastic reduction in computation time. The tool's "cost" input raster is used in FwDET v2.0 to prevent the elevation of boundary grid cells from being allocated to permanent water by assigning such grid cells a high cost value. The cost raster is calculated by assigning a value of 1000 to all grid cells with elevation equal to or less than zero and a value of 1 to all other grid cells. The advantage of using the cost function is both contained in the reduction calculation times but also in returning an output with the same resolution as the DEM. The figure 4.4 shows the flow chart in which the logic of the code in the definition of the tie rod is exposed.

In some cases, due to problems relating to the DEM or the vector dataset, it is necessary to make corrections to the result of the FwDet code, by way of example, two corrections made for the result of the high-risk area P1 of the Veneto region are reported, and specifically:

- Municipal areas of Acqua Petrarca, Monselice, Galzignano Terme in the province of Padua: in this case the vector file of the PAI area intersects part of two reliefs such as the Montericco hill and Mount Ventolone. This intersection generated a remarkably high tie rod result.
- Po mouth area: the high surface extension generates as a result an anomalous striped pattern that is not representative of the actual physical phenomenon of the flood.

The first problem was solved by performing the following post processing steps:

1. Definition of the "Absolute" FwDet given by the sum of the DEM and the Tie obtained from the first FwDet simulation;
2. Definition of a constant height matrix, physically realistic and belonging to the area of interest, in this specific case the tie has been placed at an altitude of 10m;
3. Definition of the "Correct" FwDet given by the difference between the constant quota, the absolute quota and the DEM;
4. Elimination of non-null values;

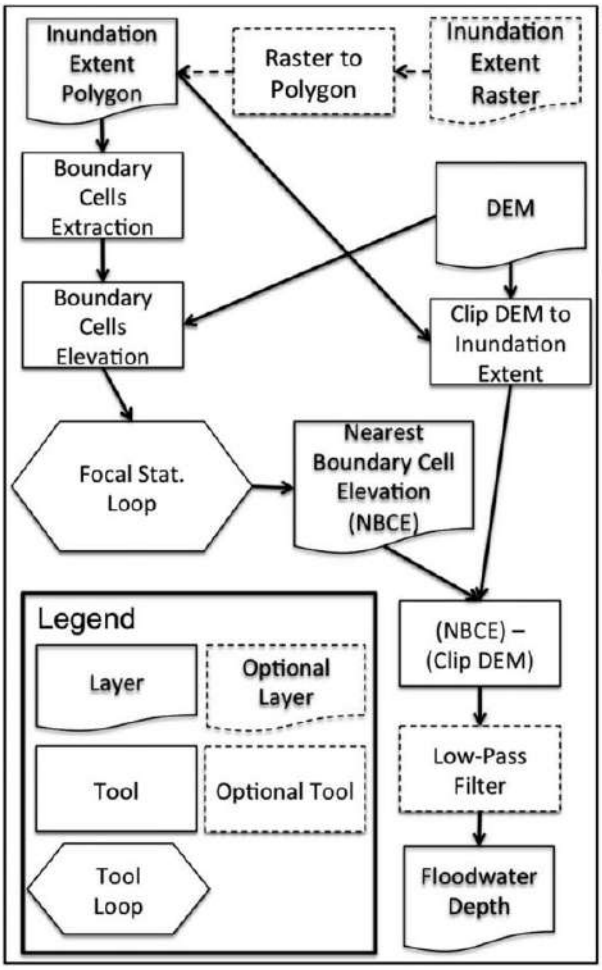


Figure 4.4: Flow diagram of the logical process used by the FwDet code for the definition of the water tie in the polygon of the flooded area (adapted from Cohen et al., 2018)

Below, the result of FwDet is reported in box a) and in box b) the correction with the method indicated above.

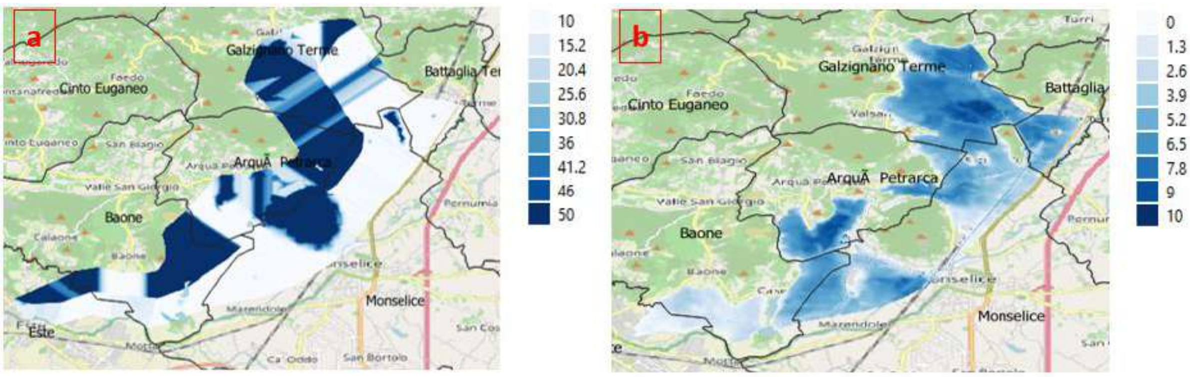


Figure 4.5: Correction of the FwDet result for the case of geomorphological error for some municipalities in the province of Padua. The two maps represent the flood depth [m].

The second problem related to the striped pattern generated on the Po area was corrected according to the following procedure:

- Definition of the "Absolute" FwDet given by the sum of the DEM and the Tie obtained from the first FwDet simulation;
- Definition of the longitudes raster
- Linear interpolation using longitude and MED altitude data
- Cleaning from values less than zero

Below, the result of FwDet is reported in box a) and in box b) the correction with the method indicated above.

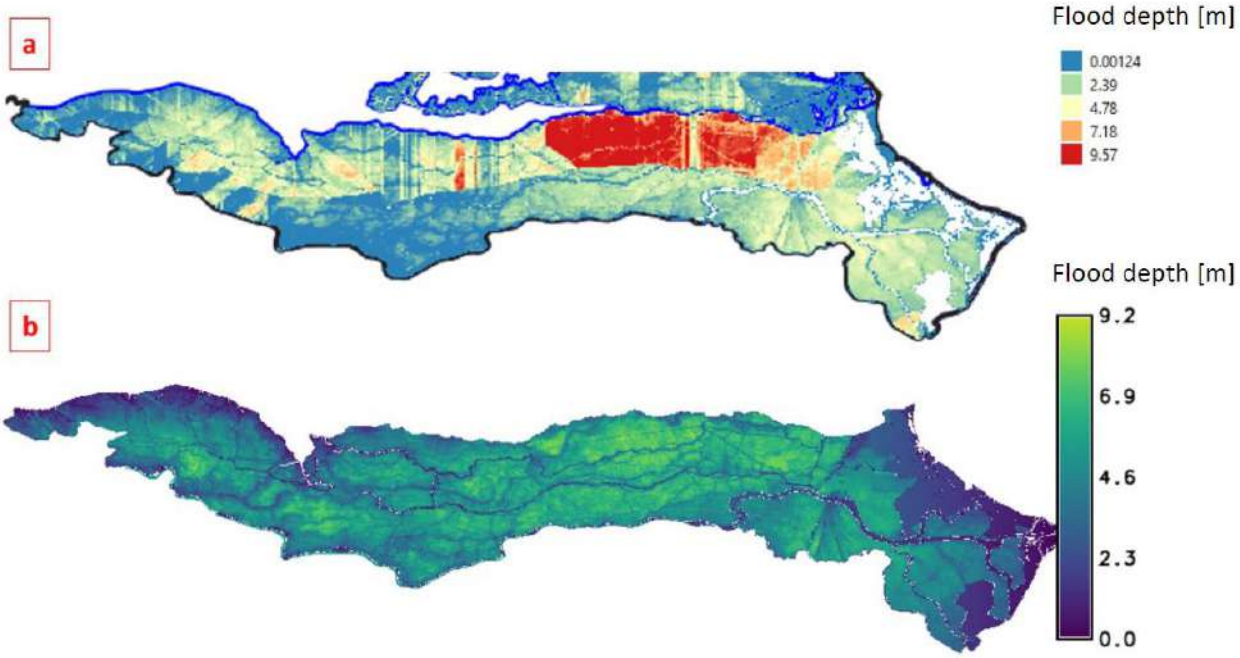


Figure 4.6: Correction of the FwDet result for the case of the error relating to the striped pattern for the Po mouth area. The two maps represent the flood depth [m].

STEP 2 - Abacus generation procedure

Starting from a number of maps for different percentiles, a set of maps is created with a specific time step, generally 1 year. That is, the maps for statistical quantiles not calculated with hydraulic simulations are reconstructed with an interpolation procedure with a 1-year step. The map interpolation procedure takes the form of the following steps:

1. Ordering of tie rod maps for each percentile;
2. Creation of an array of maps;
3. Calculation of the total volumes;
4. Calculation of the flooded area by adding the number of non-zero leaf cells;

Use of Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) necessary to keep the value of the interpolated rod between the lower value of the modeled rod and the greater value of the modeled rod. This interpolation method is characterized by the ability to maintain the monotony of the original data. As shown in figure 4.7, the use of this interpolation is a necessary and sufficient condition to avoid that there are interpolated values higher than the modeled values as could happen using a spline type function.

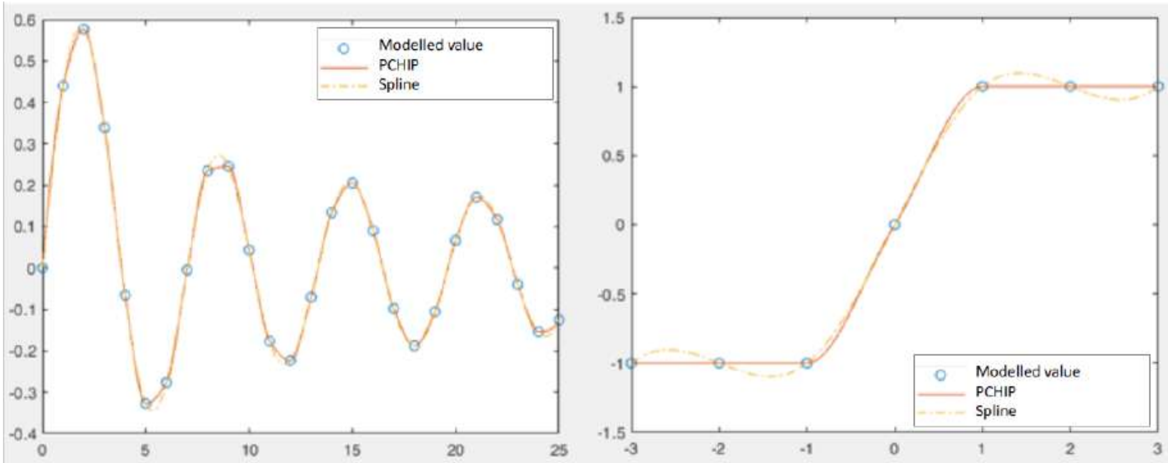


Figure 4.7: Representation of the PCHIP interpolation method compared with the SPLINE function

The two nominal maps (e.g. 50 and 100) are identified "around" the return time for which to obtain the desired map (e.g. 60).The pixels of the upper nominal map (100) are divided into crown and core, and the virtual DEM is created: in the core area, the value of the maximum head of the lower nominal map (50) is taken, and all other leaves are subtracted from it of the lower core itself, obtaining the heights of the "seabed" (in practice the seabed of the core is such that the lower nominal one fills it perfectly to the brim with a water level equal to the maximum head). It is assumed that altitude 0 corresponds to the lowest point of the nucleus bottom. In the crown, the DEM of the backdrop is obtained by adding the maximum of the leaves of the core of the lower nominal to the maximum of the leaves of the crown of the nominal superior (100) from which all the leaves of the higher nominal are subtracted.

Once the fictitious DEM of the total backdrop (core + crown) has been defined, a map of scaling factors is defined: these factors are worth 1 in all the pixels of the crown, while in the core they are such that, for each pixel, the difference between the wings of the upper core and the lower core (i.e. how much water drops between 100 and 50) is "expanded" until the lake is completely filled up to the maximum altitude which is, by definition, equal to the sum of the maximum head of the lower core the maximum head of the upper crown.

In this way the lake has two extreme water levels by definition: the minimum is at the "maximum head of the lower core" and the corresponding leaves are exactly those of the lower nominal, while the maximum is at the "maximum head sum of the lower core" height of the upper crown "and the corresponding leaves, once re-scaled with the previously scaling factors, reconstruct exactly the upper nominal. The "virtual" leaves of the lake are defined in each pixel as the difference between the share of the water level and the corresponding share of the dem, where this difference is not negative.

Once all these steps have been implemented in a series of cycles, it is obtained that by increasing the water level between these two limit quotas, by construction, maps are generated for which:

1. the area (number of pixels with non-zero head) is non-decreasing;
2. the volume is strictly increasing
3. the leaves are strictly increasing for each pixel (both in the nucleus and in the corona)
4. the whole follows a geometry compatible with the two nominals
5. at the extreme levels it reconstructs both nominals exactly
6. the change of all characteristics (area, volume, local wings) is gradual

The figure 4.8 schematically shows the initial phase of the interpolation procedure and the actual interpolation phase with the creation of a "virtual lake" and the use of a correction matrix for the values contained in the field in the "core". The drawings were elaborated by imagining to make a cross section of the water tie maps.

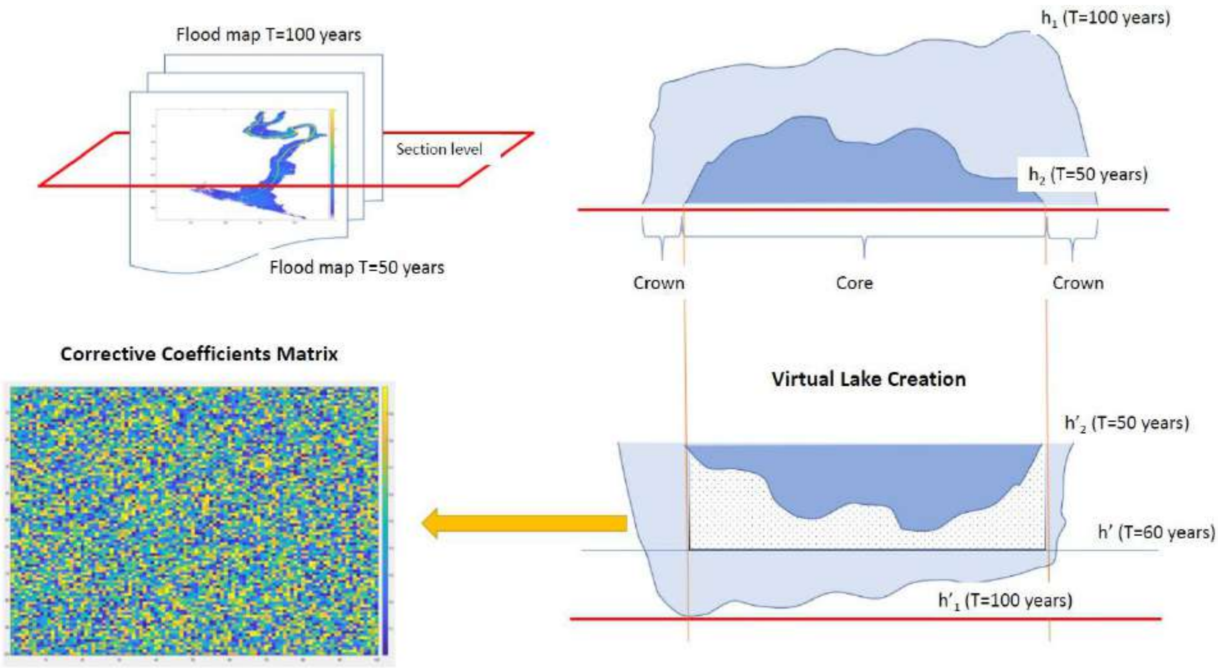


Figure 4.8: Schematic representation of the calculation phases necessary for the creation of the interpolated maps.

The results are shown below in figure 4.9:

- two-dimensional hydraulic modeling for a lower and higher return time
- from the procedure for a return time between the upper and the lower.

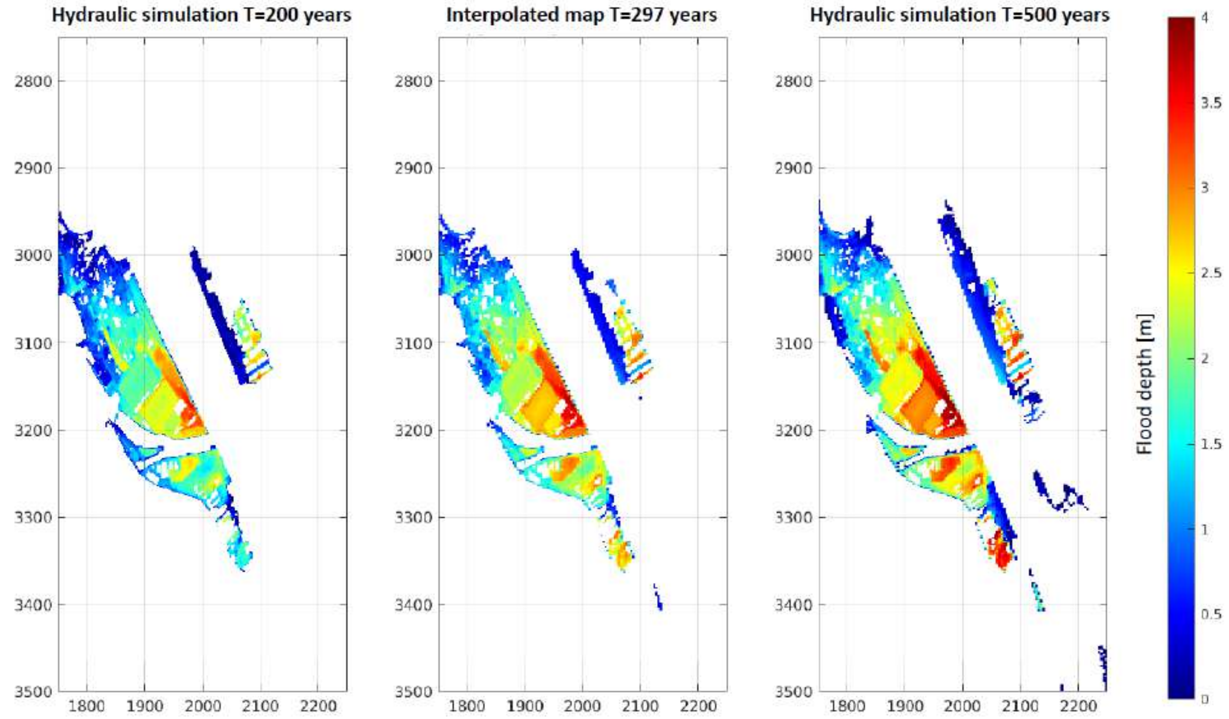


Figure 4.9: Comparison of modeled maps (T = 200 years and T= 500 years) and interpolated map (T= 297 years)

STEP 3 – Cross-border post-processing and final harmonization

The domains of the Slovenian territory located on the border with Italy and Austria present problems relating to the definition of the hazard maps for the return time.

In this area, the main problem is related to initial harmonization of the Eu Floods directive hazard maps that are not available for the same return period in the different Countries.

The Floods Directive hazard maps provided by Italy are:

- P3 hazard map: events with 30 years return period
- P2 hazard map: events with 100 years return period
- P1 hazard map: events with 300 years return period

The Floods Directive hazard maps provided by Slovenia are:

- IKPN Q10: events with 10 years return period
- IKPN Q100: events with 100 years return period
- IKPN Q500: events with 100 years return period

The Floods Directive hazard maps provided by Austria are:

- Hazard Q30: events with 30 years return period
- Hazard Q100: events with 100 years return period
- Hazard Q300: events with 300 years return period

In figure 4.10 it is reported the flow chart of the process that can be to harmonize the hazard maps for the Italy-Slovenia cross-border area. A similar procedure can be used for the Slovenia-Austria cross-border area.

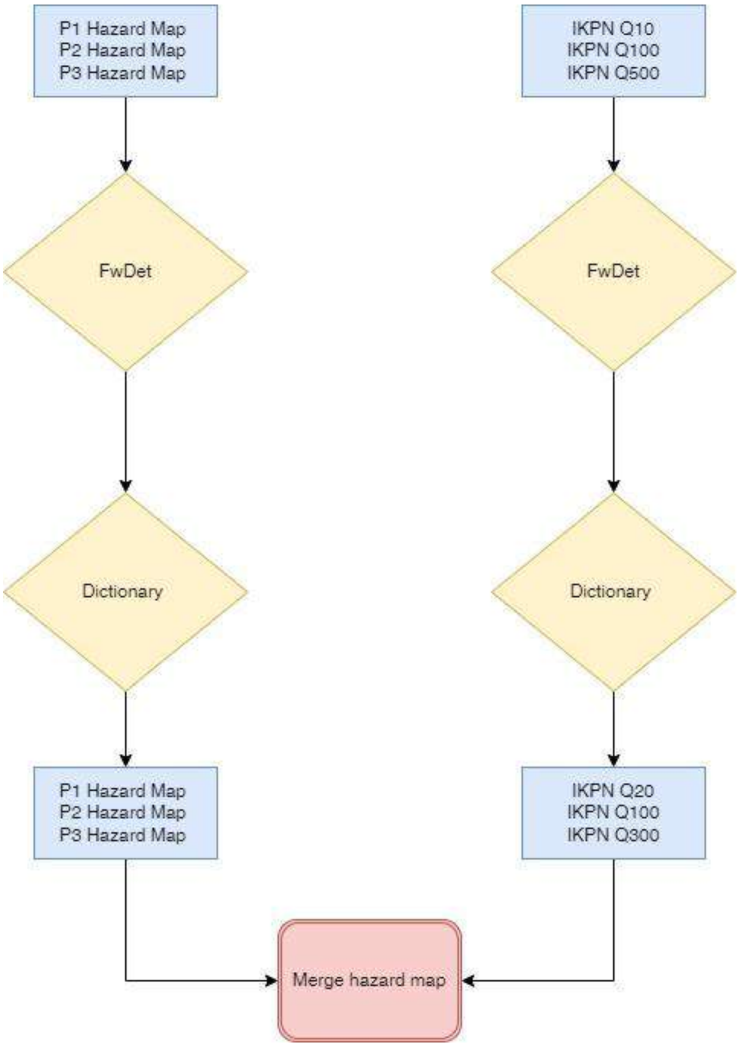


Figure 4.10: Flow chart of logicall approach for harmonization of different datasets. The figure shows the inputs in blue, the processes in yellow and the outputs in red.

Example 1. Italy -Slovenia domain

To define the hazard map for the Italy- Slovenia domain, it is necessary to carry out a pre-processing of the vector data. Specifically, the vector data can be processed following the following steps:

1. Creating the permanent water vector buffer (mainly rivers and lakes).

2. Merging the vector with the vectors of the different hazard.
3. Dissolving the geometry for each vector hazard.
4. Merging the Italian and Slovenia hazard maps.

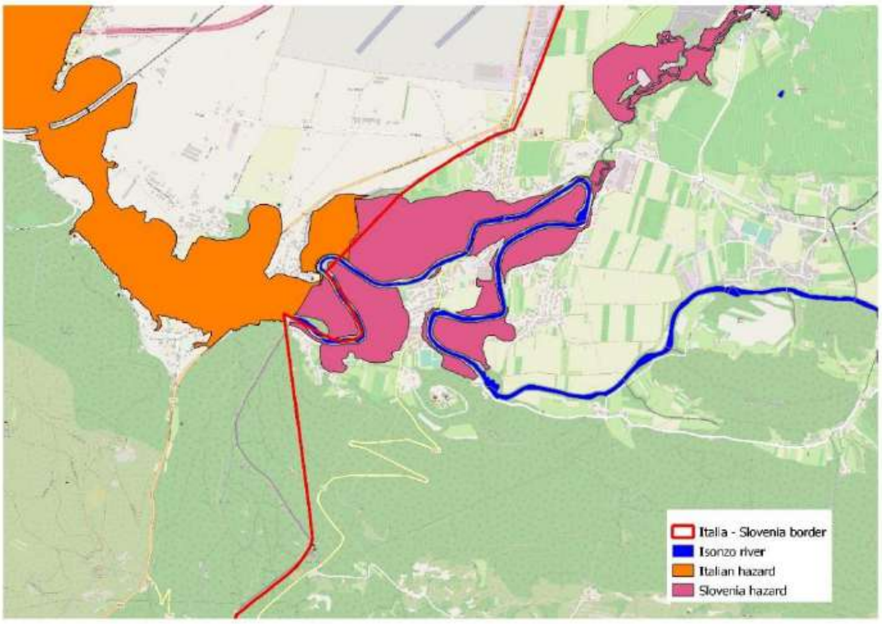


Figure 4.11: Example of preprocessing of hazard map - input

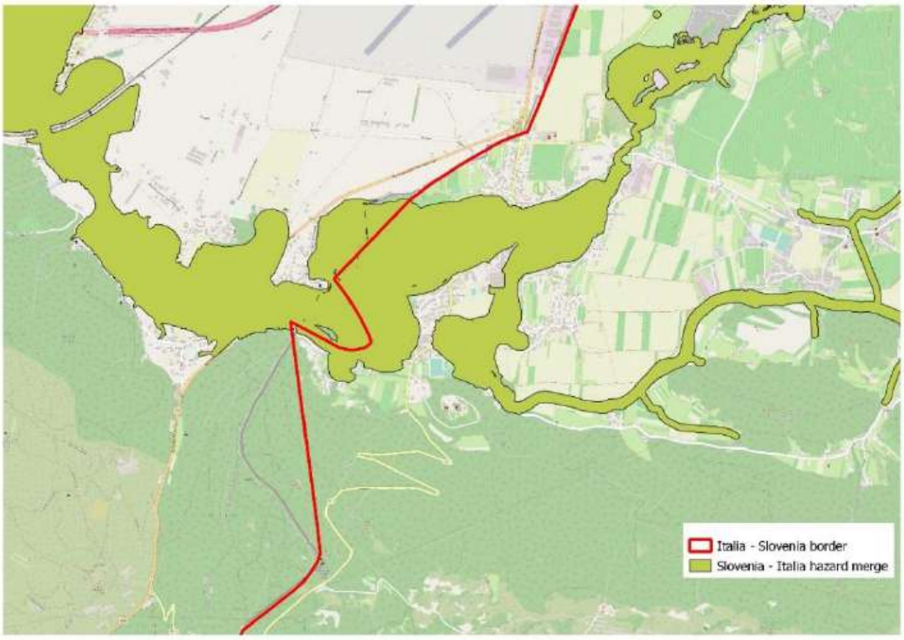


Figure 4.12: Example of preprocessing of hazard map - output

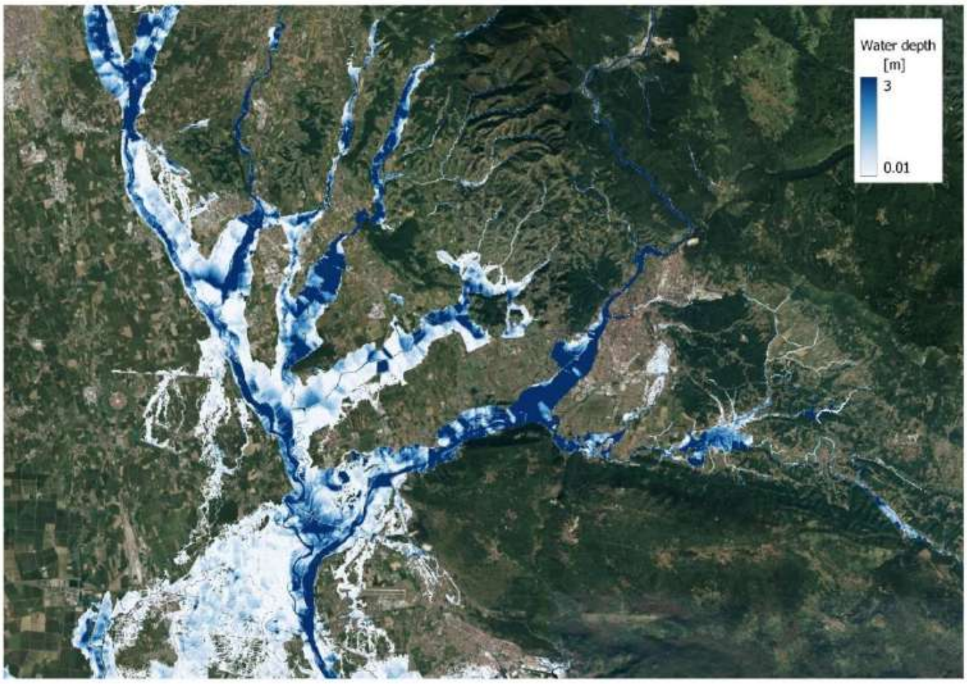


Figure 4.13: Example of harmonized flood hazard map in the Italy-Slovenia cross-border area (Isonzo river)

Example 2. Slovenia - Austria domain

To define the hazard map for the Slovenia- Austria domain, it is necessary to carry out a pre-processing of the vector data. Specifically, the vector data can be processed following the following steps:

1. Creating the permanent water vector buffer (mainly rivers and lakes)
2. Merge of the vector with the vectors of the different hazard
3. Process to dissolve geometry for each vector hazard

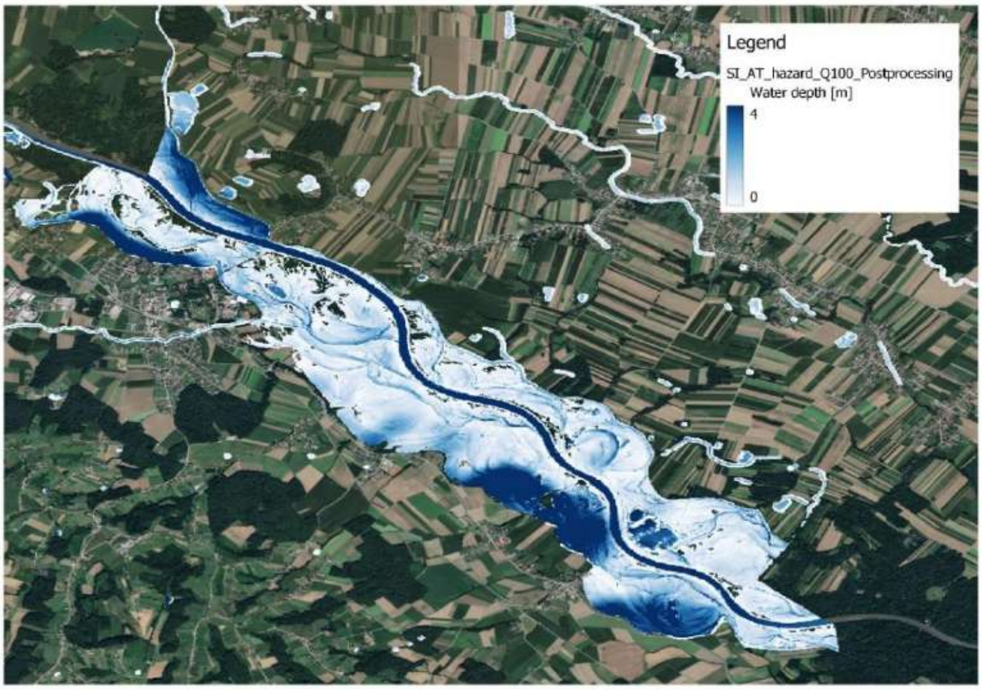


Figure 4.14: Example of harmonized flood hazard map in the Slovenia-Austria cross-border area (Mura river)

4.2.2. Harmonised exposure

As introduced in section 4.1.3 the assets at risk considered in the harmonized exposure are buildings and populations. The quality of the impact/risk assessment depends on the level of accuracy of the input data of the exposure. For the characterization of them, the following steps are proposed:

1. *Collection of the information on exposure (built-up area and population) at global level.* For each of the considered exposed elements a series of available Global Datasets will be used. These datasets have the great advantage to have a global coverage and therefore to ensure a minimum background exposure knowledge to perform acceptable risk analyses;
2. *Additional data described in a very precise and local way* identifying the building footprints for the built-up and the census data for the population;
3. *Downscaling methodology* to implement the global information on the building footprints, to determine a spatial distribution of the following indicators: residential population (which can be used to evaluate affected people); the economic values of the built-up; the factors describing the vulnerability of the built-up. When possible, the downscaling procedure is controlled with the data deriving from point 2. This buildings characterization is obtained merging in the GIS environment several sources of geographic data, available from different available institutional data portals.

For the step 1, the data can be defined through: (a) the distribution of the population over the Country with for example WorldPop (100 m resolution) or High-resolution Population Density Maps and Demographic

Estimates (30 m resolution); (b) the built-up area extension can be represented using Built-Up raster layers obtained from Remote Sensing or global datasets as the GAR exposure layer (UNISDR, 2015) or ESRM20 exposure model (Crowley et al. 2021) for building characteristics. The GAR is used as a minimum level of description, inside this exposure layer, point, representing a 5x5 km area, reports information on the economic value and the population associated to each typology of building, in terms of both occupancy (socio-economic sector) and main constructive typology. Among the reported socio-economic sectors, it is possible to identify and extract the information related to the public/private health and the public/private education sectors and use them as a minimum reference for schools and hospitals. This layer does not allow to have an accurate location of the infrastructures. The ESRM20 exposure model represents the spatial distribution of the residential, commercial, and industrial building count, population, and replacement cost. The buildings in the exposure model are classified according to: main construction material (e.g. reinforced concrete, unreinforced masonry, rein- forced/confined masonry, adobe, steel, timber); Lateral load resisting system (LLRS; e.g. infilled frame, moment frame, wall, dual frame-wall system, flat slab/plate or waffle slab, post and beam); Number of stories; Seismic design code level (CDN: pre-code, CDL: low code, CDM: moderate code, CDH: high code); Lateral force coefficient used in the seismic design.

For the step 2, the description of the population is defined from the statistical point of view at census level, that is a sub-municipal scale. The built-up can be described in a very precise way identifying the building footprints. Furthermore, the distribution of the main construction typologies (material, number of floors, elevation of the first floor etc.) can be aggregated at different scales, starting from the National scale arriving again to be reported at the building footprint scale. In fact, 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. In the harmonized procedure these characteristic are: the number of floors and the building use. If it is possible to add some additional information to the characterization of exposure, we can directly obtain some more interesting impact indicator. For instance, if we add to the exposure characterization the information on the surface of the building, we can estimate the damaged surface. Or we could add the reconstruction cost per square meter, that would allow us to understand the direct economic impact of the event.

In this framework, the countries involved in the project have different data available:

- in Slovenia, the average number of people per housing unit in each municipality is provided by Central Population Register, but it is not publicly accessible, so we will use global products. For the built-up layer, building by building data are available, that include information on predominant material of the load-bearing structure, the number of storeys, the year of construction and the net usable surface area, but there was not information on the occupancy. These building specific information are provided by Real Estate Register (REN) for the entire country and they are publicly available;
- in Italy all data related to population estimates are produced by ISTAT (National Institute of Statistics) that provides publicly accessible information on buildings, dwellings and population at census tract level. For what concern the buildings, data available are: a raster defined starting from the OpenStreetMap (OSM), since for the Friuli Venezia Giulia region it was not possible to find the layer of the Real Estate Register, but we saw how the OSM data maps very well the built on the entire regional territory; a vector layer from the Department of Civil Protection, that in collaboration with the Italian Regions and Autonomous Provinces, has drawn up the National Map of Structural Aggregates to support the activities of damage survey, emergency intervention and accessibility for buildings following an earthquake event;

- in Austria, the Statistik Austria (National Institute of Statistics) provides information about the number and composition (age, gender, nationality) of the population. There are also statistics pertaining to the individual components which are constantly influencing the size and composition of the population, i.e. births, deaths and migration. The statistics listed above are all available at the federal province level, and most are also available for smaller administrative units (NUTS 3, political districts, municipalities). These units measure 250x250 m. In Austria the building footprint is available including the building height but no associated information directly related to the vulnerability. For the built-up layer data at the municipality level are available, that include information on the number of storeys, the period/ year of construction, whereas data on predominant material of the load-bearing structure is available for newer buildings since 2011, but for buildings from the periods before data about the material is incomplete up to 80 %.

Once the building level is defined, the data are downsized both in terms of population and in terms of building data.

4.2.3. Harmonised vulnerability

All countries consider similar elements for the overall view regarding flood risk, and this is related to the requirements of the EU Flood Directive. However, approaches as to whether and to what extend vulnerability is considered or assessed differ significantly in the individual countries (see BORIS, 2021b)). Not all countries have vulnerability studies at the national level allowing to assign country-specific vulnerability curves and classes. In individual studies, there are often very detailed investigations, but these are only applied locally. In Italy and Austria, vulnerability is assumed to be present in all flood discharge areas (1) and not outside (0). In Slovenia, on the other hand, a classification of flood vulnerability classes exists throughout the country.

Considering the existing vulnerability models, introduced in section 4.1.2, in BORIS the adopted vulnerability model for cross-border risk assessment is the one proposed in HAZUS (FEMA, 2009), proposing vulnerability curves based on occupancy and number of floors, and distinguishing the curves for structure/content and for buildings with/without basement (if this information is available).

Inside the HAZUS Multi-Hazard software (FEMA, 2009; Scawthorn, 2006) - a tool for the estimation of the potential economic, financial and societal effects of natural hazards within the United States – a large number of nationally applicable depth–damage functions for buildings developed by the Federal Insurance Agency on the basis of 20yr of empirical damage data, as well as separate functions developed by the US Army Corps of Engineers (USACE) for specific regions of the United States, have been collected and applied. Within the HAZUS - MH flood model, also velocity-based building collapse curves developed by the Portland District of the U.S. Army Corps of Engineers have been utilized (except for manufactured housing). These curves relate collapse potential (e.g., collapse or no collapse) to overbank velocity (in feet per second) and water depth (in feet) for three building material classes (wood frame, steel frame, and masonry or concrete bearing wall structures). Users of the HAZUS software have to choose between a basic “level 1” analysis using default input data, a “level 2” analysis using default data supplemented with regionally specified information, or a “level 3” analysis that requires extensive additional economic and engineering studies by the user. (Jongman et al., 2012)

The HAZUS Flood Model Methodology considers the following buildings, facilities and systems:

- General Building Stock (GBS), whereas often commercial, industrial, and residential buildings are mostly grouped into five general building types and 33 occupancy classes. Examples of general building types include wood, steel, concrete, manufactured housing, and masonry. Examples of occupancy classes are single-family dwelling, retail trade, heavy industry, and churches.
- Essential Facilities, including medical care facilities, emergency response facilities and schools. Whereas school buildings are included due to their in housing displaced people.
- User-Defined Facilities (UDFs) are buildings at specific locations that are added to the inventory.
- Lifeline Systems including analysis for transportation systems (facilities associated with e.g. highways, railways, airport locations and utility systems including portable water, waste water, natural gas, electric power, and communications locations.

In Arrighi et al. 2018 and Silvestro et al. 2016 a modified HAZUS library has been developed, building vulnerability functions tailored for the European context by combining the curves for specific uses that can be found in the original library. The original occupancy classes by HAZUS-MH database distributed from FEMA were extended considering "Mixed" residential and different commercial services on the ground floor. Figure 4.15 shows a comparison between four water depth – damage curves for following content: retail trade (COM1) building (blue), generic one-floor residential (RES1) building (red), mixed retail trade on the first floor and residential on the second floor (COM1 + RES1) building (light blue), and mixed retail trade on the first floor and residential on the second and third floors (COM1 + RES1 + RES1) building (orange). The light blue curve, corresponding to the flood vulnerability function for the content of a two-storey building with mixed commercial and residential use (specifically retail trade on the ground floor and residential on the first floor), is obtained by combining the one-storey curve for generic residential (in red) with the one-storey curve for retail trade (in blue). The yellow section of the graph represents the average height of the ground floor. The left part of the mixed curve is obtained by re-scaling the blue curve. For higher values of water level, the function increases proportionally to the values that the residential curves assume (red) in the left part of the graph. It is assumed that the value of the ground floor is equal to 60 % of the whole (two-storey) building. The orange curve is built in an analogous way, considering a first commercial floor and two upper residential levels, obtained by adding two separate one-storey residential levels. The mixed-use curve definition reported in the figure are the ones proposed by Silvestro et al. (2016). . Nevertheless, as specified in Silvestro et al. 2016, generally from real estate registry and census datasets (adopted in BORIS project) it is not possible to distinguish between mixed-occupancy buildings. In fact, it is very common the case of buildings with commercial activities (shops, stores, banks, etc.) on the ground floor and dwelling on upper floors.

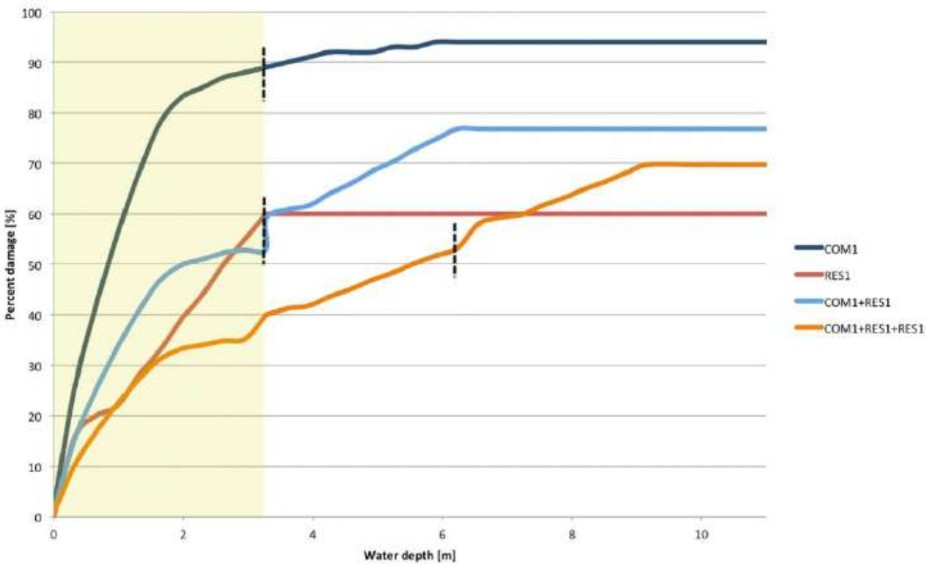


Figure 4.15: An example of mixed-use curve definition adapted from Silvestro et al. (2016).

Given a curve associated to an asset, the magnitude of the event hitting the asset in that specific scenario should be considered. Once such a value is identified, it is possible to enter in the curve and read the corresponding value on the y axes. Usually, it is expressed as a percentage, and it represent the percentage of damage to the overall asset. This is defined as the direct physical impact on a given asset for a given flood scenario.

In a probabilistic approach, it is also possible to introduce secondary uncertainty as for the hazard e.g. the uncertainty in the water level at site; for the vulnerability the uncertainty in the amount of damage, given a water level and for the exposure data the uncertainty in the location and construction details of the exposed risk.

4.2.4. Harmonised consequence functions

As mentioned in section 4.1.4, several indicators can be used to express possible negative consequences of a flood event; in the shared methodology the indicative number of inhabitants potentially affected and the economic consequences in terms of AAL and PML could be considered.

For the computation of the AAL and PML, physical damage obtained by application of the damage functions (vulnerability elements) can be transformed into economic losses (ED) using replacement cost per square meter.

$$ED[EUR] = PD \cdot A \cdot RC \cdot (n + b) \qquad (4.1)$$

where PD (%) is the physical damage, A [m^2] is the area of the building footprint, RC [Euro/m^2] is the replacement cost per square meter, and n is the number of floors, while b is a parameter function of the presence of the basement (b = 0 if the building has no basement b = 1 if the building has a basement).

In Italy, most of the replacement/recovery costs for damage categories for structures are based on the report about seismic and flood losses (Associazione Nazionale fra le Imprese Assicuratrici – ANIA-, 2011), which collects the average values for each Italian region (Arrighi et al. 2018). Also the replacements costs for contents are summarized in Arrighi et al. 2018, where the replacement costs for household contents have been assigned starting from the base recovery value (ANIA, 2011) for structures and the contents to structure ratio (CSVR) for residential use (USACE, 2006). Several other studies also suggest that residential content is roughly half of the value of the building structure (Huizinga and Szewczyk, 2017). Lower values and higher values in the range are assigned to suburban areas and historic district respectively.

Concerning the population, besides the counting of the number of persons residing in flooded areas, that is typically adopted as indicator for affected population, other indicators such as expected casualties could be considered. However, as described in Silvestro et al. 2016, despite the enormous impacts of floods, there is relatively limited insight into the factors that determine the loss of life caused by flood events. In the literature several methods have been developed to assess the loss of lives due to flood events and to identify mitigation measures (DeKay and McClelland, 1993; Jonkman et al., 2008). In general, these methods consist of a quantitative relationship between the flood characteristics (such as water depth, velocity) and the mortality in the flooded area. In order to compare possible impacts on population for different scenarios, four hazard zones (very high, high, moderate, low flood hazard) were defined based on the human instability in floodwaters. In fact, practical experiments (Abt et al., 1989; Karvonen et al., 2000) show that in flow conditions $0.5<v<3 ms^{-1}$ and $0.3<h<1.5m$ (where v and h are the velocity and the water level in the inundated street) the average human instability threshold in floodwaters corresponds to $hv = 1.35\ m^2\ s^{-1}$ (Jonkman et al., 2008). This is the threshold that differentiates the “high flood hazard” vs. “moderate flood hazard” zones. Further thresholds (upper and lower) were introduced based on “expert judgement” in order to identify two other classes: “very high flood hazard” (very high water level and velocity) and “low flood hazard” (low water level and velocity). The resulting four flood hazard zones can be ranked as follows:

i. very high hazard zone when $hv \geq 5\ m^2\ s^{-1}$ and $v \geq 2 m\ s^{-1}$;
ii. high hazard zone when $h \geq 0.2 m$ and $hv > 1.35 m^2\ s^{-1}$;
iii. moderate hazard zone when ($h<0.2m$ and $hv>1.35m^2\ s^{-1}$) or ($0.5>h\geq 0.2m$ and $v>1$ and $hv<1.35m^2\ s^{-1}$) or ($h>0.5m$ and $hv<1.35m^2\ s^{-1}$);
iv. low hazard zone when ($h<0.2m$ and $hv<1.35m^2\ s^{-1}$) or ($0.5 > h \geq 0.2$ m and $v < 1$ m s^{-1}).

In some simplified cases, the assessment of people potentially affected by a flood event is, in general, carried out assuming that, if the water level on a specific cell of the domain is above a certain threshold (e.g. 50 cm), the people, that according to the population layer are concentrated on that cell, are potentially impacted by the flood.

4.3. Indications for exportability to other countries

FwDET algorithm could be applicable for hazard assessment in Montenegro if the data regarding the flood extents for different watersheds were available (in the required format). For the time being, the flooded domain is determined (through hydraulic modelling) only for the purposes of specific main designs. For example - for purposes of the project Drin-Bojana basin Flow and Flood Forecasting System, GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit) along with the National Hydrometeorology Service (NHMS) of Montenegro, NHMS Albania, Kosovo and Macedonia, built a two-dimensional hydraulic model of Drin and Bojana watershed using HEC-Ras; so in this case – flooded domain could be exported as a separate file and possibly – imported to FwDET. However, lack of high-resolution DEMs would represent an additional problem, which means that extensive geodetic surveys should be conducted in order to improve topographic data prior to applying the proposed water depth calculation. For instance, in the aforementioned project, the terrain model of the Montenegrin floodplains was formed using the 5 m version of the LiDAR-based terrain model, but where necessary, additional topo-bathymetrical survey was conducted in order to improve the terrain model (e.g. numerous relevant embankments and dikes in the model area have significant influence on the timing, location and extent of inundation, thus, their representation in the model geometry is crucial for the simulation results).

Use of the presented interpolation methods would come in handy, since the scarcity of measured hydrological data may pose certain difficulties regarding the different hydraulic simulations (for different return periods). In the GIZ project, simulation was carried out for the return periods of 10, 100 and 500 years, but using the proposed interpolation procedure, it would be possible to generate floodplain maps for the return periods of 30 and 300 years.

Exposure models have not been established in terms of creating digitalized data. Regarding the population, only census data at a municipality level is available, therefore it would be necessary to collect information on the spatial population distribution in the areas endangered by floods, and then create appropriate data layers in the vector format. As for the building information in Montenegro, SERA exposure model offers the number of buildings and the construction type at a municipality level, but additional field surveys would be required to obtain their spatial distribution in the floodplains, and to create layers in the vector format.

For the purposes of Montenegrin NRA, no vulnerability or damage curves have been developed. These aspects have been treated in a qualitative manner, through description of presence of population/infrastructure in the flooded areas for each considered scenario separately (information of affected people and damage on infrastructure are determined based on direct observations - field data). The number of bridges, tunnels, length of affected sections of local and regional roads and of the water supply pipelines are available for each of the 4 scenarios. Also, the data regarding the estimated number of households and the population structure (men, women, children, the elderly and the disabled) is available only for the mentioned scenarios. In order to apply the harmonized vulnerability approach, it would be necessary to establish vulnerability curves – and this could only been done through field investigation and assessment of building typologies, evaluation of occupancy and number of floors, presence of basement, etc. The proposed HAZUS model would be applicable if it was possible to execute further analysis, make inquiries and organize field inspections as a means to provide the needed data in a suitable format (information on the occupancy type and the height of the first floor). In such case, depth-damage functions could be utilized to estimate the possible damage to buildings and infrastructure that may result from flooding. This would be useful, because for now, flood damage assessment has been carried out only for the considered scenarios (damage on individual properties, on farmland, ruined crops, missing cattle, roads, pipelines, buildings, expenses on sanation and reconstruction, expenses on ambulance interventions and hospitalization...), whereas other flood events lack accurate data.

Collapse potential could be predicted using the velocity-based building collapse curves within the HAZUS – MH flood model, but it would be mandatory to provide the values of overbank velocity (along with building material classes), which could be done solely through two-dimensional hidraulic modeling. Two-dimensional (2D) model system allows simulation of the overbank flow in areas where the complexity of the floodplain is such that accurate results cannot be obtained using a one-dimensional approach. HEC-RAS 2D is one example of software that has the capability of modelling both one-dimensional channel flow and two-dimensional overbank flow, and has been used for these purposes on certain watersheds in Montenegro (for the requirements of individual projects).

Currently, ongoing project "Support to Implementation and Monitoring of Water Management in Montenegro" (EuropeAid/139429/IH/SER/ME) aims to assist Montenegrin administration to effectively manage implementation and monitoring of water management and environmental policy in order to comply with EU environmental acquis. This project will provide support to the national and local institutions in the process of aligning with and implementing the EU legislation on environmental protection and climate change. Some of the most relevant project activities include preparation of flood hazard and flood risk maps, flood risk management plans in order to reduce the risk of flood damage.

4.4. Future needs

In the previous sections we presented a first approach for harmonizing flood risk among border countries sharing cross-border rivers, mainly based on models, procedures and approaches already available (e.g. flood maps from the EU Floods Directive) within the different Member States participating to BORIS. As we discussed in section 4.1 more complex procedures can be applied for defining a more detailed fully probabilistic approach in the flood risk assessment. This approach starts from the hazard definition, and it is represented by the return period-magnitude relationship that allows to associate a certain magnitude of the hazard to a certain frequency and, through the knowledge of the damage related to a certain magnitude, allows to define the link between the probability of occurrence of a flood event and the related losses.

For this reason, the future needs are related to the definition of a fully-probabilistic procedure that can overcome the limitations of the current approach based on flood hazard maps for a defined return period and resort to the use of flood hazard scenarios that represent all the possible events for a defined return period. In practical terms the flood maps (e.g. these provided for the EU Floods directive) are the convolution (sum) of all the possible scenarios defined by the probabilistic approach. The need for a probabilistic approach for flood hazard estimation lead also to provide scenario-based potential impacts computed in terms of economic losses, number of people and assets affected. For each probabilistic flood hazard scenario the vulnerability and consequences are composed by the definition of the direct and indirect losses for the different elements at risk evaluated by applying vulnerability functions (that can have also a probabilistic component). These consequence functions link the hazard intensity to the expected loss or damage, and incorporated the related uncertainty. Vulnerability functions should also be better differentiated for each typology of exposed element and should account for local factors in more detail (e.g. constructive typologies).

5. SHARED FRAMEWORK FOR MULTI-RISK COMPARISON AND RANKING

5.1. Introduction to multi-risk assessment

As explained in section 2, the BORIS project focuses mainly on the development of cross-border risk analyses having the aim to of improve the prevention and preparedness in transboundary areas, facilitating the preparation of Civil Protection plans suitably considering the cross-border regions and/or the planning of mitigation actions in risk reduction campaigns. The procedures to perform harmonized cross-border single risk analysis, specifically referring to seismic risk and flood risk assessment, were presented and discussed separately in chapters 3 and 4.

However, when different hazards threaten the same region, their relative importance has to be suitably evaluated and a proper methodology for risk comparability should be put in place.

Ideally, with the aim to perform a sound comparison and ranking of different risks potentially hitting the same area a complete Multi Risk Assessment (MRA) should be performed. In its complete acceptation, MRA entails the adoption of innovative approaches that allow risk comparison and should account for all the possible risk interactions, i.e. at the level of hazard and of vulnerability (including cascading effects) (Marzocchi et al., 2012). 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 (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 possible different vulnerability degree 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 consequence of different factors (Garcia-Aristizabal et al., 2013).

Considering interactions among the threats (hazard interaction) and the cascade effects would allow to evaluate also the potential increase of risk index with respect to the one estimated by considering each source as independent from the other. However, the path for a complete MRA accounting for these aspects is quite complex, and there is still the need to reinforce each single step towards the full MRA. As observed in (Poljanšek et al., 2019), the risk evaluation related to different sources is generally done through independent analyses, adopting disparate procedures and time–space resolutions. Moreover, different hazards differ in their nature, return periods, intensity and impacts; the consequence of such inherent differences is that also the metrics commonly adopted to measure are very different and hardly directly comparable. These problems exist independently of whether hazard interactions and/or interactions on the vulnerability level are important or not. Therefore, Zschau (2017) suggests to adopt as first step towards a full MRA, the so called multilayer single-hazard/risk assessment approach, ignoring the interactions but harmonising and standardising the assessment procedures among the different perils. The author suggests three major standardization schemes in the context of multilayer single risk assessment: (a) risk matrices, (b) risk indices and (c) risk curves.

Risk matrices are a table or graph illustrating the hazard likelihood on one axis and its potential impact on the other. Hazards are then graphically represented by being located in the appropriate section of the matrix space.

The combinations of consequence and likelihood are mapped on to a limited number of risk categories, often visualized by different colours (Duijm, 2015).

Thanks to their feature of allowing the visualization at a glance of the risk posed by different hazards, the risk matrices are a widespread tool to communicate the likelihood and potential impacts of a variety of risks. However, they are often criticized due to the subjectivity and/or lack of transparency of certain choices.

As observed in (Duijm, 2015), although the risk representation that appears through the scoring or colouring of the risk matrix is a risk definition having its own right, as it express subjective risk perceptions, it may be demonstrated that there are some inherent results depending on the design of the risk matrix, e.g. the expected loss (evaluated as product of frequency x consequence), that may have an unanticipated influence on the communication of the risk and on the level of hazard aversion expressed by the risk matrix itself.

Moreover, in several cases the frequency axis of the matrix has numerical values associated with it, typically spanning several orders of magnitude, and the consequence axis is based on a qualitative judgment based scale; while the latter scale is argued to be qualitative, it generally has implicit quantitative values associated with it, which may or may not be explicitly recognised (Elmontrsi, 2014).

Risk indices aim to represent a meaningful measure of risk obtained by the combination of various indicators. There are several examples of classification schemes based on indices, referring to hazards (Arnone et al., 2018; Dilley, 2005), vulnerability (Papathoma at al., 2003; Silva and Pereira, 2014) and risk (Dilley, 2005; De Groeve et al., 2016). In general, such type of composite indicators may be valuable to obtain risk rankings and trends at a global scale, allowing to draw country risk profiles and to assess the likelihood of needed international assistance in the near future (Marin-Ferrer at al.,2017). However, such kind of studies are not common nor justified for smaller scales of analysis.

Risk curves represent the more quantitative methods for assessing natural threats in a multilayer single-hazard approach. The risk curve relates the level of impact that will be surpassed in a given time period with the actual probability. The risk curve is also called the exceedance probability curve or Loss Exceedance Curve (LEC) and it is the usual output of the full probabilistic approach (Poljanšek et al., 2019).

Notoriously, hazard curves report the Mean Annual Frequency (MAF), or mean rate, λ, of a relevant Intensity Measure (IM) (e.g., peak ground acceleration for earthquakes or flood height for floods).

The mean rate of exceedance λ can be related to the probability of exceedance in t years P_t by using a Poisson recurrence law:

$$P_t=1-e^{-\lambda t} \tag{5.1}$$

Using the 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, etc. Such losses can be determined adopting suitable consequence functions, as illustrated in previous sections. Once the parameter representing loss is chosen and the methodology for calculating it is established, given the hazard curve, the corresponding LEC can be calculated. As example, Figure 5.1 shows a risk curve, or LEC, where the loss parameter is represented by expected percentage of replacement cost.

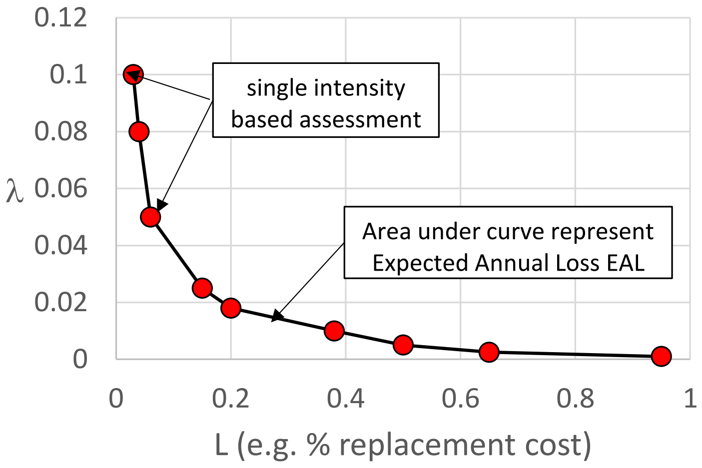


Figure 5.1: Example of Risk curve, also known as Loss Exceedance Curve (LEC). Left vertical axis shows the annual frequency λ, while the horizontal axis displays the expected loss L (in terms of % replacement cost)

When the need arises to compare different risks, it is necessary to identify a common reference metric for all the single risks. Once the kind of metric, or loss, has been selected, the different risks can be ranked on the basis of their probability to originate relevant thresholds of such loss. As example, Figure 5.2 shows the comparison of risk curves due to storms, floods and earthquakes for the city of Cologne, considering economic losses as the loss parameter.

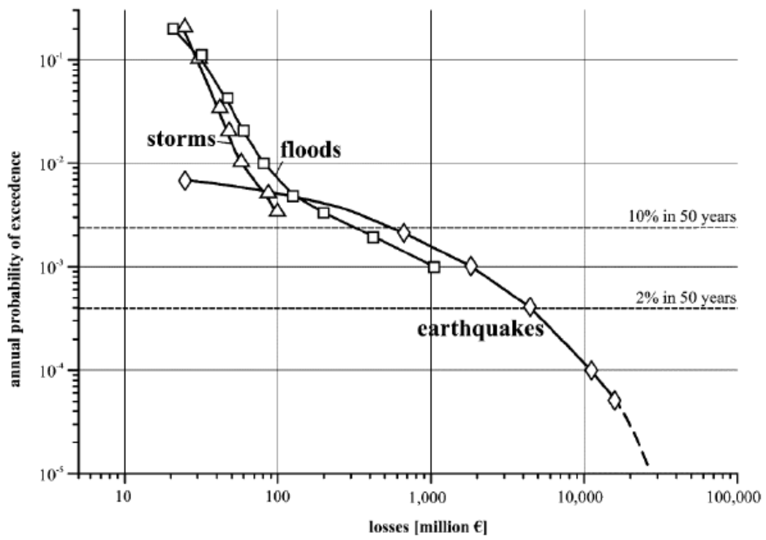


Figure 5.2: Risk curves of the hazards due to windstorms, floods and earthquakes for the city of Cologne for losses concerning buildings and contents (Grünthal et al., 2006)

Further, a global measure of risk can be represented by the Expected Annual Loss EAL, also indicated as Average Annual Loss (AAL). It represents the likely losses in a given 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.

This brief overview of available standardization schemes for multilayer single risk assessment shows that the most appropriate tool for consistent evaluation of risks in a quantitative framework are the Risk Curves.

It has to be noted that a preliminary selection of the area and time-frame of interest should be performed before multi-risk assessment is performed. Indeed, as also observed in (Marzocchi et al., 2009) depending on the hazard type as well as on the type and number of vulnerable territorial and environmental elements, the extension of the consequences due to the events may induce to expand or reduce the investigated area. Moreover, the time interval for risk analysis may be chosen depending on the final goal of the risk analysis; for instance, the time interval 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 (Marzocchi et al., 2012).

5.2. The BORIS approach to multi-risk assessment

As discussed in previous section, the multi-risk assessment in BORIS will be performed in the framework of a multilayer single risk assessment and the risk curves are the most appropriate tools for consistent quantitative assessment of the single risks towards their effective comparability.

This means that the steps for evaluation of the different risks impending on the same area should be harmonized as well as the risk metrics, that should be carefully chosen to allow useful comparison towards risk ranking. Hence, within BORIS, a double harmonization is adopted, namely a cross-border harmonization for the single risk and cross-risk harmonization for the multilayer single risk assessment towards risk comparability.

Despite a simplification of the general approach for MRA, as proposed in (Marzocchi et al., 2012), is foreseen, certain aspects such as the selection of the area and time-frame of interest or the choice of common metric for evaluating the risk are required a-priori. Because of the significant differences in terms of possible expected impacts due to different type of hazards, the definition of the metric and target area should precede the identification of the risks; for example, as noted in (Marzocchi et al., 2012) some risks can create a significant amount of economic losses without threatening the life of the persons. Both the reference time for assessment and the metric have to be chosen consistently with end-users needs; for example, emergency management and land-use planning require different space–time windows and different metrics for risk assessment.

The resulting steps for multi-risk analysis in such context are (adapted from Marzocchi et al., 2012):

1. Definition of the study area and time window for the risk assessment and the metric for evaluating the risks;
2. identification of the risks impending on the selected area;
3. identification of hazard curves for the selected risks covering all possible intensities (no hazard interactions are considered for multi-layer single risk analysis) for each point of analysis in the study area;
4. vulnerability and exposure assessment for relevant assets at risk in the study area (the vulnerability of combined hazards, i.e. cascading effects, is not considered for multi-layer single risk analysis);
5. probabilistic assessment of each scenario (i.e. for each point of the hazard curve) and calculation of losses through consequence functions;

6. assemblage of risk curves, comparative loss estimation and evaluation of EAL as global measure of multi-risk for each point of analysis in the study area;

Figure 5.3 synthetizes the approach for cross-border multi-risk analysis and representation adopted in BORIS.

Boundary conditions. Depending on the scope of the MRA, defined by the end-user, the cross-border study area, the time frame of analysis and the metric for risk evaluation should be established a priori. Referring to the need of prevention (understanding disaster risk) and preparedness through 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 study area may comprise an assemblage of municipalities close to the border of confining nations. A reasonable time frame for such analysis can be set to 50 years and the risk could be referred to expected losses in one year. Concerning the metric, both the direct economic losses and affected population can be considered as indicators that give a useful measure of the expected hazard impact.

Relevant risks, hazard curves and assets. Once the study area is selected, the relevant risks impending on it and producing negative effects in terms of the considered metric should be considered. Ideally, all the relevant assets and systems exposed to such risks should be accounted for and analysed. In BORIS only residential buildings and population will be considered; however, the methodological approach is replicable also for other type of assets, by suitably choosing the hazard intensity and vulnerability/exposure data. Because quantitative probabilistic risk assessment is foreseen, the study area should be divided in basic territorial units of analysis and the risk factors (hazard, vulnerability and exposure) should be referred to such units. Note that the risk calculation may require different scale of analysis for the different risks; for example, while the probabilistic seismic risk assessment allows direct estimation of damage and related losses at the municipality scale, the scale required for flood analysis is much smaller (see section 4.2.4). Hence, the hazard curves for each hazard, as well as vulnerability/exposure data, should be evaluated for each point of analysis relative to such risk. Chapters 3 and 4 describe the type of hazard curves, vulnerability and exposure modelling employed for harmonized cross-border seismic and flood risk calculation, respectively. The most relevant innovations for cross-border assessment proposed in BORIS entail the harmonised transboundary vulnerability for seismic risk and the harmonised transboundary hazard for flood risk. Specifically, section 3.2.3.2 describes the heuristic model proposed for harmonized cross border seismic risk assessment while section 4.2.1 explains the methodology to build simplified flood hazard curves starting from pre-existing studies developed according to the EU Flood Directive.

Results and representation. Probabilistic risk assessment is represented in terms of risk curves for each considered risk. The results are represented at the municipality level and the risk curves due to different hazards and considering the common established metric can be plotted on the same graph and compared. Also the EAL (also referred to AAL) can be computed for each risk and plotted in terms of risk maps. The latter can be produced separately for each risk; also the sum of both EALs for each municipality , representing the total annual loss expected on average each year , can be represented.

The next sections discuss the relevant issues for multi-risk harmonization towards the effective implementation of the proposed approach.

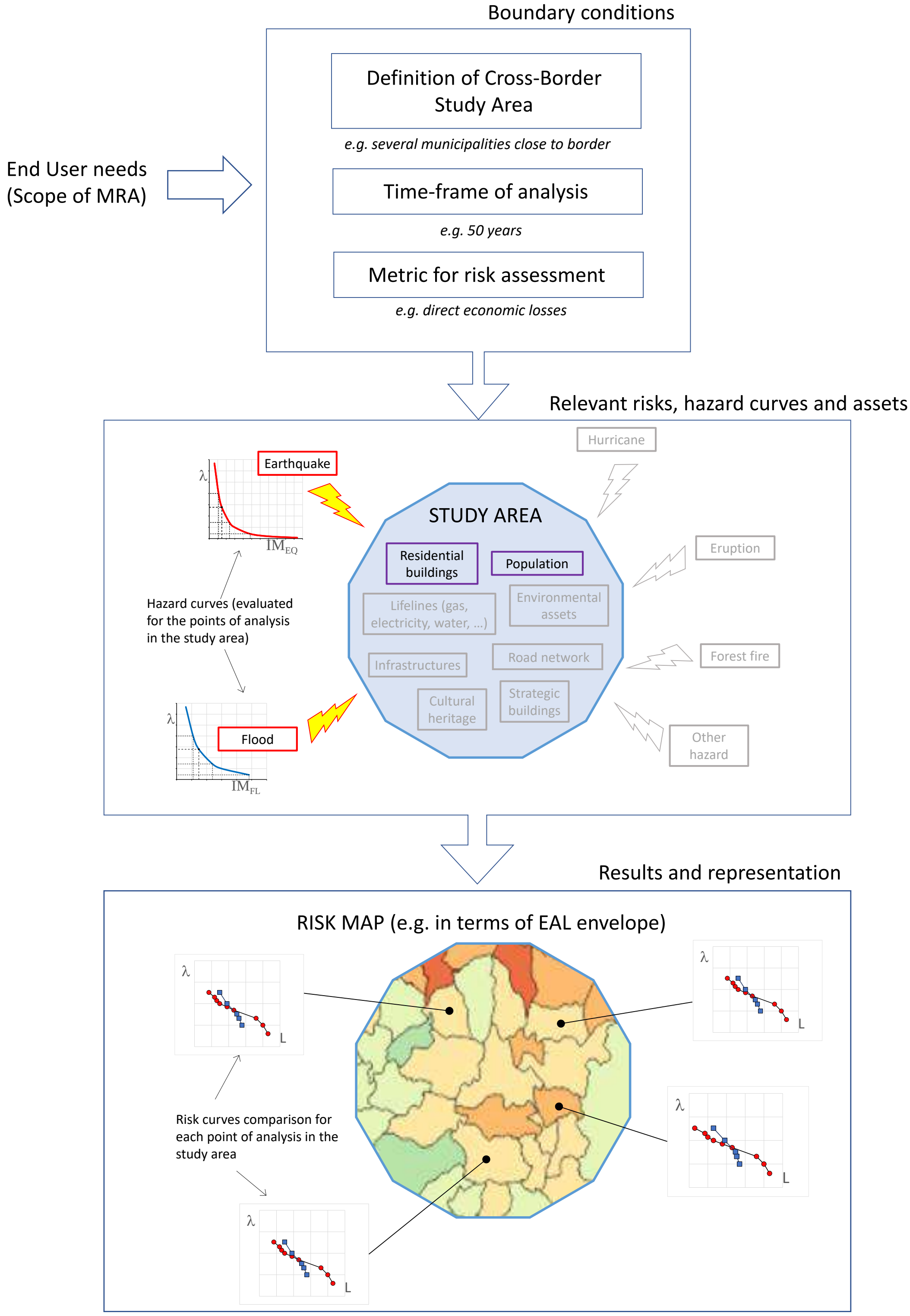


Figure 5.3: The BORIS approach for multi-risk analysis and representation

5.3. Issues for multi-risk harmonization

5.3.1 Spatial scale of assessment

In general, spatial scales in a risk assessment can be different. Usually, they are classified into three categories: micro-scale, meso-scale and macro-scale, as discussed in Section 4.1.2. In the multi-risk assessment, an issue related to the selection of the spatial scale may occur. The optimal spatial scale considered in the risk assessment for one type of hazard can be different from the optimal spatial scale considered in the risk assessment for another type of hazard. However, this issue is not related to the hazard or vulnerability analysis but only to the representation of quantities that are considered in the multi-risk ranking.

Obviously, it does not make much sense to compare and rank the levels of intensity because the intensity measures in different single-risk assessments are different. For example, it is not sensible to compare flow depth or flow velocity corresponding to a particular return period to the PGA or spectral acceleration corresponding to the same return period. Therefore, the spatial scales used in the first part of two different single-risk assessments (i.e. in the hazard assessments) do not yet need to be harmonized. In fact, it is probably better that the spatial scale in the hazard assessment is optimal for a single type of hazard, provided that the different types of hazards are addressed independently.

However, more attention is needed in the harmonisation of the damage levels and consequences caused by different hazards. In the BORIS project, it was decided to make the comparison at the level of consequences because the spatial scale of the consequences is relevant to the end-users (e.g., civil protection authorities). Based on this decision, the damage level estimated in different single-risk assessments can still differ, while the spatial scales used to present the consequences of different hazards needs to be harmonized. Such a decision may not be optimal because the consequences can be still biased when compared between the two risk assessments. In the case of seismic risk assessment, the damage level is related to physical damage of the facilities, while in the case of flood risk assessment, the damage may not be related to the physical damage of the facility or it may be related to some additional elements (e.g., vehicles, agriculture).

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 actually used in the single-risk assessments can differ, but they should allow the aggregation of the consequences to the same spatial units. For example, it can be acceptable if the consequences of the seismic hazard are initially estimated at the micro-scale level (e.g., building level) and the consequences of the flood hazard are initially estimated at the macro-level (e.g., municipality level, regional level, national level) as long as the results of the seismic risk assessment can be aggregated to the same macro-level.

However, the selection of the spatial scale used as the basis for comparison and ranking of different risks needs to also consider the requirements of the end-users. In particular, the spatial 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. At the same time, one should be aware that the selection of the spatial scale can 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. Such a spatial scale is therefore considered sufficiently small to provide risk results that can guide the end-users towards rational decision-making, while at the same time, it is attainable both in the case of the seismic and the flood risk assessment. However, in the long term, the spatial scale should be reduced to a micro-scale, which will make it possible to perform more accurate risk studies.

5.3.2 Assets at risk

Assets or elements at risk are all physical elements, population, essential facilities, socio-economic aspects, transportation facilities, economic activities, lifelines and environmental elements that are possibly affected and therefore exposed to a hazard. There are several ways to classify and to consider elements at risk often depending on the hazard process or the setting (rural, urban etc.) and the scale of the risk assessments. The optimal way to conduct a risk analysis would be to include and analyse all relevant assets and systems that are exposed to the hazards investigated, as already pointed out in section 5.1. For the work of the civil protection authorities, the number of exposed buildings, the degree of damage and economic loss, as well as an estimate of human casualties, but also the disruption to lifelines, such as electricity, road, and water networks are of high interest (BORIS, 2021c). However, the selection of exposed elements in risk analysis also depends on the availability and accessibility of the data, especially with projects that aim to access the data sets of different countries in order to do cross-border analyses. As observed in chapter 2, the level of detail and amount of data required for consistent risk evaluation considering all relevant assets at risk would hamper the possibility of application to larger cross-border areas. Indeed, typically the risk studies more oriented to response preparation, requiring information on infrastructures and lifelines post-event status, perform applications in focus areas limited to single town or districts. Therefore, with the aim to build a shared and harmonized framework for cross-border risk assessment, allowing to perform risk analyses for better prevention and preparedness at regional scale and not limited to a single town or district, the BORIS multilayer single risk assessment is focusing on two categories:

- residential buildings as physical elements at risk and
- population (intended as the number of people affected).

As discussed in previous chapters, the damage and direct economic losses evaluated with reference to the (residential) building stock can be evaluated adopting relevant hazard-dependent vulnerability and consequence functions, as reported in sections 3.2.3 and 3.2.4 for seismic risk as well as 4.2.3 and 4.2.4 for flood risk.

For what concerns the population, the seismic risk modelling and related consequence functions allow the assessment of impact parameters such as the expected number of homeless, or injured or deaths as meaningful metrics to evaluate the consequence of seismic events. Conversely, the flood risk models generally consider the sole estimation of the number of people residing in the flooded zone as meaningful parameter concerning the affected population in the area.

5.3.3 Risk metrics – indicators

Risk indicators are needed to express and communicate the risk. For natural hazard risk assessments at the global scale, the most commonly used risk indicator is the number of people affected, followed by the direct economic damage indicator, although many studies also use affected GDP and casualties (although rarely for flood risk) as a metric (Ward et al. 2020). For evaluating the risks arising from different hazards and to be able to compare and rank such risks, a common metric to display the expected hazard impact is needed.

As discussed in previous chapters 3 for seismic risk and 4 for flood risk, the consequences of such events can be measured with a number of indicators that are relevant for different planning and emergency purposes.

The most relevant impact indicators to evaluate seismic risk in view-point of civil protection planning and to enhance preparedness for an effective response, as reported in section 3.2.4, are: referring to residential buildings 1) the number of collapsed buildings; 2) the unusable buildings in the long term and in the short term; 3) the direct economic losses connected to repair and/or reconstruction of damaged buildings; referring to the population 4) displaced/homeless and 5) fatalities (injured/deaths)

For flood risk assessment, in addition to the impact on residential buildings and population, the impact on other type of assets could be further considered, e.g. on environmental assets or economic activities, as discussed in section 4.1.4.

To allow comparability of flood risk with seismic risk in a multi-risk perspective, only the following indicators will be considered: referring to buildings 1) direct economic losses; referring to the population 2) affected population.

As discussed in 3.2.4, direct economic losses due to seismic risk can be determined in monetary terms as a function of the damage expected on buildings (Eq. 3.16). A similar approach can be used also for calculation of direct economic losses connected to the damage on buildings in flooded areas (Eq. 4.1). The results of Eq. 3.16 for seismic risk and Eq. 4.1 for flood risk can be used for calculating the single point (Loss) along the risk curves employed for probabilistic risk assessment in a reference territorial unit of analysis (see e.g. Fig. 5.1 and Fig. 5.3, lower panel). Then, by integrating the risk curves, the EAL (also indicated as AAL) can be determined. It should be noted that the single terms in Eqs. 3.16 and 4.1 are not directly comparable, due, for example, to the different nature of the hazard and the different type of damages produced on buildings and contents. However, notwithstanding some inherent differences in the terms, the general approach allowing the computation of economic losses based on the estimated amount of damages to be repaired and considering the unit costs of such repair actions, is consistent. Therefore, the proposed formulations could be employed to evaluate direct economic losses, provided that consistency in the calculation of unit costs of repair and/or reconstruction is ensured.

For what concerns the affected population, in the flood risk assessment it is considered as the number of inhabitants residing in buildings that are flooded. A similar estimation of “affected population” would not be significant for seismic risk, since by definition all the buildings in an area that is affected by an earthquake are interested by the seismic excitation. With the scope to allow comparability with the indicator commonly used as a metric to measure impact on population for flood risk assessment, a possible approach 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). This approach could be applied for preliminary comparison of seismic risk and flood risk in terms of affected population; however, further judgement and considerations are needed towards a more consistent comparison in terms of affected population.

As a matter of fact, there are a number of other relevant indicators for the population affected by an earthquake, such as the number of homeless or the injured/deaths (see section 3.2.4). As discussed in 4.2.4, it could also be possible to estimate the expected casualties due to flood. However, there is not consensus on the possible formulations to use, as there is still quite limited insight into the factors that determine the loss of life caused by flood events.

5.3.4 Vulnerability and exposure data

For every risk and risk scenario identified in the risk identification stage, the evaluation of potential impacts involves the combination of the risk component of hazard, vulnerability and exposure. As shown previously, buildings and population are selected as asset at risk within BORIS project. For defining vulnerability of the assets exposed to the hazards, the exposure data should be classified according to a specific building taxonomy. This means that the exposure model categorizes buildings in classes according to attributes that can influence the likelihood of damage due to the effects of natural hazards. It is thus important to identify the most relevant attributes for the characterization of the vulnerability to the various hazards and focus on the collection of data that can enable the definition of these attributes. Relevant building's attributes for seismic risk evaluation are the material of the structural system resisting to later loads, the load-resisting system type, the age of construction, that may give indication about the code design level, as well as building height above ground expressed in terms of the number of stories. It is worth noting that not all parameters affecting seismic vulnerability are relevant for other natural hazard, as well (Dabbeek and Silva, 2020; Crowley, 2022). As a matter of fact, among the indicators of building flood vulnerability, the presence of basement and the height of the first storey are the most relevant building's attributes, while the construction material does not affect it significantly.

Ideally, for multi-risk assessment purposes the vulnerability classification should involve both factors crucial for the identification of the earthquake vulnerability and flood vulnerability and the interaction among the aforementioned hazards should be accounted in the definition of the vulnerability functions. However, according to the multi-layer single risk assessment procedure adopted herein (see section 5.2) no interaction on hazard and vulnerability level is considered. The harmonized cross-border risk assessment procedure is proposed for each hazard analysed and impacts arising by different hazards in transboundary regions will be compared in the WP5 pilot applications. The single-risk harmonization in transboundary regions is obtained selecting common hazard and vulnerability models or suitable ones specifically developed for cross-border harmonization purposes. Thus, towards vulnerability harmonization, a heuristic approach is proposed to harmonize cross-border seismic vulnerability (see section 3.2.3.2). This approach is based on the combination of the vulnerability models adopted in cross-border countries involved. For seismic vulnerability assessment a typological-based classification is adopted, that defines building classes based on attributes such as construction material, age of construction and number of storeys. On the contrary, for cross-border flood risk assessment the HAZUS vulnerability model is adopted. For describing flood vulnerability of asset at risk, this model needs information concerning the number of floors, the occupancy type and, if available, the presence of basement. Thus, if the presence of basement is neglected, the classification parameters considered for flood vulnerability can be considered as a subset of those already needed for seismic vulnerability characterization.

Available exposure data could vary for cross-border countries involved. In Italy, information on buildings and population are provided by ISTAT at census track level, but disaggregated data on construction material, age of construction and number of storeys are available only at municipality level. In Slovenia, REN provides building by building data available for the entire country. Detailed data concerning the population is included in the Central Population Register. However, because the latter is not publically accessible, only the average number of people per housing unit in each municipality is provided. Therefore, the municipality level is selected as scale of analysis, as also explained in section 5.3.1, and if the available data are not enough for building classification, other source of information could be employed (e.g., ESHM 2020).

However, this scale of analysis is not suitable for flood risk assessment. As a matter of fact, 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, as described in section 4.3.1, exposure data for flood risk should be evaluated at building level and a procedure to derive these data (if no building specific data are available) is proposed, as well. The latter is based on the statistical treatment of global data available at large scale in order to downscale it implementing the global information on the building level, through the use of additional information on buildings footprint.

Therefore, different analyses at different scales are performed for seismic and flood risk assessment:

- For seismic risk, municipality level is selected as 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.
- 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).

Finally, in order to allow comparison and ranking of the analysed risks, results of flood risk assessment should be aggregated at municipality scale.

5.4. Future needs

The approach adopted in BORIS for cross-border multi-risk assessment relies on the adoption of a multi-layer single risk assessment for each one of the risks impending on the transboundary area, namely seismic risk and flood risk. Such risks are singularly previously harmonized to allow consistent cross-border risk assessment for confining countries, as described in chapters 3 and 4.

The discussion provided in section 5.3 highlights that there are a number of issues to deal with for an effective multi-risk assessment, even when the possible hazard interactions and the vulnerability interactions are not considered.

A first aspect to be considered is the spatial scale of assessment. As noted in 5.3.1, the choice of the final (uniform) scale of assessment is driven by the requirements of the end-users and it should be small enough to enable the use of the risk assessment results in the decision-making process. Therefore, for the BORIS project it was chosen to adopt the municipality scale, which is also the lowest level at which administrative decisions are taken. This way a balance is obtained between a scale that is not too small, e.g. at the level of the census tract, for which it would be necessary to acquire a quantity of inventory data that is not always available or easily retrievable, and a scale that is not too large, e.g. provincial or regional scale, which would not allow risk assessments useful for civil protection decisions to be carried out. However, while the analysis at municipality level simplifies the problem of data availability, the adoption of such scale hampers the possibility to perform more refined risk studies, allowing to determine more accurately the areas within a municipality that are most prone to the considered risks and/or to organize the response capacities in a town-level planning. It has to be recognized that the refinement of the scale of analysis is attractive, however often not feasible due to economic or temporal constraints. Nevertheless, further studies allowing to investigate on the level of accuracy of results that can be obtained varying the scale of analysis would allow a better understanding of the optimal solution. As example, the multi-risk assessment performed for an ensemble of municipalities adopting the municipality as basic unit of results representation could be compared to the assessment for the same area but with the census tract as basic unit. This comparison would allow to answer to basic questions such as if the final results representation could lead to different decisions, or if a more refined scale of analysis could determine significant variation in terms of resulting risk (e.g. in terms of EAL). The confrontation of results, that could be performed initially at the level of each single risk, should take into account also the multi-risk; indeed, the ranking of the risks could be affected not only by the extension of the area of analysis, but also by the unit scale adopted for analysis. Therefore, further studies allowing such comparison should be encouraged.

Another important aspect to be considered is the need to ensure harmonised approach for the evaluation of consequences due to the different risks. Indeed, as highlighted in section 5.3.3 a common metric to compare and rank the risks should be defined; to this end, with reference to seismic risk and flood risk two main type of indicators are considered, namely indicators based on direct economic losses and indicators based on affected population.

Concerning the affected population, the proper harmonization of the approaches to evaluate such indicator is not trivial. Indeed, as observed in 5.3.3, the sole consideration of inhabitants residing in buildings affected by the hazard (flood or earthquake) does not allow a proper comparison between the two risks. At the same time, the matureness of models to estimate other indicators for the affected population, e.g. the number of injured or casualties, are not comparable for the two risks; indeed, the studies devoted to evaluate the factors that determine the loss of life or injuries caused by flood events are quite scant.

The direct economic losses can be computed based on relevant damage-to-loss models. The functions currently used for seismic and flood risk assessment allow the computation of direct economic (monetary) losses based on the expected damage on buildings, and therefore allow a comparison or risk if economic losses is used as a metric. However, there are still relevant differences in such consequence models that need to be addressed for a more harmonized assessment. For example, referring to the evaluation of direct economic losses due to earthquakes, the actual consequence model allow to compute the monetary losses based on a function that suitably considers the repair costs associated to different damage levels of the EMS98 damage scale as a percentage with respect to unit replacement cost. Conversely, the economic consequence model for floods calculates the exected monetary losses by simply multiplying the expected damage, roughly repesented as % of (overall) damage on buildings or contents, by the replacement cost. Obviulsy, further efforts should be devoted towards most effective harmonization of such consequence functions, e.g. by introducing a more refined graduation of the damage scale due to flood and by assigning percental incidence of repairing each damage level with respect to the replacement (reconstruction) cost, similarly to what is done for the case of seismic risk.

Although the BORIS project provided an important step toward transboundary multi-risk assessment, the proposed methodology should be further developed. The final solution would be to trigger the development of the EU standardization for multi-natural-hazard risk assessment by focusing on location-independent and unbiased risk assessment and communication for single and multi-hazard risk assessment.

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