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Summary

1 Introduction

This document presents guidelines for the multi-scale mapping of the earthquake, flood and landslide risk for cultural heritage (CH), including some concluding remarks on the volcanic risk as well.

The objective of these guidelines is to describe general, exportable approaches to generate multi-risk maps aimed at municipal, regional and national administrators, natural parks and museum directors, researchers and research bodies in the field of CH or natural hazards, private or public owners of historical buildings and monuments, civil protection operators.

UNESCO (2015) defines cultural heritage as:

- monuments: architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features, which are of Outstanding Universal Value from the point of view of history, art or science;
- groups of buildings: groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of Outstanding Universal Value from the point of view of history, art or science;
- sites: works of man or the combined works of nature and of man, and areas including archaeological sites which are of Outstanding Universal Value from the historical, aesthetic, ethnological or anthropological points of view.

One of the main challenges faced in this study is the nature of the multiscale approach; a thorough discussion on how to pass from a scale to another and on what are the peculiarity of each scale is presented in section . In this section, for a better understanding of the entire guidelines, some definitions are proposed. The scale is defined as a ratio, therefore a 1:100.000 scale is considered smaller than a 1:5.000 scale; therefore "upscaling" means zooming in from national to asset scale. The opposite goes for "small" scale and "downscaling". The smallest scale covered is called "national scale", that typically ranges from a few tens of thousands to a few hundreds of thousands of km^2. The intermediate scale is the urban, that is suitable for small towns, large city centres and even entire cities, with areas generally ranging from around 1 km^2 up to a few tens of km^2. The largest scale considered is the asset scale, which includes mapping involving one single CH asset, whether a monument (like an arch, a statue, a fountain), a building (like a palace, a church, a museum), a complex (like a monastic complex that can be composed of several buildings like a church, a bell tower, a cloister, and a monastery).

It is important to underline that the areas expressed in km^2 above are just for reference, as the real distinction between scales is not as much quantitative as qualitative and it depends on the depth and amount and spatial resolution of the information available (see section for further discussion). For example, a 1 km^2 subset of a national database does not make it an urban scale, since the information included in the dataset lacks the detail typical of an urban scale map. With this logic it is easy to understand that areas of a few hundreds to a few thousands of km^2 can either fit in the national of urban scale depending on the detail of the dataset. Biosphere reserves can fit in this category, but also present some specific issues that are discussed in section 5. The scale used for biosphere reserves is therefore called "regional" since it is intermediate between the national and the urban scale.

Multi-scale risk maps play a key role in assessing and managing potential impacts on CH (Guzzetti et al., 1999; Fernandez-Merodo et al., 2023; Arrighi et al., 2023). They offer detailed insights into the natural and human factors that contribute to risk, enabling a comprehensive representation of the threats faced by heritage sites. These maps contribute to informed decision-making and the implementation of preventive measures and assist in the development of effective emergency response plans. Taken singularly, an earthquake, flood or landslide risk map is already a valuable managing tool, which can aid decision makers in investing funds where they are most needed (Segoni and Caleca, 2021; Iadanza et al., 2021). Even more so, a multi-risk method introduces the possibility to manage a territory or a single site synoptically, since it adopts the same approach for the different risks considered, making them comparable using semi-quantitative risk values; this allows for holistic assessments and enables an all-inclusive vision of the total risk threatening the CH; for example, in a multi-risk approach the elements at risk are all valued using the same criteria (Bosher et al., 2020; Themistocleous et al., 2016; Carpignano et al., 2009; Schmidt et al, 2011). As a result, specific measures can be applied based on the nature of the hazard and the scale at which the elements at risk are managed. Multi-risk mapping can also be used as a planning tool that assists the efforts to ensure that moveable CH is located in low-risk areas.

However, drafting such maps is a difficult task due to several factors. First of all, the scientific literature is lacking a standard procedure that is suitable to assess multi-risk for CH, therefore any attempt to create these maps is set to start from different, inhomogeneous methodologies that may or may not consider the specificity of CH. Moreover, multi-risk mapping requires specific competence for each different kind of risk, therefore an interdisciplinary group is necessary to define one such methodology. The present guidelines can facilitate this process and indicate a procedure that takes advantage of public, findable datasets whenever possible.

Due to the constraints derived from any mapping approach, these guidelines do not cover features lacking a well-defined spatial extension, such as intangible CH, which are defined by UNESCO as “traditions or living expressions such as oral traditions, performing arts, social practices, rituals, festive events, knowledge and practices concerning nature and the universe or the knowledge and skills to produce traditional crafts” (UNESCO, 2024). Instead, they take into account tangible CH (most commonly represented by monuments, museums, churches, historical architecture) and naturalistic heritage, namely the biosphere reserves mapped by UNESCO. In the following pages, the term CH is therefore meant with this meaning.

It is worth noting that, since the focus of these guidelines is the CH, consequences on people or the environment are not considered. This means that the risk for a CH building is only referred to the building per se and not to the people that may inhabit it. Risk analyses on people are necessary and must be integrated with assessment on CH, but are not dealt in this document since they are the default kind of risk assessment, not within the scope of these guidelines.

2 Hazard and susceptibility

The hazard is the probability of occurrence of an event of a given magnitude in a given area. Depending on the type of risk considered this definition is adapted accordingly.

In the case of landslides, information about the temporal probability of a future collapse is generally not available, therefore the hazard analysis is usually replaced by a susceptibility analysis, that refers to the likelihood or propensity of a specific area to experience landslides and encompasses the spatial distribution of factors predisposing an area to landslide occurrence. A multitude of susceptibility mapping methods exist (Shano et al., 2020). One common method is to rely on statistically-based models, that have a huge variability of approaches; Reichenbach et al. (2018) identified 596 different variables used in the scientific literature to obtain landslide susceptibility maps and grouped them into 23 classes belonging to five thematic clusters i.e., geological, hydrological, land cover, morphological, and other variables. Other methods rely on the definition of landslide inventory, that are achieved through a landslide detection using different approaches depending on the scale, from satellite analyses to geomorphological surveys.

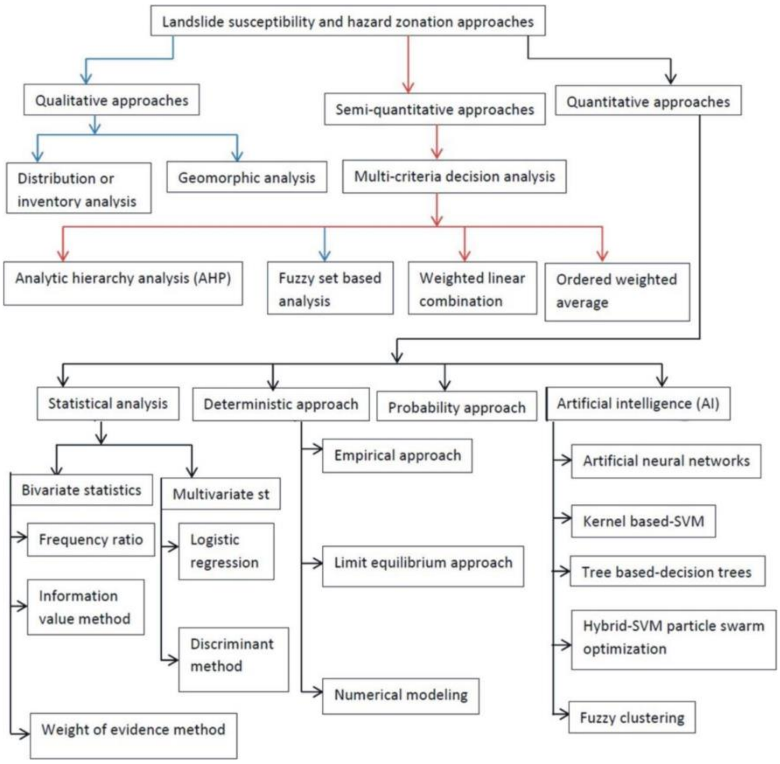

Figure 1. Landslide susceptibility and hazard zonation techniques (Shano et al., 2020).

Flood hazard is commonly defined as the probability of occurrence of an inundation of assigned severity in a certain geographical area and certain time. Flood hazard maps identify areas affected by floods of different probabilities of occurrence. The severity of the flood can be expressed in terms of inundated area, flood depths, flood velocity or combination of these variables, depending on the adopted methodology and spatial scale. The detail at which the hazard maps are developed reflects not only the spatial scale of analysis but also the purpose of the study and the stakeholders' perspective. Usually, flood hazard maps require several input data ranging from spatial data (e.g., land-use, digital terrain models and cross sections of rivers), meteorological and hydrological data, as well as information on defence infrastructures, e.g., levees. Flood simulations are commonly carried out for probabilistic synthetic flood events.

Seismic hazard is defined as "the potential for dangerous, earthquake-related natural phenomena such as ground shaking, fault rupture, or soil liquefaction" (Reiter, 1990), or "a property of an earthquake that can cause damage and loss" (McGuire, 2004).

2.1 Hazard and susceptibility on a national scale

2.1.1 Landslide susceptibility on a national scale

In national-scale studies, the spatial and temporal assessment of landslide hazard is considered separately. First, a spatial prediction called "landslide susceptibility" is performed to assess the spatial probability of occurrence, afterwards a temporal analysis on landslide frequency is implemented to get a comprehensive overview of the landslide hazard (Fell et al., 2008; Corominas et al., 2014; Caleca et al., 2021). Both aforementioned procedures are strongly dependent on the quality, quantity, and characteristics of the available input data.

The first dataset needed to build a hazard/susceptibility assessment is a dataset of landslide data. The best circumstance is met when working with a dataset that specifies the landslide typology, because different landslide types should be modeled separately as they may have very different triggering mechanisms, predisposing factors and geometrical features. Usually, a rigorous susceptibility assessment is performed separately for three big landslide types: (i) falls (including also topples), (ii) shallow rapid landslides (including shallow translational slides, small rotational or compound slides, and fast debris-flows and mudflows), and (iii) slow deep-seated landslides (including rotational slides, large translational slides, and complex movements triggered as rotational slides). These landslides should be mapped as precisely as possible; the exact time of occurrence is mandatory only for complete hazard assessments involving a temporal prediction, while for landslide susceptibility the time of occurrence is not needed.

The rationale of a landslide susceptibility assessment is to understand how the spatial distribution of the mapped landslides is influenced by the spatial distribution of the predisposing (and/or preparatory) factors. Consequently, the next step of the susceptibility analysis is to build a geographic database with thematic layers about all environmental parameters that can be used as explanatory variables to explain the absence or presence of landslide over the space. On overwhelming number of parameters can be used to this purpose, including lithology, land use – land cover, and different topographic parameters or compound indexes that can be derived from a DEM (digital elevation model) to describe the local morphology and hydrology (e.g., slope gradient, slope aspect, slope curvature, upslope drainage area, topographic wetness index, terrain roughness).

After organizing the input datasets, landslide presence and absence over selected spatial units (e.g., pixels or slope units) should be sampled to train, test and validate the susceptibility model. The sampling strategy largely depends on the quantity and quality of the available data. Several studies concerning sensitivity issues in landslide susceptibility models highlighted that it is preferable to sample landslides in the source area and that a random sampling strategy is the best option, provided the input landslide dataset is complete and homogeneous. If this is not the case, then it is preferable to sample only in the areas where a high-quality landslide dataset is available and to extrapolate the results outside those areas.

Different models exist to analyze the sampled data, to perform the susceptibility assessment and to draw the resulting maps, but at present the cutting-edge technique is to use machine learning and deep learning algorithms, including e.g. artificial neural networks, random forest, support vector machines, adaptive boosting algorithms and so on. Compared to still widely used statistical methods, these algorithms have several advantages including the possibility to handle huge amounts of data, account for interdependencies between the variables, preventing overfitting, and adapting to different configurations of the susceptibility model. These algorithms can be implemented into the most common programming languages and can be complemented by additional features to understand the collinearity of input parameters, the predictive power of input variables, and to identify and discard uninfluential, redundant, or pejorative variables (thus obtaining a forward selection of parameters until the optimal configuration of the model is found). The modeling algorithms can also be enhanced to automatically carry out a robust validation of the susceptibility model (for a review of the most used validation metric see e.g., Frattini et al., 2010; Reichenbach et al., 2018), provided a subsample of the input data has been kept aside from the calibration procedure to have a statistically independent subsample to be used for validation purposes.

If the quality of the susceptibility assessment is deemed satisfactory, the predictive model can be applied to the whole area of interest, obtaining the spatial distribution of a susceptibility index over the spatial units used to partition the study area. The index is usually a percentage value, expressing the spatial probability of each unit to be interested by a landslide in an unspecified future. The index may be represented in a susceptibility map, which is usually reclassified into a desired number of classes to ease visualization and interpretation.

To pass from a susceptibility map to a complete hazard assessment, it is necessary to define also the temporal probability of occurrence of a landslide of a given magnitude or greater (Varnes, 1984; Corominas et la., 2014). On a national scale, the magnitude of a landslide can be expressed as its size (i.e., areal extension); therefore, if landslides are mapped as polygons in the input dataset, the relative frequency of landslides of each size can be easily determined. It is well consolidated that landslide area and frequency are linked by an inverse power-law distribution, and it is important to empirically derive it in each application without relying on literature relationships, as the empirical parameters of the power law distribution are strongly site-specific (Corominas and Moya, 2008).

To incorporate temporal elements in the hazard assessment, it is necessary to pass from the temporal frequency to a probability, applying statistical distributions (e.g., binomial, Gumbel, Poisson, etc.) to extrapolate the temporal dimension from the landslide sample to the full landslide population (virtually including future landslides). An alternate approach is to consider other research products specifically conceived to account for the triggering factors, as the rainfall thresholds for landslide occurrence, and to carry out a time-series analysis to evaluate the probability that future rainfall can overcome the triggering threshold amount of precipitation. This approach is scientifically sound, but it is hard to implement on a national scale due to the spatial variability of rainfall thresholds.

In principle, the modelling of landslide susceptibility and hazard at the urban scale could be performed with the same techniques. However, from a practical perspective, when working at the urban scale data with different resolution and thematic accuracy became available, thus allowing for more refined procedures and products.

2.1.2 Flood hazard on a national scale

At small spatial scale (national or supra-national, e.g., continental or world scale) flood hazard is obtained by the following methods:

- Hydrodynamic methods
- Geomorphic methods

Hydrodynamic methods for flood hazard mapping at small scales (i.e., global) have been developed to allow for applicability in international risk reduction strategies and for reinsurance portfolio risk assessments using catastrophe models (Aerts et al., 2020). Among the most known and documented global flood hazard models are GLOFRIS, JRC and Fathom. GLOFRIS has a data resolution of 30 arc seconds (approximately 1 km at the Equator) provided for 8 return periods between 5 and 1000 years. The unit of the data is inundation depth in meters. GLOFRIS has been developed for the World Bank (Winsemius et al., 2013; Ward et al., 2013). The JRC global model (Dottori et al., 2016) has 1 km resolution and describes floods from 1-in-10-year to 1-in-500-year. The JRC European Maps have instead 100 m resolution. Fathom has built hazard map at 30-meter globally (Sampson et al., 2015) with the possibility to include flood defences.

Geomorphic methods do not consider hydrodynamic aspects of the flooding but are based on the DEM. They have been proved quite accurate when compared to 2D inundation models (Manfreda et al., 2014). These methods however are not fully capable of describing inundation in flat floodplains or when flood defences are not well captured by the DEM.

The spatial resolution of the above products and the importance of a correct description of flood defences for a realistic risk assessment in countries makes the large-scale maps not very useful for assessing risk at specific locations such as in the case of CH. However, some works highlighted at global level river flood risk to UNESCO Heritage sites (Arrighi, 2021) by making use of JRC global flood hazard maps.

On a national/regional scale some works on flood hazard and risk to CH have been published (Figueiredo et al., 2020; Arrighi et al., 2023; Garrote and Escudero, 2020; Jia et al., 2023). In these works, flood hazard is not modelled on a small scale but it is the result of a mosaic of detailed-scale hydraulic models also with different numerical approaches, e.g., 1D or 2D, which compose the overall national/regional hazard picture. In the work by Arrighi et al. (2023), CH is represented as a point dataset counting approximately 250,000 items in the Po river catchment and flood hazard is only represented by flood extent for assigned probability. This approach considers the use of water depths assigned to CH points poorly representative of actual flood depths firstly because of the point representation and secondly for the peculiarities of CH buildings whose elevation can be higher than the surrounding terrain. In the work by Figueiredo et al. (2020) flood depths for assigned probabilities are considered, the peculiarities of CH buildings are resolved by assigning the same ground floor elevation to similar class of objects, e.g., churches or fortified architecture, to all Portuguese CH. In the work by Garrote and Escudero (2020) also the lag time of the catchment is adopted as a proxy of flood hazard.

On the Mediterranean scale, it is worth mentioning a work about sea level rise risk to UNESCO world heritage sites (Reimann et al., 2018).

The national scale however does not allow one to fully understand flood hazard and actual exposure due to the topological representation, i.e., point representation, of CH and the large number of items.

Flood hazard analysis of CH on a small scale, either global or regional, highlighted that the main issue is not in reconstructing inundation characteristics, although global maps showed significant errors when compared to locally developed hydrodynamic models. The main issue is assigning flood severity to CH points without further information on CH characteristics, such as surface area, elevation on the ground etc. Furthermore, vulnerabilities and exposed values can only be simplified on a small scale (see sections 3.1.2 and 4.1).

As highlighted by the review of the state of the art, flood hazard modelling can be performed with different methods and working assumptions. On a national scale, in combination with a large number of potentially exposed CH assets with simplified geographic representation, flood hazard classification as requested by European Directive can be adequate to inform risk assessment. The knowledge of water depths or flood velocities contrasts with the limited information available on the areal extent and constructive characteristics of CH.

2.1.3 Earthquake hazard on a national scale

The seismic hazard at national level is generally provided by the national classifications developed by each country's geological service. For example, in Italy they are published by INGV (Stucchi, et al., 2004) and adopted into the Italian technical codes for the constructions (NTC, 2018). The latter has contributed realizing seismic hazard maps for the Italian territory referred to stiff soils expressed in terms of horizontal soil acceleration based on given probabilities of exceedance. The hazard of the different areas of the territory is obtained accounting for the historical data of past earthquakes (Boschi, et al., 1999) as for geological and seismological information and the presence of faults. The seismic hazard has been evaluated for over 10.000 points constituting a reticular 5x5 km^2 grid on the country according to standard methodologies (Cornell, 1968; Bender & Perkins, 1987) and validating the results through diffusive seismicity approaches (Frankel, 1995). Given a building, the reference period to evaluate the seismic hazard (V_R) is obtained through:

$$\boldsymbol{V_R = V_N \cdot C_U} \quad \textbf{(1)}$$

where V_N represents the nominal life of the construction for its design and C_U a coefficient related to its use and importance. Although CH buildings are intended to stand across the centuries, their nominal life is often assumed equal to a certain range of time (such as 50 years; MIBACT, 2011). Concerning the importance class, for CH this can be assumed as Class III, which leads to a C_U equal to 1.5, thus obtaining a V_R equal to 75 years.

An approach to evaluate the seismic intensity is represented by the European macroseismic scale EMS-98 (Grunthal, 1998), which expresses the effects of a ground motion on a specific territory. This scale has promoted cooperation between seismologists and practitioners; thus, it has been widely used to correlate the seismic intensity to vulnerability and fragility curves. Empirical formulations are available in the literature to convert the macroseismic intensity into a peak ground acceleration adopting the following:

$$\boldsymbol{a_g = C_1 C_2^{(I-5)}} \quad \textbf{(2)}$$

where $a_{g,}$ represents the peak ground acceleration (PGA) and C_1 and C_2 are two coefficients that need to be calibrated to fit the recorded correlations. Between the different proposals (Giovinazzi & Lagomarsino, 2004), in the current research the values proposed by (Margottini, Molin, & Serva, 1992) are recommended.

Other more refined approaches are possible, such as the one used in Italy. Once the reference period is defined, the seismic hazard is associated to the probability of exceeding specific limit states P_{VR}, still defined by (NTC, 2018). Namely, these are Operative Limit State (P_{VR} = 81%), Damage Limit State (P_{VR} = 63%), Life Safety Limit State (P_{VR} = 10%), and Collapse Limit State (P_{VR} = 5%). Hence, the return period of the seismic action Tr associated to each limit state can be computed according to:

$$\boldsymbol{T_R = -\frac{V_R}{\ln(1-P_{VR})}} \quad \textbf{(3)}$$

For CH buildings, the following return periods are defined to the different limit states: SLO = 45 years, SLD = 75 years, SLV = 712 years, SLC = 1462 years. So, the consequent hazard maps on a national level for soil category A can be plotted.

2.2 Hazard and susceptibility on an urban scale

2.2.1 Landslide susceptibility on an urban scale

The landslide susceptibility assessment on an urban scale for CH is structured in several phases to better manage threats to historical and artistic assets in urban contexts. The proposed methodology involves assessing the spatial distribution of assets by overlaying them with hazard maps, aiming to determine their susceptibility to landslide risk. The starting point is an inventory map of landslides, which can be derived from the territorial administrators, official national bodies and ca be drafted anew with a combination of photointerpretation, geomorphological surveys, interferometric satellite data interpretation and news collection on past landslides. For example, in Italy the referenced mapping is derived from the National Hydrogeological Asset Plan (PAI, *Piano per l'Assetto Idrogeologico)* drafted by Local Basin Authorities and the Inventory of Landslide Phenomena in Italy (IFFI) database (Trigila et al., 2007).

The PAI serves as a territorial planning document usually adopted at the regional or national scale, with the primary objective of managing and preventing risks arising from hydrogeological events. It acts as a significant technical-regulatory tool, outlining strategies, measures, and actions to preserve the safety of individuals, residences, economic activities, and the natural environment. An essential component for the effective transmission of information regarding the hazards and hydrogeological susceptibility of the territory is represented by the cartography included in the context of PAI. These detailed maps offer a clear visualization of areas prone to risk, facilitating understanding and access to such information by authorities, industry professionals, and the interested public. PAI maps typically illustrate the zoning of the territory based on levels of hazard and hydrogeological susceptibility (Iadanza et al., 2021). This division of the territory into different zones or classes, each characterized by specific conditions of hazard and hydrogeological susceptibility, is a crucial element. Through this zoning, areas with different degrees of risk are identified, allowing for the adoption of targeted measures for management and prevention. Zones, depending on the associated hydrogeological risk level, can be classified, as very high (P4) high (P3), medium (P2), or low risk (P1), providing a detailed understanding of specific threats, such as landslides, concerning hydrogeological hazards.

The IFFI database represents another fundamental element for the implementation of this approach. The IFFI Inventory Database consists of digitalized cartography and its alphanumeric and iconographic database contains information on landslides recorded in Italy. The scale adopted for landslide detection and mapping is 1:10,000 over much of the national territory and 1:25,000 in high mountain or sparsely populated areas (ISPRA IFFI, 2024). The database is in the public domain and is provided with a shapefile containing basic information such as location, type of movement, and activity status of each landslide phenomenon (ISPRA IdroGeo, 2024). This database is crucial as it provides a level of detail beyond the national scale, allowing for a more precise assessment of the position and aiding in determining if and how an asset is threatened by landslides.

Subsequently, the practical implementation of the project is carried out by overlaying the database containing all cultural assets with information from IFFI and PAI. This process allows for assigning specific values to each individual asset based on its intersections with the aforementioned areas. In particular, null values are assigned in cases where there are no intersections, moderate values if there is an intersection only with IFFI, higher values if the intersection concerns only PAI areas (weighted depending on the area involved, increasing values will be proportionally attributed to the degree of hazard between P1, P2, P3 and P4), and maximum values when intersections occur with both databases. Assigning these values allows for categorizing cultural assets based on their level of exposure to hydrogeological risks, thus providing a detailed mapping of susceptibility on an urban scale.

Finally, it is possible to sum the values assigned to each cultural asset for the entire area under consideration, this final step provides an overall view of the susceptibility of the entire territory considered. In fact, the project serves as a valuable support tool for the protection of CH in urban contexts, integrating geospatial data and hazard information into a systematic and targeted approach.

2.2.2 Flood hazard on an urban scale

Urban scale is an intermediate scale for flood risk assessment of CH. Usually on this scale hydrodynamic models considering the peculiarities of flood defences, mitigation works and infrastructures, which affects surface water profiles of rivers, are available, especially if CH lies inside an urban area. In case CH is isolated, ad-hoc hydrodynamic models can be developed. In European Countries, the "Floods" Directive 60/2007/EC requires member states to produce flood hazard maps, which are often obtained by urban scale or catchment scale hydrologic-hydraulic simulations. The 2D numerical approach is the most appropriate for urban scale flood hazard modelling. High resolution DEMs, such as LiDAR derived 1-2 m resolution models, are needed to describe the street-building pattern and account for local altimetry. The main examples of CH analysis on an urban scale are the works by Trizio et al. (2021), Arrighi et al. (2018), Hapciuc et al. (2016), Kalogeropoulos et al. (2023). A different approach, besides hydrodynamic modelling is the use of remote sensing data to identify past inundated areas, this method has been applied to the area of Angkor World Heritage Site (Liu et al., 2019).

Depending on the number of CH buildings, the urban scale allows for a better understanding of flood hazard by means of a statistical analysis of water depths on the built footprint which might highlight partial flooding or different flood severities for structures with a significant surface area. Moreover, the knowledge of constructive styles and typologies in the site might allow the better description of actual inundation depths. As an example, in some areas certain types of churches are characterized by monumental entrance stairs which reduce flood depths through elevated floors.

With respect to the national scale, on an urban scale a better characterization of flood depth and velocity is recommended, because CH is better georeferenced and spatially described. 2D unsteady hydrodynamic models of cities with computational meshes capable of representing urban texture, i.e., roads and buildings, should be adopted.

2.2.3 Earthquake hazard on an urban scale

On a urban scale the earthquake hazard is deepened involving the microzoning (MS) maps for a given municipality. MS is referred to the techniques addressed at identifying areas characterized by a homogeneous seismic behaviour. To this aim, MS maps indicate the stable areas susceptible to local amplifications as the unstable susceptible ones. MS provides from one side an input for urban planning and earthquake mitigation prioritization, on the other side, it enables to obtain more reliable risk scenarios (Ansal et al., 2009; Brando et al., 2020; Abate et al., 2020; De Risi et al., 2019; Amendola and Pitilakis, 2023). These studies follow distinct levels of analysis, from level 1 to level 3, characterized by an increasing level of accuracy. Level 1 consists of a preparatory level; it regards the collection of pre-existing data, subdividing the territory into qualitatively homogeneous micro-zones. Level 2 introduces the quantitative element associated with the homogeneous zones; additional surveys are implemented, and specific MS maps are realized. Finally, level 3 consists of an in-depth study providing territorial maps highlighting amplifying factors and subsoil conditions. The adoption of MS studies leads to more reliable hazard quantifications significant for proper risk analysis.

2.3 Hazard and susceptibility at the asset scale

2.3.1 Landslide susceptibility at the asset scale

At the asset scale landslide susceptibility can be evaluated through different means. Qualitatively, the presence of a landslide can be assessed through geomorphological surveys aimed at detecting mapping indicators of activity. This can be further investigated using ground-based instrumentation to retrieve basic information regarding the rate and the extent of deformation of single (or a group of) landslide (or landslides) (Casagli et al., 2023). Topographic instruments and more low-cost monitoring devices like crack-meters installed on structures or extensometers and inclinometers installed on the landslide are commonly used. Remote sensing devices can also be employed; ground-based interferometry, for example, can be used for rapid mapping by performing 2D acquisitions to cover areas beyond those that were initially considered of interest and potentially to detect further unstable portions of a slope. Lidar is widely used in landslide characterization and detection. For example, the visual inspection of high-resolution digital elevation models provided by lidar often greatly improves landslide mapping capabilities as interesting features, such as fractures, strata, debris deposits, overhanging rocks and so on, can be recognized on a 3D reconstruction. The high resolution of point clouds acquired by terrestrial lidars allows for a complete geomechanical characterization of rock masses, especially in demanding environments. Finally, the comparison of two point clouds taken at different times allows for landslide volume estimation and identification of rockfall source areas.

Aside from the instrumental and survey approach, the asset scale also allows for the collection of enough detailed information to perform slope stability analyses aimed at assessing the factor of safety (i.e. the ratio of the resisting forces to the driving forces acting on a slope) or the conditions of triggering. A multitude of slope stability analysis methods exist, and they can be classified into deterministic methods, like limit equilibrium methods (LEMs), limit analysis (LA), finite element analysis (FEM) and finite difference method (FDM), and probabilistic methods (reliability approach) (Kaur and Sharma, 2016). In limit equilibrium methods the equilibrium of a soil mass tending to slip under the influence of gravity is investigated. Failure in this method is described as the condition when driving forces (or moments) exceeds the resisting forces (or moments). Such methods are simple and less accurate than other available deterministic methods like FEM, FDM, and limit analysis but these advanced methods need more time and knowledge to be employed. The reliability approach consists in addressing uncertainty in the analyst's knowledge of material properties and loading conditions (Christian et al., 1994); therefore, it is a way to deal with relative (not absolute) probabilities of failure.

Furthermore, these slope stability assessment methods can be integrated with the detection and monitoring methods described earlier. In other cases, the choices between these approaches and then between all the different methods within each type of approach, depends on the availability of data (especially for the model approach) and money (especially for the instrumental approach).

2.3.2 Flood hazard at the asset scale

In flood hazard assessment, asset scale simulations are usually not performed. The nature of the phenomenon which propagates with dynamics at the catchment scale makes it difficult to set numerical models describing flood hazard of a specific building or complex. In fact, local hazard characteristics such as water depths, flow velocity etc. depend on how floodwaters propagate with respect to the surrounding terrain and land use. Few examples of local flood hazard assessments are available in the scientific literature (Musumeci et al., 2021). The work by Musumeci et al., (2021) describes debris flow hazard at the UNESCO site of Villa del Casale (Sicily) to understand risk and propose mitigation measures, nevertheless the area considered for the simulation spans over the upstream catchment. The work remains one of the few examples where the hazard assessment has been specifically carried out for a CH site and debris flow depth has been extracted over specific points of the archaeological complex.

At the asset scale, flood hazard can be ad-hoc simulated with 2D or 3D hydrodynamic models coherent with the general flood propagation in the surrounding area, e.g., city or floodplain. The possibility of inspecting or collecting information on the characteristics of the building, such as its elevation above the ground, presence of underground spaces or openings, allows for simulating actual inundation inside the building, by setting up consistent boundary conditions upscaled from urban-scale flood models. This approach, however, has never been attempted according to the current state of the art, but would constitute a promising advancement. Besides river flooding, other phenomena such as debris flows, or flash floods would benefit of a more local analysis of hazard and its interactions with the structure.

2.3.3 Earthquake hazard at the asset scale

The earthquake hazard at the asset scale is investigated through experimental in-situ testing, such as geotechnical surveys, down-hole tests or core drilling tests. These are required to define the local seismic response of the area, as well as to determine the mechanical characteristics of the soil for different conditions (static and dynamic).

The determination of the design seismic action can be pursued identifying the seismic stratigraphy of the area to define the consequent subsoil categories. In alternative, more refined local seismic response analysis can be carried out. They require knowledges involving the geometric and stratigraphic characterisation of the soils for the selection of a group of seismic records. They can be classified into artificial, synthetic and recorded.

The selection of the natural accelerograms should be justified based on the expected PGA of the site and on seismogenic characteristics of the source, the conditions of the recording site, the magnitude, the distance from the source. Then, the recorded signals need to be scaled to follow the seismic design spectrum of the area.

Geotechnical and geophysical investigations can deepen the understanding of the geological stratigraphy, and the characterization of the studied area in terms of seismic shear wave velocity (V_S) and can help evaluate the damping effect and determine the geotechnical parameters, such as the dynamic elastic moduli, the Poisson coefficient, the shear modulus decay curve,.

3 Vulnerability

The vulnerability is the degree of loss due to a catastrophic event of an exposed element and it depends on both the intensity of the phenomenon and on the typology and functionality of the considered elements at risk.

3.1 Vulnerability on a national scale

3.1.1 Landslide vulnerability on a national scale

The vulnerability (degree of loss) of elements exposed to landslides broadly depends on two factors: the energy of the landslide at hand and the structural resistance of the impacted element at risk. Thus, vulnerability is a complex factor depending on intrinsic characteristics of the landslides, of the exposed elements, and on the interaction between the two. Moreover, at this scale of work, it is not possible to specifically account for every single element (each landslide and each building). Consequently, simplifications are necessary and averaged assessments have to be performed over broad spatial units (e.g., large cells of a regular grid, hydrographic catchments or municipalities) to characterize them in terms of expected landslide intensity and typical resistance of the CH. Afterwards, relational matrices can be used to combine landslide intensity classes and building resistance classes to obtain a vulnerability class, which can be translated in a percentage value (degree of loss) assigned to a spatial unit.

Similarly to susceptibility/hazard assessments, a separate analysis must be performed for every group of landslide type, given the peculiarity of their physical features. Therefore, a specific procedure is followed for slow deep-seated landslides, rapid slides/flows, and rockfalls. A matrix-based approach can be followed to combine the different characters found in each spatial unit (regular grid cells in the example in Figure 2), but some elements may be quantified with different parameters according to the landslide type considered. Moreover, the scheme will be replicated three times and calibrated separately for each landslide type.

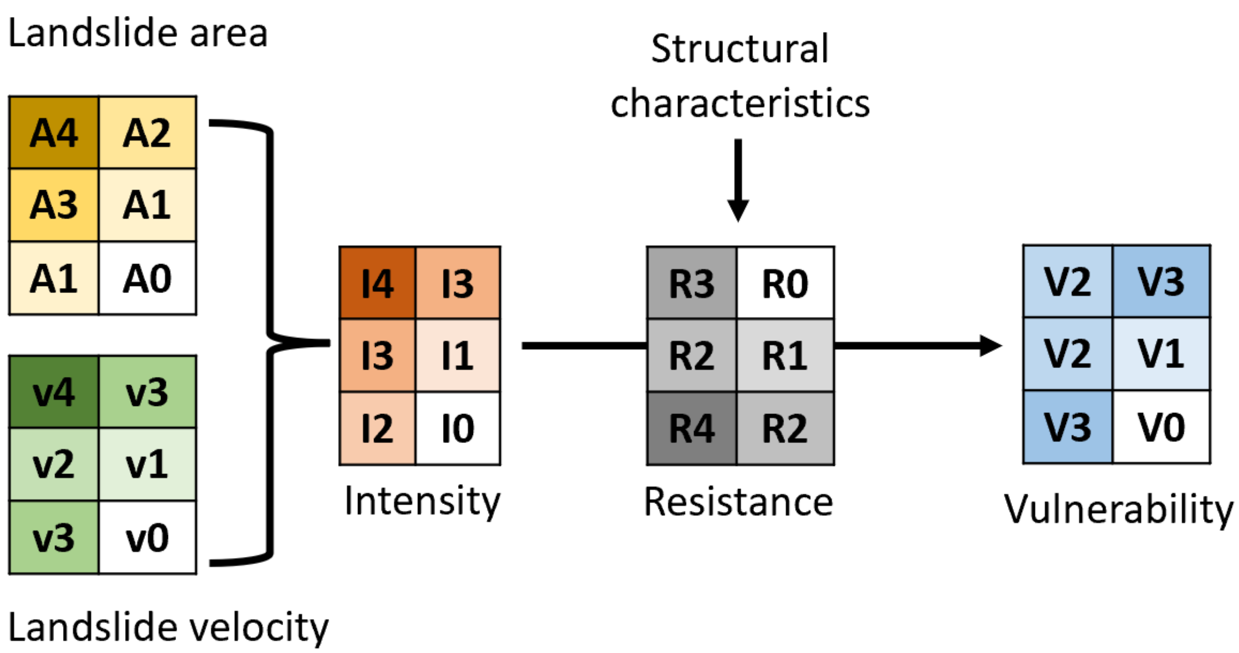

Figure 2. Approach to identify quantitative vulnerability classes for national-scale landslide vulnerability assessment.

The procedure regarding slow-moving landslides is largely derived from Caleca et al. (2022). The landslide intensity across each spatial units can be estimated as a function of the landslide area (A) and the landslide velocity (*v*). The former can be easily defined in GIS environment by overlaying an inventory of landslides (e.g. IFFI database) with the spatial units to characterize them in terms of landslide area. The continuous values found can be classified into a desired number of classes (e.g. 4, to keep the parameterization simple) based on objective techniques like natural breaks intervals. Concerning velocity, satellite interferometry represents the most viable tool for a nation-wide characterization of slow-moving landslides. For this purpose, a number of MT-InSAR (multitemporal-interferometric SAR) products can be used to perform a cluster analysis aimed at identifying partitions of the territory that are affected by moving landslides and characterizing those areas in terms of average velocity. An overall velocity can be assigned to the whole spatial unit by a weighted average of the different values encountered inside it, or by selecting the highest velocity (conservative risk assessment, based on a worst-case scenario). Velocities values are reclassified into the same number of classes used for the landslide area and a symmetric matrix is built to combine landslide area with landslide velocity to obtain an intensity class.

The resistance of the element at risk is parameterized separately for broad classes of building typologies, according to a common scheme based on easily retrievable attributes (construction type/material, dimension, maintenance state). Using empirical relationships established in the international literature (Li et al., 2010; Uzielli et al., 2015) and recently updated by Caleca et al (2022), a total score is assigned to each element at risk based on the sum of the partial scores assigned to each attribute. Afterwards, the value is aggregated at the spatial unit level and each spatial unit is assigned to one of 4 quantitative resistance classes (based on natural breaks intervals performed over the entire range of values).

A vulnerability class will be assigned to each spatial unit based on a correlation matrix that combines the resistance classes and the intensity classes.

Concerning shallow rapid movements (including debris flows and shallow rapid landslides) the procedure significantly differs from the previous one only in the method applied to estimate the expected landslide velocities. Based on Martinelli et al (2022), the "energy line" approach, first developed for slope-scale applications by Heim (1932) can be applied on distributed approaches to all mapped shallow landslides. The method combines geometric parameters easily derivable from DEMs (horizontal distance and differences in vertical elevation) to estimate the potential velocity of landslides. The maximum velocity found is assigned to each spatial unit. The range of velocities is subdivided into 4 quantitative classes according to natural breaks intervals, then the velocity classes are combined with landslide area classes in a relational matrix specifically calibrated for fast-moving shallow landslides to assign an intensity class to each spatial unit. The procedure for the elaboration of resistance and vulnerability is similar to the one described for slow deep-seated landslides but it is specifically calibrated for fast-moving slides and flows.

Lastly, for rockfalls the procedure is identical to what proposed for shallow landslides, but a specific application and calibration is envisaged.

3.1.2 Flood vulnerability on a national scale

The evaluation of flood vulnerability requires the information on building characteristic, construction materials, state of conservation, finishing levels, just to cite a few. Thus, the amount of information is sensitive to the scale of analysis at which the evaluation is performed. Vulnerability functions usually model the degree of loss based on flood depth or other flood characteristics and they are commonly used mostly for residential buildings.

On a national scale, given the peculiarities of CH and the number of items usually exposed, significant simplifications are required. Vulnerability functions are not widely adopted at this scale given the paucity of information on actual losses which prevent the model validation. Vulnerability is usually classified based on CH typology, i.e., distinguishing for instance churches from castles, often by means of a purposedly taxonomy developed. On a national or similar scale, all the examples available in the literature adopt a qualitative classification of vulnerability based on CH typology (Figueiredo et al., 2020; Garrote and Escudero, 2020; Arrighi, 2021; Arrighi et al., 2023). In these approaches religious and residential buildings are usually considered the most valuable and vulnerable ones while fortified or industrial architectures are considered less vulnerable.

Particularly, in the work by Arrighi (2021), which considers a global scale analysis of flood risk for UNESCO World Heritage sites, seven classes of vulnerability are used with decreasing potential damage, i.e., (i) historical city centres, (ii) religious architectures, (iii) residential architectures, (iv) defensive architectures, (v) industrial architectures, (vi) archaeological sites, (vii) hydraulic infrastructures.

In the work by Figueiredo et al. (2020), which explores flood risk at national level in Portugal, again 7 CH classes are distinguished. By decreasing vulnerability, they are: (i) buildings with flood-susceptible contents of significant value, (ii) buildings with flood-susceptible contents of limited value, (iii) castles and walls, (iv) isolated vertical constructions, (v) other constructions and buildings, (vi) archaeological sites, remains and ruins, (vii) rock art. These classes are used to derive simplified qualitative linear vulnerability functions.

The work by Garrote and Escudero (2020) considers the Spanish region of Castile and Leòn and assumes three main types of vulnerability, i.e., materials vulnerability, structural vulnerability and content vulnerability, which are finally combined together into a single vulnerability index. The classes of CH considered are: civil, industrial, religious, defensive, archaeological structures and hydraulic infrastructures.

In the work by Arrighi et al., 2023 carried out for the whole Po River District in Italy with ca. 125,000 CH point locations, an ad-hoc taxonomy has been developed and used to classify flood vulnerability. Four vulnerability classes have been adopted, namely a very high vulnerability for religious, residential, tertiary and fortified architectures and museums, a high vulnerability for industrial and rural architectures and monuments, a medium vulnerability for infrastructures, plants and archaeological sites, and low vulnerability for open spaces and parks. An index of flood damage to CH is developed to represent an aggregated value of loss at the census section scale.

As emerged by the analysis of the state of the art, also flood vulnerability assessment methods are strongly dependent by the scale of analysis and data availability. Existing literature suggests that at national scale the most viable approach consists in classifying CH according to the function, e.g., religious or rural architecture or expected average building characteristics which allow for a very simplified, expert-based vulnerability classification.

3.1.3 Earthquake vulnerability on a national scale

On a national scale a macroseismic approach for vulnerability is considered using average vulnerability indices calibrated on the Italian territory for cultural heritage (Lagomarsino et al., 2004). Each manufact is classified according to the general taxonomy on based on architectural morphology (church, castle, palace, tower, etc). Hence, for each building type a vulnerability curve defining the relationship between macroseismic intensity (I) and mean damage grade (μ_D) is provided:

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25V - 13.1}{Q}\right)\right] \quad (4)$$

where V is the macroseismic vulnerability index obtained based on the CH taxonomy, I is the macroseismic grade (from I to XII) and Q is a ductility index. Values of V and Q for the different CH typologies calibrated for the Italian territories on the basis of previous earthquakes are in Table 1 (Lagomarsino et al., 2004).

Table 1. Reference values of V and Q for the different structural typologies (Lagomarsino et al., 2004).

Typology	V	Q
Arch bridges	0.296	2.30
Castes	0.456	2.30
Churches	0.890	3.00
Columns	0.456	1.95
Monasteries	0.736	2.30
Mosques	0.730	2.65
Obelisks	0.456	1.95
Palaces	0.616	2.30
Temples	0.500	1.95
Towers	0.776	2.30
Trilithes	0.456	1.95
Triumphal arches	0.456	2.30

It is possible to convert the vulnerability curve in terms of PGA through the empirical formulations reported in Section 2.1.3. Finally, the probability associated to a structure of attaining a given damage grade D_k (k=0, 1, 2, …5) can be expressed through a binomial distribution as a function of the mean damage grade:

$$p_k = \frac{5!}{k!(5-k)!} \left(\frac{\mu_D}{5}\right)^k \left(1 - \frac{\mu_D}{5}\right)^{5-k} \quad (5)$$

Numerical fragility curves can be then derived, although this procedure is generally applied to the single structural units composing a manufact:

$$p_{V,k}(I) = P(DM \geq D_K | I) = \sum_{i=k}^{5} p_i \quad (6)$$

On a national level, the vulnerability index will be attributed to each CH building identified on the territory through a rough approach, accounting each manufact as single structural unit, regardless of the actual number of structural units, the surface or the volume involved. Finally, the V-value for each municipality will be obtained by a weighted average of the values over the total number of buildings located in the territory.

3.2 Vulnerability on an urban scale

3.2.1 Landslide vulnerability on an urban scale

An approach for quantifying the intensity of the landslide hazard impacted on manufacts can be represented by detecting ground movements based on satellite Synthetic Aperture Radar Interferometry (InSAR) data elaborated through Persistent Scatterers Interferometry (PSI) technique over historical built-up areas and in particular the potential instability of single building at local scale, with particular attention to CH structures.

In cultural heritage surveying, the evaluation of the condition of structures can be presented as a rating based on numbered classes. These classes serve as an output to convey the structural preservation status concisely and informatively, thereby providing a succinct and schematic overview (Pratesi et al., 2015; Salim & Zahari, 2011; Wahida et al., 2015).

PSI technique is capable of measuring displacements with millimetre precision, dense spatial sampling, wide area coverage and systematic temporal updating. The basic principle relies on the detection of stable radar targets within SAR images, the so-called Persistent Scatterers (PS), which correspond to anthropic or natural objects characterized by a stable phase signal (Ferretti et al., 2001; Massonnet and Feigl 1998; Rosen et al. 2000). The PSI approach allows for measuring the movements of each PS along the satellite line of sight (LOS) with respect to an assumed stable reference point and it is particularly suitable in urban areas, where many potential coherent PS such as buildings and road lines can be retrieved.

The PSI approaches are nowadays validated techniques which can permit a quantitative estimation of the degree of instability of an area, an enclosed sector and even single clusters of buildings/elements on the ground to be performed, with a temporal reconstruction that can dates back up to 1992, i.e. in case of availability of ERS-1/2 satellite imagery (Tapete & Cigna, 2012). This actually corresponds to the so-called *back-analysis (*Cigna et al. 2011) and can be specifically adapted to structural monitoring and early-stage warning of CH sites (Tapete et al. 2012b).

The demonstration that PSI data can support the preventive diagnosis of monuments and historical buildings induces to consider such techniques as potential routine tools to monitor and assess the stability and, more generally, the condition over time, to be used by heritage bodies, superintendences, public administrations in charge of CH management, conservators, and practitioners (Tapete & Cigna, 2012).

A further step forward on the exploitation of InSAR PSI-based products is fostered by the increasing number of services, projects and acquisition programmes at regional, national, and transnational level, which are aimed at the creation of databases containing processed PSI data thought to be finally used by public bodies, local authorities, and a wide spectrum of stakeholders and end-users, in their ordinary activities of land and urban environment planning and management. Even if such initiatives are frequently designed for other uses than application on CH sites, it cannot exclude that this typology of PSI data can constitute a precious reservoir of information for the preservation of monuments and historic centres for landslide risk assessment in CH sites (Trigila et al. 2011).

In particular, an interesting procedure that can be applied to evaluate ground motions on built-up fabric relies on PSI analysis for building-scale instability assessment by means of classification indexes, starting from experience of some previous works on this topic (Bianchini & Festa, 2022; Pratesi et al., 2015; Pratesi et al., 2016). Thus, the stability and potential deformation on urban fabric at the single manufact scale are analysed by considering ground deformation rates of satellite PSI data on each building. The PS deformation estimates are converted into indexes whose range classes allow us to rate the instability of buildings due to structural or terrain deformation.

We consider a buffer area around individual manufact of some metres in order to avoid possible georeferencing shifts between buildings and PSI layers and to consider even PS that are not included within the building plain-edge, but that are the result of a backscattered radar signal, which could be even influenced by the structure itself, as a consequence of the metric resolution cell of space-borne radar images. We dimensioned this buffer area according to the spatial resolution of the employed SAR image, i.e. 5 m if using medium resolution C-band data.

Figure 3 shows the proposed set of indexes to classify the information content of PSI data and to rate the deformation conditions of CH: for each CH, PSI coverage and deformation rates are translated into the classification indexes. In practise, the boundaries of buildings (plus a 5 m buffer) are intersected with the PSI data falling within such areas, then 5 class values and thus the indexes are extracted. This procedure is feasible when the PSI coverage over every single CH is sufficient. PSI data in ascending and descending geometries must be merged and considered as a unique dataset. In particular the Data Coverage Index (I_d) is defined to express the spatial distribution of PSI data covering the CH to be survey. This index is scored from E to A to signify poor PS to optimal coverage for an individual manufact.

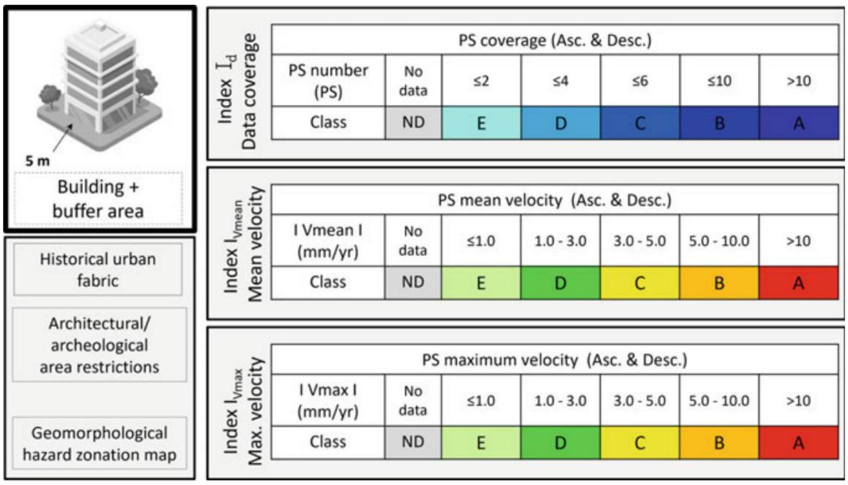

Figure 3. Rating of PS coverage and instability indexes for building classification

The Mean Velocity Index (I_{vmean}) and the Maximum Velocity Index (I_{vmax}) are defined according respectively to the average value and the maximum value of the velocity ranges of PSI within the building buffers. The absolute value of velocities was considered since deformation rates with negative and positive sign (which stands respectively for movements away and towards the satellite sensor) are merged when the ascending and descending orbits are fused.

I_{vmean} and I_{vmax} range from class E to A and are colour-coded from green to red (from “stable” to “critical deformation”). Values of 5 classes are dimensioned according to the PSI VLOS (velocities recorded along the LOS in mm/year). It is worth noting that the ranges of Class E, which means the most stable condition, are set as variable according to the standard deviation value of the PSI population of interferometric data. The No Data (ND) class of each Index refers to CH where no PS are identified within their buffer area boundaries.

Overall, the output of the procedure is a value of intensity of the movement (I map) assigned to each CH. Then, this value can be cross-compared with the CH database as elements at risk map on an urban scale based on the type of the CH element at risk as well as their nature, importance and functionality. Thus, the E map and the I map are combined by means of a contingency matrix for providing the vulnerability map (V) of the CH of the area.

3.2.2 Flood vulnerability on an urban scale

On an urban scale, some more coherent hypothesis on the common characteristics of CH can be made or fast surveys can be used to collect information regarding building materials. Also, on an urban scale, vulnerability functions are not widely adopted and are often replaced by a qualitative assessment of vulnerability based on one or more parameters, e.g., the type of building, materials etc.

In the case study of Dordrecht Brokerhof et al. (2023), the concept of “value density” is introduced but it refers mainly to a standard application of risk matrices which incorporates the concepts of footprint, height of the building, function, and significance.

For the case study of Alzira (Jucar basin, Spain) (Trizio et al., 2021), vulnerability was analysed by evaluating the expected response of the building, based on the intrinsic characteristics of the building itself and its conservation condition. The parameters are not weighted as they are considered equally critical in the overall response of the building. CH vulnerability to floods considers the footprint, building typology, vertical constructive system, and wall thickness, which are used to measure the CH’s exposure to risk. Constructive characteristics such as architectural elements (foundations, plinth, type of wall, rendering), materials and constructive techniques are also included, providing information on the vulnerability of the building. Each characteristic was assigned a numerical value, from 1 (very low) to 5 (very high), on a scale of values by level of influence. This type of vulnerability analysis is facilitated by the limited number of buildings to be surveyed i.e., 12 vernacular heritage dwellings and 2 examples of monumental architecture.

For the analysis on an urban scale of the city of Florence (Arrighi et al., 2018) two complementary aspects were considered: the degree of building vulnerability and the degree of vulnerability of contained artworks. In this case, the number of heritage buildings, i.e., more than 150, did not allow for surveys to assess construction materials etc. Heritage buildings and artworks were classified based on typology. Churches and religious structures (cloisters, chapels) were classified in the high vulnerability class because they commonly host underground spaces (crypts) and their walls are usually covered by frescoes and decorations. Moreover, religious buildings are on average those with the most ancient origins. Libraries and archives were assigned to the low vulnerability class since most of their significance is due to their content. Museums, theatres, and noble palaces are included in the medium vulnerability class since they show intermediate characteristics between religious buildings (less frequent presence of frescoes and decorations) and libraries. Regarding the artworks/books contained inside these buildings, vulnerability was classified into four categories: paintings on canvas and wood; books, archive documents, art prints; sculptures (wood, stone, clay, etc.); goldsmith's art, coins, medals.

An example of vulnerability function which considers indirect impacts to CH was developed by Arrighi et al., 2022. Flood damage in this work is measured as the time required to a cultural attraction to reopen after a flood based on flood depths and describes a resilience-based approach to flood impact Arrighi et al., 2022).

On an urban scale, further information on constructive typologies and building features or presence of artworks inside cultural buildings allows for a better understanding of vulnerability classification. It might also contribute to the development of simplified urban-scale stage-damage vulnerability functions, that at least identify zero-damage and maximum damage water depths.

3.2.3 Earthquake vulnerability on an urban scale

Consistently with the approach defined on a national level (Section 3.1.3), on an urban scale the macroseismic approach is deepened by introducing structural behaviour modifiers to analyse the different structural units. While the approach at the national level accounted each CH manufact as a single one, on an urban scale each asset is subdivided according to the number of structural units composing the system and defined according to the International Building Code (IBC) (NTC, 2018). Then, for each structural unit, the macroseismic approach including the seismic modifiers is carried out thus obtaining *n* vulnerability curves for each structural unit composing the CH asset. The modifiers are increasing or decreasing quantities to be summed to the initial vulnerability V based on specific parameters such as the state of preservation, the damage level, the position etc. (Table 2). The results are vulnerability maps at the urban level with colour scales for the different CH spatially located in the municipality of interest.

Table 2 – Vulnerability modifiers for CH buildings

Parameter	Vulnerability score
State of preservation	worst (+ 0.04) – medium (0) – good (−0.04)
Damage level	severe (+ 0.04) – light (+ 0.02) – none (0)
Architectural transformations	Yes (+0.02) – no (0)
Effective recent interventions	yes (−0.02) – no (+ 0.02)
Masonry quality	yes (+0.05) – no (0)
Plan regularity	It depends on the typology

Section regularity	It depends on the typology
Position	It depends on the typology
Site morphology	ridge (+ 0.04) – sloping (+ 0.02) – flat ground (0)
Additional parameters for churches	
Domes/Vaults yes	yes (+ 0.04) – no (0)
Nave typology	central (–0.02) – one (0) – three (+ 0.02)
Raising elements / facade	yes (+ 0.04) – no (0)
Position	included (–0.02) – additions (+ 0.02) – isolated (0)
Lateral walls height	low (< 6 m) (–0.02) – medium (> 6 m and < 12 m) (0) – high (> 12 m) (+ 0.04)

The final vulnerability index for each structure V_{SU} is given by:

$$\boldsymbol{V_{SU} = V + \sum V_K} \tag{7}$$

Hence, vulnerability curves, damage distributions and fragility curves can be computed according to equations 4, 5, 6.

3.3 Vulnerability at the asset scale

3.3.1 Landslide vulnerability at the asset scale

The vulnerability of a CH asset to landslides depends on characteristics like the velocity and the extension of the landslide and the type of the element at risk that can be tackled also at smaller scales (such as urban and national); however, at the asset level, it is possible to delve deeper into the knowledge of the specific risk scenarios and to rely on fragility and vulnerability curves; fragility curves provide the probability for a given building to reach or exceed a certain level of damage severity as a function of deformation intensity. Therefore, it expresses the vulnerability of buildings in probabilistic terms, incorporating uncertainties (Mavrouli et al., 2014). Vulnerability curves show the relationship between the average level of damage severity of a given (aggregate of) building(s) and the value of landslide intensity (Peduto et al., 2017).

Fragility curves are derived by combining the data on levels of equivalent damage or damage severity with the corresponding magnitudes of the specific intensity parameter, that in this case can be the cumulative displacement measured with on-site instrumentation (whereas the displacement measured at national or urban scales is derived from satellite interferometry).

While the concept of fragility curves for buildings affected by seismic shaking is well-established, and various mathematical procedures for developing such curves can be found in the scientific literature (Mavrouli et al., 2014), regarding landslide events, the literature appears to be concentrated especially in the last decade. The first integrated analysis on the study of building behavior concerning various types of landslide phenomena was carried out by Heinemann (1999), who attempted to determine the vulnerability of various construction typologies through an indicator-based methodology. Glade's (2003) overview of scientific research on the vulnerability of buildings to landslides of various kinds highlights the high degree of uncertainty due to analyzed data, the propensity for empirical methods, and the lack of detailed explication of results, revealing the absence of a general strategy leading to a lack of shared methodologies within the scientific community.

Recent studies have sought to address the issue in a more specific manner, often focusing on individual landslide types, primarily concentrating on estimating the intensity of landslide phenomena and secondarily on the potential damages resulting from them. From the survey conducted, it is possible to discern how the methodologies proposed over the years can be divided into three different approaches:

- Vulnerability curves: An approach aimed at establishing a specific relationship between the considered element and the intensity of the related phenomenon. Generally, it is based on quantitative aspects, but often the initial data can be qualitative, derived from field observations.
- Vulnerability matrices: A qualitative approach often relying heavily on empirical data or expert judgment.
- Vulnerability indicators: An approach focusing on investigating individual aspects of the at-risk element and how they contribute to determining the overall vulnerability of the investigated element.
- Hybrids: Approaches that jointly utilize, in a diversified manner, the previously defined approaches.

Many of the applications carried out in Italy regarding slow-moving phenomena are based on statistical approaches, through the analysis of interferometric data (InSAR) for assessing the intensity of phenomena and on field surveys for assessing the damages suffered by buildings. By cross-referencing the data from InSAR analyses and the observed damages, vulnerability curves for various types of buildings regarding the intensity of the considered phenomenon can be obtained based on statistical relationships. Applications of this kind have been presented by Peduto et al. (2017; 2021), Infante et al. (2016), and Nicodemo et al. (2017). An additional methodological approach, based on the multi-scalarity of vulnerability analysis, is proposed by Infante et al. (2016) and Ferlisi et al. (2018).

Although there has been a real proliferation of studies in recent years regarding the determination of vulnerability, there still exists today a lack of a standardized methodology shared by the scientific community.

Del Soldato et al. (2017) propose a procedure for the classification of the damages experienced by constructions. This method allows for a quick and non-invasive analysis, as it only involves visible fractures on external surfaces and their relative extension, without requiring access to the interior of the structure or information about the foundations (which can be very difficult to obtain). The method consists of two distinct activities:

- the recognition, survey, and classification of fractures affecting buildings through a detailed survey of the terrain to be integrated with drawings, annotations, and photos, possibly using a survey form to include all information about the structure under examination.

- categorizing the damaged structures, defining a damage class for the entire building based on the severity and extent of what was assessed during the on-site inspection directly on the structure. Del Soldato et al. (2017) define seven damage classes: no damage, negligible, slight, moderate, severe, very severe, potential collapse.

In the second phase of the procedure, the collected data are synthesized for the generation of fragility and vulnerability curves following the method proposed by several authors (Fotopoulou and Pitilakis, 2013a; Fotopoulou and Pitilakis, 2013b; Mavrouli et al., 2014).

Other approaches that are possible at asset scale can take into account 3D information both of the hazard and of the element at risk. For instance, for slow-moving landslides affecting buildings, a relatively fast estimation of the vulnerability can be obtained by comparing the depth of the foundations with the depth of the landslide. Against fast-moving landslides like debris flows and rockfalls, the relevant asset-specific information concerns the type of construction material and its strength, to assess its resistance to energetic impacts.

3.3.2 Flood vulnerability at the asset scale

There are few examples of vulnerability analysis of CH at the asset scale. At present only one example of asset-specific, component-based flood vulnerability functions had been developed, and it has been used for two churches in Portugal (Figueiredo et al., 2021). The vulnerability function for a CH building is developed as a function of the value, susceptibility, and elevation of its components. A component taxonomy for Portuguese churches, containing the most prevalent components of relevance and their respective most common materials or techniques was developed based on building (including attached elements) and contents. Given that component values and potential impacts cannot be expressed in absolute terms, the vulnerability function quantifies impacts in relative terms, i.e. as a fraction of the global cultural value of an asset. A three-level scale to score the value of each component is adopted from unique components with exceptional cultural value, which are determinant for the global cultural value of the asset, to components that are not unique and that contribute in a limited manner to the overall cultural value of the asset. An inventory of all contents of the churches used as a case study was performed, with a significant effort for on-site data collection.

At the asset scale, component-based vulnerability functions can be derived after careful onsite inspection of structure, contents, and their position with respect to potential water levels. Such high detail vulnerability functions are quite demanding in terms of data collection and also require a description of the vertical distribution of heritage values and specific vulnerabilities with respect to a specific hazard. In this case, also the shape of the vulnerability function can be defined besides zero-damage and maximum damage water depths.

3.3.3 Earthquake vulnerability at the asset scale

At the asset scale general Performance-Based Assessments (PBA) are carried out, and the vulnerability is evaluated through numerical approaches on structural models. The choice of the most suitable strategy to investigate a CH is made case by case based on the intrinsic architectural and structural features of the asset. In the seismic analysis of masonry structures, to carry out reliable analysis is important to understand the expected behaviour of the buildings under seismic actions, categorizing at first between local and global behaviours (Touliatos, 1996). This distinction is based on the capacity of a structure to face an earthquake involving the different parts composing the building. This peculiarity is given by the presence of structural details leading to the so-called box-behaviour, such as the inter-locking at the connection of the orthogonal walls, the presence of tie-rods or rigid/semi-rigid membranes. In these cases, a global behaviour can be expected, thus 3D structural models can represent advanced solutions for the vulnerability assessment. They are characterized by in-plane failures. On the other hand, whereas these features are lacking, masonry buildings do not involve the different parts to the earthquake resistance, and they rather behave through local and independent mechanisms. They are characterized by out-of-plane mechanisms. In case of independent behaviours, global structural models do not provide reliable assessments, and different strategies are recommended such as geometry-based approaches based on the static and kinematic theorems (Heyman, 1966; Gilbert & Melbourne, 1994). These strategies can involve linear or nonlinear analyses and they generally require the following steps: i) the identification of the different macro-elements based on the structural features of the construction; ii) the identification of different plausible hinge positions according to the observation of the existing damage, general damage patterns and expert judgement; iii) the determination of the multipliers activating or leading to the collapse for the different analysed systems. Based on the previous hypotheses, the lowest multiplier is identified like the most likely to be expected in case of earthquake for each macro-element. The structural performance of each mechanism is firstly compared with the seismic demand of the area, including the amplification effects given by the vertical development of the building through the floor spectra. This is made according to the limit state defined in the hazard sections, finally obtained safety indexes defined in terms of Capacity over Demand ratios.

In the case of global behaviour, different numerical strategies are available (D'Altri, et al., 2020). Finite-element (FE) approaches and equivalent frame (EF) methodologies are within the most used strategies at the asset scale. In this numerical models, linear and nonlinear constitutive laws can be implemented for the seismic analyses. Nonlinear static analyses (NLSA) nowadays represent acknowledged tools the evaluate the structural integrity of existing buildings, as their use is recommended in National and International codes (MIT, 2019; FEMA, 2005; CEN, 2004). They are based on the application of a horizontal monotonic force leading to computing a "capacity curve" expressed as the horizontal displacement of a top node of the structure and the supported base shear carried by the building. In alternative, nonlinear dynamic analyses (NLSA) using scaled real ground motions represent the most advanced strategies. In this context, Incremental dynamic analyses (IDA) (Vamvatsikos & Cornell, 2002), multi-stripe analyses (Jalayer & Cornell, 2009; Baker, 2015) or the cloud method (Jalayer et al., 2014) are between the most acknowledged procedures.

The analysis of a CH needs to be based on the structural characteristics of the asset. Guidelines for performance-based assessment of cultural heritage masonry structures are presented in (Lagomarsino & Cattari, 2015). In Figure 4 a list of the standard, possible and rare approaches for the numerical investigation of CH buildings according to Continuous Constitutive Law Models (CCLM) approaches, Structural Elements Models (SEM), Discrete Interface Models (DIM) and Macro-Blocks Models (MBM) is provided. FE methods belong to the CCLM group, EF methods to SEM, while the macro-elements approaches for the local mechanisms lead to the MBM group.

ARCHITECTURAL ASSET CLASS		MODEL TYPE			
		CCLM	SEM	DIM	MBM
A	Assets with a box behaviour Palaces, castles, religious houses, caravansaries, collective buildings	Rare	Global (Standard)	Rare	Local (Standard)
B	Assets analysable by independent macroelements Churches, mosques, modern theatres, markets, industrial buildings	Possible		Rare	Standard
C	Assets characterized by monodimensional masonry elements Towers, bell towers, minarets, lighthouses, chimneys	Possible	Standard		Rare
D	Arched structures subject to in-plane damage Triumphal arches, aqueducts, bridges, cloisters	Rare		Possible	Standard
E	Massive structures with prevailing local failure of masonry Fortresses, defensive city walls, Roman and Greek theatres	Possible		Standard	
F	Blocky structures subjected to overturning Columns, obelisks, trilithes, archaeological ruins, Greek temples			Possible	Standard

CCLM: Continuous Constitutive Law Models - SEM: Structural Elements Models – DIM: Discrete Models – MBM: Macro Blocks Models

Standard (red) | Possible (orange) | Rare (yellow)

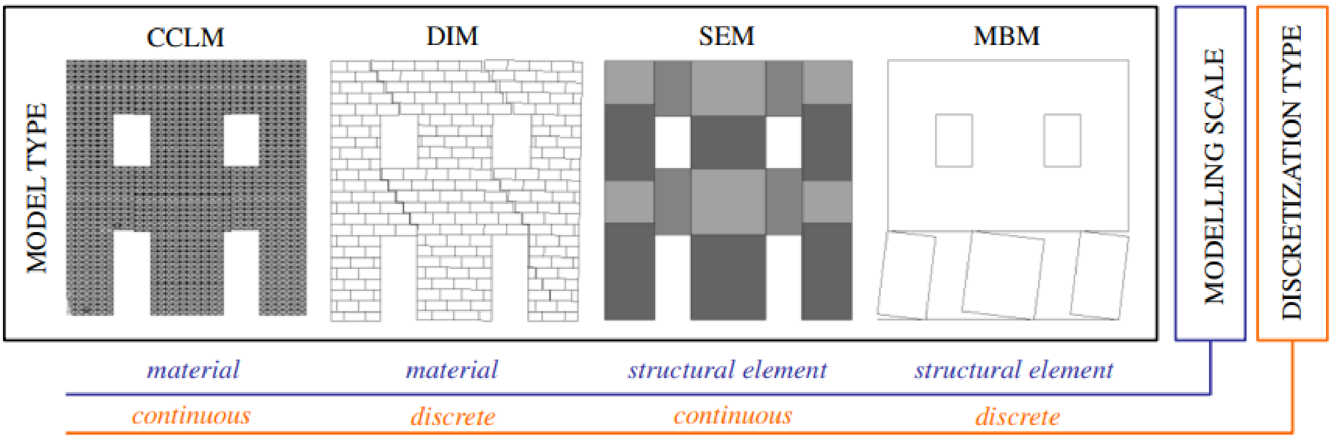

Figure 4. Above, classification of architectural assets and related types of models for the seismic analysis; below, classification of the modelling strategies (from Lagomarsino and Cattari, 2015).

4 Values of the elements at risk

According to UNESCO (2015), cultural and natural heritage stands as invaluable and irreplaceable assets, not merely for individual nations, but for humanity collectively. The degradation or loss of any of these assets represents a depletion of the global heritage. Certain elements of this heritage, distinguished by their exceptional qualities, are recognized as possessing "Outstanding Universal Value", deserving special safeguards against the growing threats they face. Then, criteria for assigning Outstanding Universal Value to assets are defined based on the fulfilment of one of more of the following (UNESCO, 2015):

- represent a masterpiece of human creative genius;
- exhibit an important interchange of human values, over a span of time or within a cultural area of the world, on developments in architecture or technology, monumental arts, town-planning or landscape design;
- bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared;
- be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history;
- be an outstanding example of a traditional human settlement, land-use, or sea-use which is representative of a culture (or cultures), or human interaction with the environment especially when it has become vulnerable under the impact of irreversible change;
- be directly or tangibly associated with events or living traditions, with ideas, or with beliefs, with artistic and literary works of outstanding universal significance;
- contain superlative natural phenomena or areas of exceptional natural beauty and aesthetic importance;
- be outstanding examples representing major stages of earth's history, including the record of life, significant on-going geological processes in the development of landforms, or significant geomorphic or physiographic features;
- be outstanding examples representing significant on-going ecological and biological processes in the evolution and development of terrestrial, fresh water, coastal and marine ecosystems and communities of plants and animals;
- contain the most important and significant natural habitats for in-situ conservation of biological diversity, including those containing threatened species of Outstanding Universal Value from the point of view of science or conservation.

What stands out is that neither of the aforementioned criteria defined by UNESCO (2015) is related to the economic value of the assets and all of them are qualitative and largely subjective. Different countries can have different criteria and listings of assets, some of which can be of interest to local communities only (Romão and Paupério, 2021), but, in general, the evaluations are made according to non-economic values that are usually considered like, for example, the existence, option, bequest, spiritual, social, historical, symbolic, authenticity, aesthetic and recreational values of CH (Figure 5). The use of economic evaluations arises from the need to establish comparisons and rankings, that is to introduce quantitative measures of the value (Romão and Paupério, 2021).

Ensuring the protection of CH assets is a crucial theme, especially when considering the natural hazards they face, such as landslides, floods, earthquakes, volcanoes, and other extreme weather events. Numerous studies highlight the significance of a thorough understanding of disasters and associated risks to formulate effective strategies for safeguarding these invaluable historical and cultural artifacts (Bonazza et al., 2018; Romão et al., 2016).

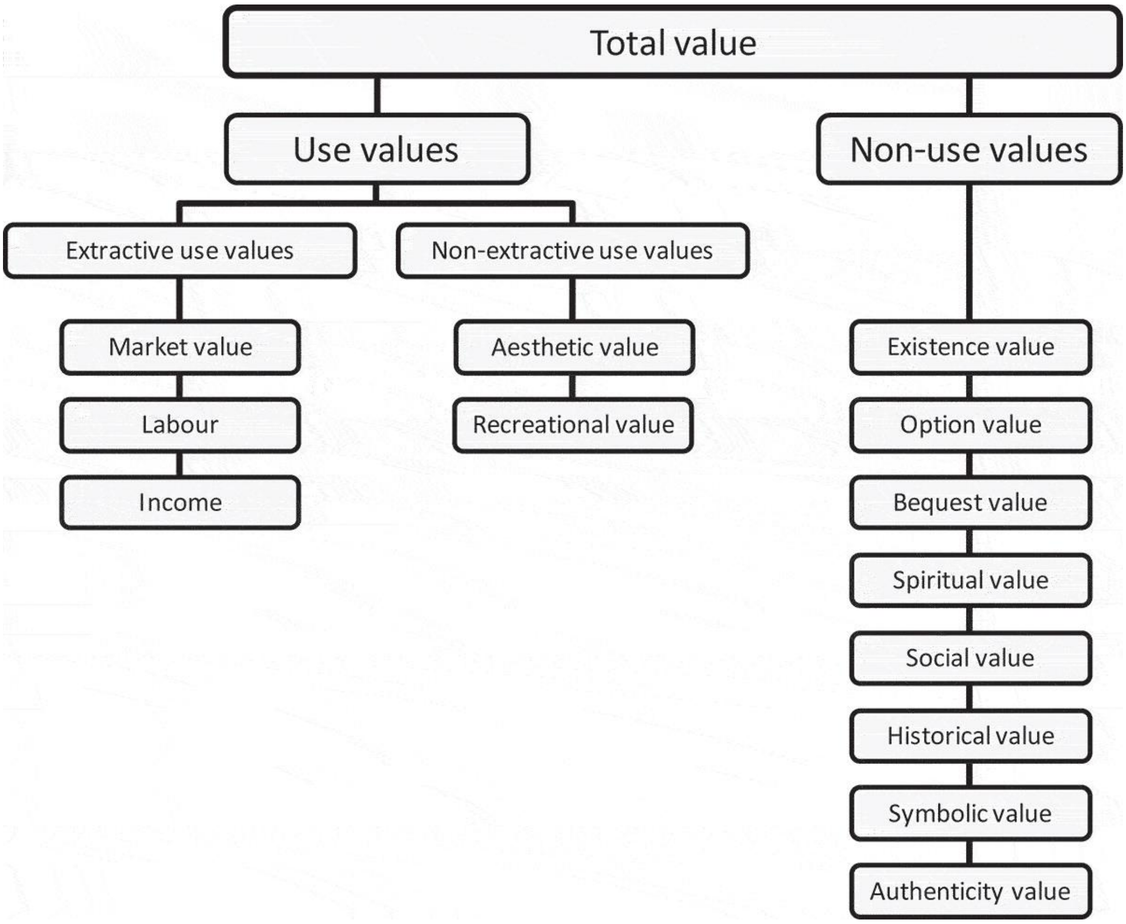

Figure 5. The total value of cultural heritage assets (Romão and Paupério, 2021).

Furthermore, recent research has introduced innovative proposals concerning the evaluation of risks linked to CH, specifically focusing on the impact of climatic conditions on artworks. These approaches not only consider external atmospheric agents but also internal conditions that can influence the preservation of artworks, contributing to a more precise and detailed risk assessment (Andretta et al., 2017; Bonazza and Sardella, 2023).

Although evaluating the exposure value of cultural assets is often a complex challenge, authors have proposed some methods to address this issue, like the creation of indices, based on a multi-level visual survey procedure (Sevieri et al., 2020). This approach facilitates the collection of data on multi-risk exposure, enabling the subsequent prioritization of risk for the studied assets. Utilizing accurate data, risk prioritization indices can be calculated and calibrated based on the structural and non-structural characteristics of CH assets. The resulting indices are then consolidated into a single multi-risk prioritization index, accounting for the intangible value of CH (Sevieri et al., 2020). This approach establishes a score that reflects the cultural significance of each asset, providing a more comprehensive and precise assessment of the risks it faces.

Recognizing that the protection of CH demands an integrated methodology, considering the complexity of natural risks and employing advanced methodologies for risk assessment, an approach based on the creation of ad-hoc indices derived from the categories of cultural interest is recommended.

4.1 CH on a national scale

The evaluation of national-scale exposure of cultural assets should be based on the official CH database provided by government bodies. For example, in Italy the Ministry of Culture has established a database consisting of 185.708 assets subdivided into four main categories: Declared Cultural Interest (DCI henceforth), Ongoing Verification of Cultural Interest (OVCI henceforth), Unverified Cultural Interest (UCI henceforth), and No Cultural Interest (NCI henceforth).

These classes form the framework through which CH is assessed and protected on a national level. DCI refers to officially recognized assets, acknowledged for their cultural significance. This classification implies a well-documented and reknown cultural value, leading to specific measures for preservation and safeguarding. OVCI suggests that the assessment process is currently underway to determine the cultural significance of the asset; this indicates a dynamic approach to evaluating cultural value, ensuring that the status of cultural assets is periodically reviewed and updated as necessary. UCI encompasses assets that are believed to hold cultural significance but have not undergone a formal verification process. This category acknowledges the potential cultural value of these assets, yet emphasizes the need for further investigation and assessment to recognize their importance officially. NCI denotes assets that, after thorough evaluation, are deemed to lack significant cultural value. This classification allows for a clear distinction between cultural and non-cultural assets, ensuring that resources are directed towards the preservation of genuinely important CH. Since every category provides a piece of clear information about the importance of each element, each class was assigned a weighted value on its cultural importance.

The first, representing assets of unequivocal significance, is the DCI category which is recommended to potentially assign the highest value, equal to or close to unity, followed by OVCI which the suggested value corresponds to about half of the value assigned to DCI. Regarding UCI, no specific value is defined. This category houses assets with presumed cultural importance, yet their value remains indeterminate until a formal assessment is completed. Contrastingly, NCI is assigned a value of 0, highlighting their perceived lack of significant cultural value. To characterize areas with a unique value each element inside each zone could be summed. The cumulative values of assets within each category are amalgamated, resulting in a singular value for each region and providing a comprehensive understanding of the cultural significance within specific geographic areas.

The implemented method for evaluating the national-scale exposure of cultural assets stands out not only for its comprehensive approach but also for its inherent capacity to seamlessly connect the national and asset scales. This method serves as a bridge between macro and micro perspectives, providing a flexible framework that can be effectively applied at both scales.

4.2 CH on an urban scale

On an urban scale, the approach gets more detailed, as it is feasible to examine each cultural element within the urban landscape. Unlike the national-scale assessment, this method allows for a more focused understanding of the spatial positioning of cultural assets. This approach provides a finer level of detail and allows for a more granular exploration of different types of risks. Unlike a national assessment that might give a general overview of risks in an area, the urban scale helps identify diverse risks in different zones within the area. Additionally, the urban scale reveals how CH assets in an urban landscape are interconnected. This highlights the ripple effects of risks on multiple assets, emphasizing the need for a more sophisticated approach to risk analysis and mitigation within the dynamic and interdependent urban system.

Moreover, the evaluation of the exposed elements at the urban scale can be effective to start integrating CH tangible (such as, for example, the source of income generated by touristic activities connected to a particular monument) and intangible values (the social cohesion generated by places or monuments significant for the history of a given community). These intangible values emerge as a subjective component, where the community itself participates in the definition and attribution of meaning to its own CH, defining its identity function. Therefore, a holistic approach becomes essential here, with the aim of encouraging a more comprehensive analysis of the CH. Thus, here, traditional "top-down" context analyses should be integrated with community engagement processes (be they public institutions, local stakeholders or the citizens themselves), aiming at identifying the specific elements characterizing the CH of a specific territory. Communities can bring a deeper understanding of their local environment, the exposed elements, their vulnerabilities, and local hazards, also giving the opportunity to identify effective disaster risk reduction procedures and policies, tailored on community needs and priorities. Moreover, involving communities in decision-making processes can generate positive side-effects, such as empowering the community to take ownership of its well-being and CH elements, increasing the commitment of the community in designing and implementing Disaster Risk Reduction and Climate Change Adaptation (DRR/CCA) procedures and measures.

The engagement of a community requires a structured and rigorous approach, accurately considering some key points: i) the engagement of the target community should be integrated across all phases of the community-based project, spanning from its initiation to the final evaluation phase; ii) specific financial resources should be allocated to it; iii) the community-based process goals and objectives should be presented and discussed with the community in the very first phases of the project, specifically focusing on project outcomes useful for the community. Different tools and methods can be used to engage the local community to assess the CH exposed to disaster risks (e.g. workshops, field visit, transect walks, interviews, focus groups). For a more detailed description on community-based approaches in the DRR and CCA field and on the different tools and methods available to engage the population, the reference is the RETURN task 4.1 deliverable “Disaster Risk Reduction and Climate Change Adaptation: Advancing Community-Based Approaches, Community Trust, and their Effectiveness Evaluation”. The level of engagement of a community and the stakeholders to activate in the activities strictly depend on the dimension of the target municipalities. In big cities, engagement can focus on specific sectors stakeholders or on particular neighborhood, whereas, in very small towns, the community-based process can be aimed at the whole community.

4.3 CH at the asset scale

At the asset scale, it becomes essential to consider not only the tangible value but also the intrinsic and non-measurable value of cultural assets, going beyond purely economic analyses. A more detailed approach can be adopted by introducing different levels of evaluation is therefore necessary. For example, in the case of a museum, the assessment can go beyond counting ticket sales, extending to the consideration of the intrinsic value of the exhibited objects. The quantification of this value may involve not only the rarity or production cost of artifacts but also their historical, cultural, or artistic significance. Furthermore, it is possible to introduce a broader perspective by considering the symbolic value of the museum for the community or society.

The engagement of the local community becomes crucial at this scale, giving the opportunity to have a comprehensive picture of the CH, taking into consideration a plurality of tangible and intangible dimensions, but also increasing the awareness of the local community on risks and possible coping procedures and strategies.

5 Biosphere reserves

Biosphere reserves (BRs) are "learning places for sustainable development", sites for testing interdisciplinary approaches to understanding and managing changes and interactions between social and ecological systems, including conflict prevention and management of biodiversity (UNESCO, 2024). BRs implement a zoning approach. Each BR consists of three zones with different functions and degrees of protection: (1) the core area focusing on strict protection and conservation of biodiversity, (2) adjacent buffer zones which allow for ecologically sound activities such as environmental education and training with respect to local knowledge and traditions and limited human interference, and (3) the transition area with least restrictions for sustainable ecosystem service use and socio-culturally sustainable economic and human activity (Price et al., 2010; Palliwoda et al., 2021).

Risk assessment in BRs requires a tailored methodology because of two main reasons. First, considering the typical areal extension of BRs, they fit somewhere between the national and the urban scale, thus framing the problem into a very specific scale of analysis that can be called "regional" and which, in an extension scale from national to urban, is closer to the urban end. Second, BRs can be considered complex elements composed of a multitude of sub-elements, each with its own specific vulnerability to different hazards.

As a consequence, a holistic approach, largely based on the methods used in Environmental Impact Assessment and Strategic Environmental Assessment studies, is proposed here as an original methodology.

On a first step, the BR is de-structured into its main natural elements, for instance: fauna, vegetation, habitat, landscape. If necessary, some of these elements can be further subdivided into sub-elements. E.g., in peculiar settings it may be suitable not to analyse the vegetation as a whole, rather to distinguish between two or more groups of species that may have a very different ecological value (e.g. endemic or endangered species may be valued more than other species) or a very different vulnerability to the same hazards. The elements defined are possible targets of the hazardous processes, which are analysed in the next step. To define such processes, it is necessary to take into account the physical setting of the area where the BR is situated. The expected impacting natural and anthropic processes that may evolve into a relevant magnitude are then listed, resorting to expert judgment and with evidence coming from hazard and intensity maps. These maps can be thematic maps from national or regional datasets or may be obtained from products of research projects (see DV 7.3.6 Multi-scale MR assessment Proof of Concept within RETURN project). For instance, in the Po delta in Italy, landslides and volcanic activity would not be listed since the hazard for these two types of risk is zero, while floods should be (at least preliminary) selected. It is necessary to include in this list also some possible multi-hazards. Building on the example above, floods may lead to environmental pollution (pollutants transported by the flood and released in the flooded areas).

Once the list of targets and hazards is complete, they are organized in a matrix highlighting all the possible interactions between hazardous events and targets. Taking into account the typical magnitude expected for the hazardous processes, the table will be filled for each target/hazard intersection, to differentiate between the target/hazard couples that may lead to significant impacts on the target and those who are not. Only the positive occurrences will be further evaluated. In other words, this step of the procedure identifies the BR elements that are exposed and vulnerable to certain hazards of a given magnitude, possibly assigning an expected degree of loss of that element.

The consideration of the exposure is very peculiar when evaluating BRs, as most of their components are by definition intangible or not-monetizable. Therefore, we propose an absence/presence approach, where the exposure ranges from 0 (absence) to 1 (presence) and can be further graded according to the "ecological value" of the zone of the BR where the element is located: it may be 1 in the core areas, 0.66 in the transition zones, and

0.33 in the buffer zones (such coefficients are just an example and may be adjusted according to the specific element/hazard of given intensity at hand).

This procedure can be also considered an overall evaluation to set priorities and to identify the elements most exposed to certain risks. Such circumstances may undergo more thorough analyses, which involve detailed and specific studies.

6 Risk maps

There are three approaches to obtain the total risk:

- Qualitative: based on risk classes categorized by expert judgment; **risk classes** are defined, like high, moderate and low.
- Semi-quantitative: based on ranking and weights assignments by a given criteria; a dimensionless **risk index** is defined as ranked scores, for example from 0 to 10.
- Quantitative: based on probability or percentage of losses expected; a **risk value** is defined as a probabilistic value (0-1) over certain amount of monetary loss.

The quantitative approach is more common in the scientific literature, although most of them are based on a large amount of assumptions and simplifications due to scarcely available data (Castellanos Abella, 2008).

The qualitative method relies on experts' judgement, categorizing risk areas as "very high", "high", "moderate", "low", and "very low2. While the number of qualitative classes may vary, typically three to five classes are considered, since each must translate into practical actions. Fell (1994) proposed terminology definitions for qualitative risk assessment considering classes for magnitude, probability, hazard, vulnerability and specific risk. Qualitative approaches are more commonly applied at national or regional levels as in these scales the quantitative variables are not available or they need to be generalized. The Australian Geomechanics Society and the Sub-committee on Landslide Risk Management (AGS, 2000) proposed a contingency matrix to define the risk starting from qualitative definitions of the hazard/susceptibility (here defined as "likelihood") and the consequences (derived from the combination of vulnerability and value of the elements at risk) (Table 3). Although being defined for landslides, this table is easily exportable for any other type of risk.

Table 3. Qualitative risk analysis matrix – level of risk to property (AGS, 2000). VH: Very High, H: High, M: Moderate, L: Low and VL: Very Low risk.

Likelihood			**Consequences**		
	Catastrophic	Major	Medium	Minor	Insignificant
Almost certain	VH	VH	H	H	M
Likely	VH	H	H	M	L-M
Possible	H	H	M	L-M	VL-L
Unlikely	M-H	M	L-M	VL-L	VL
Rare	M-L	L-M	VL-L	VL	VL
Not Credible	VL	VL	VL	VL	VL

In semi-quantitative approaches scores are assigned to each component of the risk equation so that the results are numerical outcomes with no physical meaning instead of qualitative classifications. Semi-quantitative risk assessments are useful as an initial screening tool to pinpoint hazards and risks; when the perceived risk level does not warrant extensive time and effort; and in situations where obtaining numerical data is constrained (AGS, 2000). Such methods are mostly used at national to urban scale.

Quantitative risk assessment (QRA) consists in the computation of each component of the risk equation that are then multiplied. This method combines the probabilistic interpretation of the hazard with the value and vulnerability of the elements at risk.

The multi-risk approach introduced more complexity since it requires the aggregation of different risks (Gallina et al., 2016). Multi-risk modelling had been defined by Schmidt et al (2011) as the "quantitative estimation of the spatial distributions of potential losses for an area (a confined spatial domain), multiple (ideally all) natural hazards, multiple (ideally a continuum of) event probabilities (return periods), multiple (ideally all) human assets, and multiple potential loss components (for each of the assets, e.g. buildings, streets, people, etc.)".

The single risks within a multi-risk assessment are computed using a common unit of measure (e.g. loss of lives, economic losses, 0–1 normalization) to allow for a direct comparison and aggregation among different kinds of risk (van Westen et al., 2002).

The comparison of quantitative risks is much easier than the comparison of hazards as the single risks can be expressed in hazard-independent units but in damage. However, a general analysis framework defining which parameter to compare is needed (Kappes et al., 2012). This framework can be qualitative (classification), semiquantitative (indices), or quantitative (monetary values, probabilities, etc.). Finally, the issue of hazard interactions resulting in amplified risk or differing patterns has to be considered.

A prerequisite for multi-risk analysis is that the spatial resolution and the elements at risk dataset are the same for all the risks.

Importantly, the multi-risk mapping should keep available and visible the risk level of each single type of risk. In the long-term planning hits is useful to provide information to the decision-makers about what kinds of interventions are needed and to set priorities; in the short-term risk management (during emergencies) this helps to focus on the specific risk that is undergoing a paroxysmal phase, while keeping the possibility to check for cascade effects by consulting the multi-risk analysis.

7 Remarks on the volcanic risk

Multiscale volcanic risk mapping faces issues that are specific to this type of risk. Two main characteristics set volcanic risk apart from landslide, flood and earthquake risk:

- multi-risk nature: the volcanic risk is potentially more multi-faceted than the other risks treated here. The UNDRR (2021) identifies as many as 12 risks (volcanogenic risks) that can be caused by volcanic activity, and which are shortly discussed below. Therefore, each different volcanogenic risk requires a separate procedure which, in the case of lahars, volcanic triggered landslides and volcanic earthquakes can be the same described in this document.
- Spatial nature: this characteristic is particularly clear for a Country like Italy, where landslides, floods and earthquakes are well spread all over the national territory and, while not being strictly ubiquitous, are so diffused to make national mapping reasonable. On the other hand, volcanic risk exists only in the surrounding (within a range of some km) of active volcanoes, which are concentrated in well-known areas of the world. Therefore, the scale ranges from regional to asset for some types of volcanogenic risks and from urban to asset for others.

The volcanogenic risks identified by the UNDRR (2021), excluding the lightning risk which is not relevant to CH risk, have been clustered for our purposes as follows:

- Lava flows: are outpourings of fluid, relatively low-viscosity molten rock (Kilburn, 2015). Most volcanoes erupt lava flows and/or domes during their lifetimes (Kilburn, 2015). Effusions of lava commonly continue from days to months, but occasionally for decades. Lava flows damage and destroy land and property but usually advance slowly enough for populations to escape. Understanding where future lava may be erupted from (the vent or vents), how far a lava flow may advance, the velocity of the flow front and the area that may be covered are critical for hazard assessments (Kilburn, 2015). Lava flows tend to be channelled by the topography. Typically, basaltic lava flows may reach lengths of 1–10 km; intermediate and silicic lavas are usually shorter in length, typically up to 5 km but some are up to 15 km. Hazard models should include an analysis to establish the expected areal probability of future vent opening (mainly based on volcanological and structural geology data) , followed by an estimation of the areas of inundation by lavas flowing from those vents (e.g., Connor et al., 2012). In general, given the relatively short travel distance of lava flows and their recurrence, cultural heritage assets are not easily found along the way of a lava flow. On the national scale, the presence of large active volcanoes like Mt Etna or Mt Vesuvius, characterized by important effusive activity, very close to densely inhabited areas with a long history of civilization prompts for the analysis of this risk.
- Tephra fall: tephra is a collective term for fragmented magma and old (i.e., preexisting) rocks ejected into the atmosphere from volcanic vents during an explosive eruption. Tephra can be classified as ashes, lapilli or blocks and bombs depending on the clasts size. Along with emissions of gas, tephra is the most frequent and widespread volcanic hazard. It is ejected into the atmosphere and transported laterally by wind and/or lateral gravitational spreading of umbrella clouds before falling out under gravity. Depending on the intensity of the eruption, tephra can affect very large areas; volcanic ash can remain airborne for days and can be transported for thousands of kilometres. The accumulation of tephra on roofs can cause their collapse; a loading of 300 kg/m^2 is expected to result in significant (>80%) damage of weak flat wooden, reinforced concrete and steel roofs (Costa et al., 2009), and a loading of 400 kN/m^2 to cause the collapse of the 42% of common residential buildings (Pareschi et al., 2000; Orsi et al., 2004; Zuccaro et al., 2008). Other effects on cultural sites can also derive from deposition of thin ash layers, which could produce damages for example to pictorial surfaces or also heavily impact the accessibility of important cultural sites.

Depending on the intensity and magnitude of an eruption such loadings can occur over areas with a radius from some km to some tens of km (Jenkins et al., 2015). The thickness of tephra and therefore the loading depends more on the duration of the eruption. Probabilistic tephra fallout hazard maps are obtained through the numerical simulation of the dispersal and sedimentation of airborne tephra: input data are generally the expected ranges (in the form of a probabilistic distribution functions) of erupted volume and column heights, together with a multi-year statistic of atmospheric data (mainly values of wind direction and velocity with height). Hazard maps generally show the areal probability of overcoming a fixed threshold of mass loading at the ground (e.g. 300 kg/m^2), or the areal distribution of mass loading at the ground for a fixed probability threshold. Building vulnerability is mainly dependant on the type of roof, which represents therefore the crucial characteristic to be investigated at urban and asset scale. Fallout of thin (centimetric to millimetric) ash layers and their following remobilization by natural and anthropic agents can have an important impact over large areas (up to hundreds of km^2 for the eruption scenarios presently expected for future events at some Italian volcanoes). Focussed vulnerability studies should be addressed to evaluate the expected impacts.

- Ballistics: Ballistics comprise fragments of magma and old (i.e., pre-existing) rocks ejected during an explosive eruption at variable velocity and angle on cannon ball-like trajectories (UNDRR, 2021). Ballistics may be a few centimetres to several metres in diameter. In most cases, the range of ballistics is a few hundred metres to 5 km, but they can be thrown to distances over 10 km in the most powerful explosions (Blong, 1984). The high kinetic energies of ballistics when they land makes them hazardous to cultural heritage; their terminal velocity is typically <150 m/s, so their impact energy is strongly controlled by their size and density. They may retain sufficient thermal energy on landing to burn certain building materials. Even more than lava flows, ballistics interest a small area, generally not much populated by cultural heritage assets except for specific volcanoes, like for example Vesuvius or Campi Flegrei, highly inhabited even in proximity (from hundreds of meters to few km) from the vent. While ballistics hazard scales to a minor hazard during most eruptions (for which other, more impacting phenomena are present), this can be important in case of low intensity magmatic activity or phreatic explosions at volcanic fields like, e.g., Campi Flegrei.
- Pyroclastic density current (PDC): Pyroclastic density currents are hot, fast-moving mixtures of volcanic particles and gas that flow according to their density relative to the surrounding medium and the Earth's gravity. They typically originate from the gravitational collapse of explosive eruption columns, lava domes or lava-flow fronts, and from explosive lateral blasts (UNDRR, 2021). Because of their high density, velocity (tens to hundreds of km/h), temperature (200-600 °C) and runout (from few to tens of km) PDCs are highly destructive. Risk to building structures has not been systematically assessed but dense PDCs can bury buildings and destroy their openings (windows, doors) and, in dilute PDCs, dynamic pressures of a few kPa can cause moderate to heavy damage to buildings (Valentine, 1998; Zuccaro et al., 2008). Therefore, the openings of a building are a critical feature to be characterized at asset scale, also at distances close to the maximum runout of PDC. Other hazards related to PDCs in inhabited areas are related to the effects of infiltration of ash and hot gases into closed environments also through not damaged openings , which can rapidly bring to a high T, ash-charged, not-respirable atmosphere with high risk for buildings and their occupants (Spence et al. 2004; 2007) The rapid increase of temperature inside closed environments, also in the absence of important damages to structures or openings and even in case of an early evacuation of their occupants, should be so considered as an additional important impacting factor for historical buildings or museums.
- Lahars and landslides: Lahars are discrete, rapid, gravity-driven, water-saturated flows containing water and solid particles of volcanic rock, sediment, ice, wood, and other debris that originate at volcanoes (Gudmundsson, 2015; Vallance and Iverson, 2015). They share similarities with debris flows, so the methods to calculate the vulnerability of CH to lahars can be derived by the method described in this document for debris flows. Lahars can be extremely mobile, flowing at high speeds on steep volcanic terrains and for long

distances (tens of kilometres) along valleys, as they are typically topographically confined flows, so existing channel networks often control the dominant flow routing. Secondary lahars, that is those that occur due to the remobilisation of erupted pyroclastic deposits, often during intense and/or long-lasting rainfall, even years after an eruption, can be considered debris flow concerning risk mapping, provided that the presence of newly deposited, potentially unstable and generally loose material is addressed during the landslide susceptibility analysis. Ground shaking caused by volcanic eruptions and the explosions themselves can cause other types of landslides, like rock avalanches, also favoured by the generally steep slopes of volcanic edifices.

- Volcanic earthquake: volcanic eruptions can cause earthquakes. Most of the recommendations described in this document are valid for volcanic earthquakes as well. Typically, volcanic earthquakes do not exceed magnitude 3-4, although during the 20th century a few events close to M 6 were recorded (McNutt and Roman, 2015). Volcanic earthquakes are typically shallow (<5km of hypocentre depth), which can increase local effects at surface. Instrumental measures of shaking include peak ground velocity (PGV) and peak ground acceleration (PGA). Although it has been found that earthquake damage is much more closely correlated with PGV than with PGA (Wu et al., 2003), PGA continues to be the more used of these parameters. An commonly used relationship between intensity and PGA and PGV (Wald et al., 2019) suggests that shaking below 0.0005 g or 0.002 m/s will not be felt and that above 0.4 g or 0.4 m/s structural damage can be expected. In many cases, PGA attenuation is very rapid around the epicentre. Cumulative effects of repeated ground shaking with other independent eruption processes (overload of tephra over buildings, effects of PDCs, etc.) can increase the vulnerability of buildings, and should be taken in consideration (Zuccaro et al., 2018).
- Volcanic gases and aerosols: Volcanic gas includes any gas-phase substance that is emitted by volcanic or volcanic-geothermal activity. Volcanic aerosols include liquid or solid particles that are small enough to be suspended in the air, and that are emitted by volcanic or volcanic-geothermal activity (UNDRR, 2021). Typically, the most abundant volcanic gas is water vapour (80% or more of the gas mass). Other common gases are carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrogen sulphide (H_2S), hydrogen chloride (HCl) and hydrogen fluoride (HF) (UNDRR, 2021). The abundance of emitted volcanic gases and aerosol varies greatly among eruptions. Recent large eruptions of Holuhraun in Iceland 2014–2015 and Kīlauea Hawaii in 2018, emitted as much SO_2 per day as anthropogenic activities in China (50–200 kt/day) over several months (Pfeffer et al., 2018; Kern et al., 2020). There are tens, or potentially hundreds, of volcanoes worldwide which emit smaller amounts of SO_2 (0.5–5 kt/day) (Carn et al., 2016) but sustain the emissions over years-to-decades (e.g., Mount Etna; Aiuppa et al., 2008) and over areas of about 100 km. This means that this phenomenon can be assimilated to air degradation, where the threshold for air concentration of pollutants for CH is generally than the threshold considered for human health safety. Large areas in highly inhabited volcanic fields, like Campi Flegrei or other extinct/dormant Italian volcanoes, are subject to an intense diffuse CO2 degassing from soil, which can locally expose buildings and cultural heritage to an important localized risk (for example in basements or subterranean archaeological areas) also during periods of unrest, not directly related to eruptions.
- Tsunami: a tsunami is a series of waves created when water surrounding a volcano is displaced following an eruption, a landslide, or failure of a volcanic edifice into surrounding water. In Italy, small volcanic tsunamis have been recently caused by Stromboli volcano in 2002 (Tinti et al., 2006). Cultural heritage located along the coasts, within 1-12 m (at least considering recent tsunamis in Italy) above sea level and within a few tens of km from the volcano are potentially exposed to tsunami risk. Larger areas could be at considerable risk in case of landsliding of large sectors of volcanic islands or of submarine volcanic complexes. Damage and destruction from tsunamis are the direct result of three factors: inundation, wave impact on structures, and erosion. Tsunami associated wave forces have demolished frame buildings, openings, and other structures. Considerable damage is also caused by floating debris, including boats, cars,

and trees. Strong tsunami-induced currents have led to the erosion of foundations and the collapse of bridges and seawalls. Damage can also derive from deposition of sediments over inundated areas and saltwater flooding.

- Fire: triggers from volcanic eruptions include lava flows, pyroclastic density currents, tephra, and ground shaking, therefore the area of this type of risk depends on the specific trigger, described above. Showers of coarse ballistic projectiles can also trigger fires. This phenomenon commonly affects the vegetation close to the volcanic vents, so it must be considered for biosphere reserves in volcanic environments.
- Subsidence and uplift: uplift and subsidence may occur before, during and after volcanic eruptions (Dzurisin, 2007). Uplift is typically associated with pressurisation ("inflation") of a shallow (few kilometres below the surface) magmatic or hydrothermal system, caused by direct injection of magma or by advection of magmatic fluids and heat. Subsidence is associated with depressurisation ("deflation") of a magmatic/hydrothermal system and may be caused by magma cooling and solidification, outflow of magma or general fluid pressure relaxation by increased permeability or fluid migration. A famous case affecting cultural heritage is the Roman settlements at Campi Flegrei in Italy (Vitale and Natale, 2023). The Campi Flegrei caldera is 12 km across and lies under the outskirts of Naples. Up to 19 m of cumulative uplift were recorded in the area of Pozzuoli in the two years preceding the last eruption at Campi Flegrei in 1538, resulting in the seaward retreat of the shoreline by '200 paces' (Di Vito et al., 2016). Campi Flegrei experienced major uplifts in 1950–1951, 1969–1972 and 1982–1984 which cumulatively raised the town of Pozzuoli by 4 m. Pozzuoli experienced a maximum of 1.8 m of uplift during unrest in 1982–1984 (Berrino et al., 1984). This phenomenon generally takes place at urban-asset scale so, similarly to landslides, satellite technologies such as InSAR have the potential to make a significant contribution to volcano ground deformation monitoring. Damage can be caused to buildings (Pingue et al., 2011); most damage during unrest at Campi Flegrei in 1982–1984 occurred within 2 km of the centre of uplift where total vertical movement exceeded about 60% of its maximum value of about 1.8 m (Barberi et al., 1984; Berrino et al., 1984; Charlton et al., 2020). After a period of subsidence, uplift restarted again in 2005, and the ground level in the area of Pozzuoli at the end of 2013 exceeded the maximum level reached in 1984 by about 20 cm.

8 Multiscale approach

The scientific literature concerning multiscale approaches is somewhat lacking; a limited number of studies can be found concerning multiscale risk and CH for a specific risk (Sammartano et al., 2023) or multiscale and multi-risk together for an element at risk (Maragno et al., 2021), but papers addressing multiscale and multi-risk approaches for CH are completely missing. It has been noted that misunderstandings can arise from applying the same scale definitions using assessment frameworks from countries with different natural and political-management characteristics, since the extension and number of administrative units and the population density can change considerably from one Country to another (Castellanos Abella, 2008).

The scales covered in these guidelines range from national (ranging from a few tens of thousands to a few hundreds of thousands of km^2), to regional (one or more biosphere reserves), to urban (a single city or city centre, generally ranging from around 1 km^2 up to a few tens of km^2), to asset scale, which can be a monument (like an arch, a statue, a fountain), a building (like a palace, a church, a museum), or a complex (like a monastic complex composed of a church, a bell tower, a cloister, and a monastery). However, as detailed below, the real distinction between scales is not as much quantitative as it is qualitative; that is, the scale is not a measure of the extension of an area but of the depth, amount, accuracy and spatial resolution of the information available for that area, although these two parameters – extension and information quality – are generally correlated.

Another way to define the scales can be strictly Country-specific and be administration-oriented. In this case the scales correspond to different administrative levels existing in a national government structure. The advantage of this approach is that it provides products that are immediately translated for a practical use. The drawback is that changes in the administrative level my not correspond to actual changes in the data available and vice versa, as generally administrative boundaries do not correspond to dataset boundaries; for example, different sub-parts of the same administrative unit could be available at different detail levels but must be flattened to the worse quality dataset for homogenization. In other cases, two different scales could be redundant if the data available are the same even at different administrative levels. Therefore, the correspondence between a risk map and the boundaries of public administrations is important, but it is not necessary for them to match exactly.

What is certain is that, whether the definition of the different scales, each scale requires a different treatment. The differences lie both in the rendition (that is how the final output map is rendered and at what resolution) and in the initial dataset (that is the quality and quantity of input information available for all the components of the risk equation).

8.1 Rendering

Concerning the output, the scale can define if a map is represented using raster or vector layers, the general rule being that larger scales (higher detail) are more conveniently represented with vectors, although many reasons can determine differently. For example, at the national scale a map can be a raster, that is a matrix of pixels where the resolution cell can be defined by a square element (1 km x 1 km); the resolution can depend on the original resolution of the data used as input; the lowest resolution among all the input data is the bottleneck for the output. Another possible representation at this scale is as a polygonal vector map where the minimum resolution element can be the territory of a single municipality. In general, the resolution cell at national scale (either a pixel or a polygon) can contain more than then one CH asset and as many as hundreds. Therefore, in this case the resolution cell shows a single risk value valid for all the assets included.

At the urban scale the raster rendering becomes less fitting; in fact, a raster is a spatially continuous representation of a territory, however, since at this scale a detailed knowledge of the location and extension of the single CH assets is possible, that is an element at risk is discretely visible as a vector point or polygon, it is useful to exclude from the mapping all those areas that have no CH relevance. A raster representation is still possible, using grids with the appropriate cell size (in the order of 1 to 10 m) and showing no data for the locations with no asset's presence. At this scale each asset is characterized by its own risk value.

Still focusing on the output of a multi-risk map, at the asset scale an element at risk can be assessed as a 3D object. The minimum resolution element can be the asset as a whole (in which case it can be represented as a polygonal vector or as a solid) or a raster representation can be used to differentiate the risk values between distinct parts of the same asset.

8.2 Initial dataset

As anticipated, also the input of a multi-risk map depends on the scale; in fact, while moving across scales, not only does the spatial resolution (the output) change, but also the level of detail in the knowledge of the hazard/susceptibility, vulnerability and exposure components.

Moreover, moving from one scale to another implies to define a direction, which can be from national to asset scale or viceversa. In the former case, upscaling maps is not just a matter of redistributing hazard parameters in space, but it requires to deepen some aspects and adjust modelling approaches. The main aspects of hazard/susceptibility are:

- Resolution of digital terrain models (DTM). DTMs typically span from cell sizes of ca. 1 km to 1 m. A higher detail enables to consider morphological peculiarities which might affect hazard, like the topography influencing the drainage (for the flood risk), relief affecting seismic amplification, or geomorphological features indicating the boundaries of a landslide.
- Monitoring data. Climatic data can be available at continental scale, like remotely sensed Copernicus products, at a coarse resolution; to upscale, on-site sensors like rain gauges are needed. Displacement data obtained from satellite interferometry are not well versed for asset scale investigations, where on site instruments like total stations, ground-based interferometers, crackmeters etc. are more suitable, but they are suitable for both the urban scale. At the national scale their spatial resolution is so high that data clustering and aggregation can be necessary.
- Description of anthropogenic features. The presence of infrastructures, also designed for risk mitigation, cannot be fully described at national scale; for example, bridges or levees for floods and retaining walls for landslides are not captured by hazard models unless they are conceived at urban or asset scale.

The vulnerability also changes from national to asset scale:

- Structural information. At the national scale the information available for cultural heritage assets is hardly homogeneous, therefore any consideration must be based on parameters that are known for each asset, like possibly the position and the type of asset (church, museum, monument etc.). The asset scale can benefit from more information about the element at risk, like the way it is constructed, the material, the time period, the state of preservation. For example, concerning the earthquake risk, the natural frequencies and modal shapes, the mechanical behavior of the materials and construction techniques of a building can be evaluated, while for the landslide risk the depth of the foundations, the behavior of the building under settlements and the presence of past damages on the structure can be assessed.
- Geometrical information. While at the national scale an asset can be represented as a point, at the urban scale it can be shown as a polygon; as such it is possible to assess if its area is totally or partially exposed to

a hazard. Moreover, at the asset scale it can be characterized by a three-dimensional model. For example, considering the flood risk, this allows to determine the height, number and location of openings of a building, and to intersect this information with the predicted height of the water level at that particular side of the building, both information that are not available when evaluating the risk at a different scale. Furthermore, at the asset scale an element at risk can be characterize in all of its parts, that can be assessed separately.

Similarly, also the exposure:

- Elements at risk dataset. CH datasets are different according to the scale of analysis. At national level databases are generally created by national institutions, whereas at larger scale local institutions can provide more databases with specific information and different priorities among the assets.
- Value assessments. At the national scale exposure can be classified based on the number of CH assets within an area, and use this density to distinguish between more or less exposed territories. At the urban scale the aggregation is no longer necessary and specific evaluations become possible and even more so at the asset scale. Such evaluations can include the economic estimate of the asset, the income generated from it, or other types of value (symbolic, historical, artistic etc.). This means that the asset scale enables and even requires completely different methodological approaches with respect to the national one.

In general, the upscaling can be simplified as a process of acquiring more and more detailed information and changing data elaboration approaches consequently. The new information collection can just be gathering more data to be added to what is known at a smaller scale or it can translate into completely dismiss a dataset and acquire a new one. It is impossible to set precise boundaries between the different scales and in any case such boundaries would be more based on the “depth” of a dataset rather than its area extension. Although seemingly counterintuitive, it is apparent by considering a dataset containing coarse a basic information at the national scale, which can be spatially subsampled to obtain the extension of a city or a building, without making it more suitable for an urban or asset scale mapping.

Concerning the passage from the asset to the national scale, it can be largely deduced as the inverse process of the above, with some issues to be aware of, since the downscaling is not just a mere data aggregation. For example, food hazard maps developed at urban/asset scale according to the Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (“floods directive”) are merged together to obtain a national picture of flood hazard; however each portion has been obtained according to different modelling approaches (e.g. 1D, 2D, coupled 1D-2D), hydrodynamic methods, and spatial resolution. Upscaling these hazard maps to a single national scale information bears uncertainties which should be acknowledged and understood.

Downscaling exposure and vulnerability information would be possible only if the same type of attributes would be available for locally built datasets. On the contrary merging inconsistent multiple local datasets would make it impossible to adopt a common approach at national scale unless a common baseline which intersects geographic attributes is found.

In conclusion, the outputs at the different scales are obtained from different input and methods. Consequently, the risk value calculated at the national scale and referred to a specific city is not necessarily the same as the average risk value of all the CH assets in that city calculated at the asset scale, unless for that city a thorough and detailed investigation has been performed for all the assets. In the hypothetical case of a dataset with asset-level details available for every single asset of a country, a national scale map would just be the spatial average of large-scale risk values and the difference between the scales would just be concerning the representation.

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