

Virtual testbed for multi-risk assessment: defining RETURNVILLES to support the analysis and testing of DRM and CCA solutions in realistic urban contexts

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ABSTRACT

Urban areas may be considered as hotspots for disaster risk. The intrinsic complexity and interdependency of urban systems in a multi-risk framework call for integrated, system-based approaches to understand and model multi-risk processes and to support effective Disaster Risk Management (DRM) and Climate Change Adaptation (CCA) strategies.

In this context, Virtual Testbeds (VTBs) have emerged as effective instruments for the development, benchmarking, and testing of quantitative community resilience and multi-risk assessment methodologies. VTBs are explicitly designed to enable controlled experimentation, stress-testing, and exploration of possible present or future risk scenarios through simulation.

This paper presents the development of two imaginary, yet realistic urban Virtual Testbeds created within the RETURN project. The proposed VTBs represent typical Italian urban settlements: a coastal RETURNVILLE, RV1, and an inland, intra-mountainous town, inland RETURNVILLE, RV2. Their structural foundation is derived from a hybrid approach that combines urban components from real cities to ensure realism while avoiding sensitivity and data-access constraints. The paper describes the GIS-based exposure datasets forming the operational backend for hazard and risk simulations. Moreover, with the aim to illustrate a possible approach for investigating complex multi-risk scenarios instantiated for the VTB, the conceptual framework for a bottom-up multi-risk assessment methodology, based on risk storylines and impact chains, is presented. The proposed framework may be used for testing of DRM and CCA strategies through

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what-if scenarios, supporting decision-makers for the assessment of the potential consequence of actions (e.g. reducing the impacts) according to alternative design scenarios towards a holistic, transferable, and policy-relevant urban resilience analysis.

1. Introduction

Urban and metropolitan settlements host large part of the world population, with more than 55% of the world population living in an urban environment in 2018 [1] and a forecast increase of 68% by 2050; the percentage of the European population living in cities, towns, and suburbs is even higher and up to 72% according to estimates of the European Environment Agency [2]. Due to the agglomeration of people, infrastructure and assets, urban expansion, and inadequate management, urban areas concentrate disaster risk [3]; also, considering the inherent complexity and interconnection of the systems and sub-systems forming a city, urban areas emerge as hotspots for multi-risk and impact amplification, even further exacerbated by intensification of extreme weather-related phenomena due to climate change. The multi-risk analysis entails the assessment, in the same geographic area, of the overall risk arising from a series of possible adverse events and their interactions with the different specific vulnerabilities of the exposed elements [4]; considering the hazard interactions and possible cascade effects and impacts in complex interconnected systems the overall risk may be amplified.

Hence, there is an urgent need to understanding and modelling multi-risk in urban areas, supporting most effective Disaster Risk Management (DRM) as well as Climate Change Adaptation (CCA) strategies for cities.

The evaluation of city phenomena as well as risk and multi-risk conditions at the city scale, towards enhancement of community resilience and sustainability, requires interdisciplinary systems-based approaches depending on many disciplines, including engineering and socioeconomic and information sciences. When integration is key to improving simulations, a number of management, social, and technical barriers arise [5]; barriers such as model complexity, user friendliness, administrative fragmentation, and communication have restrained the effective implementation of integrated models.

As a result, the development of methodological approaches and tools to measure performance and resilience at the community level has begun quite recently and it still requires much implementation efforts. In the last decade, a number of community resilience initiatives were launched, including [6], [7], [8], [9]. Among the proposed approaches, those based on quantitative based simulations, particularly stemming from the engineering fields, are progressing towards the understanding of the interrelationships between physical and social infrastructure systems that determine community resilience and are supposed to facilitate resilience planning and risk communication among stakeholders [7].

In the framework of quantitative based community resilience analysis, the Virtual Testbeds (VTB) have revealed as effective tools to benchmark the development and preliminary testing of community resilience algorithms. Such virtual cities are useful tools for both the management and administration of cities, and for the study of socioeconomic phenomena, supporting through simulations the planners and administrators in the evaluation of both existing and future city policies [10].

Amin Enderami et al. [11] define Virtual testbeds (VTB) as “an environment with enough supporting architecture and metadata to be representative of one or more systems such that the testbed can be used to design experiments, examine model or system integration, and test theories”.

VTBs for a city are different from City Information Modeling (CIM) and from urban digital twins. CIM typically represent a structured 3D digital model of a city that integrates spatial and semantic data (GIS, geographic information system + BIM, Building Information Modeling) to provide a semantically enriched, spatially explicit representation of the urban environment [12]. The main purpose is to support urban planning and infrastructure coordination for real cities and in static mode. Using CIM as a structural foundation, urban digital twins extend it by introducing real-time data streaming and the use of IoT (Internet of Things) sensors as well as behavioral modeling to facilitate monitoring and control towards operational decision support in a dynamic framework (see e.g. Refs. [13], [14]; as well as the review proposed in Ref. [15]); data layers and simulation models in urban digital twins are often connected in a pragmatic manner when they become available for technical connection and implementation, therefore ensuring effective integration only locally without a holistic view.

While CIM and urban digital twins are based on reality and are supposed to represent the ground truth, the VTB, that may be based on reality or imaginary as discussed next, are explicitly designed to perform experiments and stress-tests as well as explore future conditions through the use of digital simulations. VTBs are designed to represent communities with digital simulation on a computer network, and the simulated community may be imaginary or real. Considering real-world communities (RWC) as the base for simulation of a VTB has the advantage of allowing to mirror the real conditions of the county as best as possible and, when available, to use real damage data and reports to validate the testbeds model as for the case of Joplin tornado [16], [17], [18], Galveston for hurricane-induced hazards [8] or Gilroy for earthquakes [19]. As a drawback, VTB based on real communities, often needing a large amount of data and analytical power, may be limited in use due to restrictions imposed for security or business reasons by service providers feeding required data or to avoid sensitivity problems to real communities potentially harmed by hazardous events.

The level of detail of the data for analysis and representation in VTBs may vary according to the purposes and extent of the VTB. For example, with reference to the building inventory, it ranges from the coarsest typological characterization at the level of census tracts or larger sub-areas (e.g. Refs. [19], [20]) to a more detailed level that can go up to the building by building definition [21], [22].

Imaginary (IM) VTB can be entirely fabricated, including all required data. They are commonly used when data availability is limited or when research aims to be broadly applicable to regions with similar geography, population, and infrastructure. Imaginary

testbeds can be easily modified for simplicity and convenience. For instance, researchers can first test a simplified version with only a few dozen components for more manageable analysis and verification before scaling up to a larger testbed. Imaginary testbeds are also advantageous in scenarios where security is a concern or when the sensitivity of outcomes requires added discretion.

A comprehensive review of both RWC based and IM VTB developed over the last decades is reported in Amin Enderami et al. [11].

Examples of IM VTBs are Centerville [7], representing a middle-class Midwestern State city in the US with a population of about 50,000, or Benchmark city [9], based on a common mid-size city located in the southeastern coastal region of China. Both cities are designed to represent typical settlements for the respective countries. For example, Centerville, that is approximately rectangular in shape and covering an area of about 104 km², is formed by seven residential neighborhoods, from high-income/low-density to low-income residential areas and a mobile home park is also included close to an industrial area, as typical in many Midwestern cities for United States. As for Benchmark city, it consists of 5 city zones that mimic the demographics, site conditions, and potential hazard exposure of a medium-sized city in the in southern China; in particular, it includes 14 residential areas as well as business zone, industrial park, government agencies, schools, hospitals, and physical lifeline systems, covering an area of approximately 344 km².

Moreover, Tomorrowville [23] developed within the Tomorrow-cities project and representing a Global South urban setting based on Nairobi (Kenya) and Kathmandu (Nepal) contexts, is a VTB designed with the purpose of providing a basis for risk-informed decision making in future urban planning and design.

The extended partnership RETURN - multi-Risk sciEnce for resilienT commUnities under a changiNg climate - financed by NEXTGEN-EU, has within its objectives to achieve a better understanding of environmental, natural, and anthropogenic risks, as well as their interrelation with the effects of climate change. Starting from updated assessments of both natural and anthropogenic hazards, RETURN aims to develop strategies for the mitigation and adaptation of climate and environmental risks. This objective is pursued through the advancement of methodologies for development of quantitative risk scenarios, while also integrating the modeling and evaluation of social and economic impacts. In particular, the Spoke TS1 'Urban and Metropolitan Settlements' of RETURN aims to develop a framework for the holistic understanding and modelling multi-risk in urban and metropolitan areas. Moreover, TS1 aims to harmonize approaches to Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA) to enable synergistic mitigation and adaptation strategies within a comprehensive risk management framework tailored to urban and metropolitan areas, with the overarching objective to enhance resilience and integrate sustainable climate neutrality. In this context, it is chosen to model an imaginary virtual testbed, but based on real case studies cities, as an instrument to allow testing and chaining hazard and risk simulation algorithms developed within the broader scopes of RETURN. The scope of such VTBs is to realize a virtual digital representation of urban settlements allowing to instantiate the simulation of multi-risk processes in communities and to test the application of DRM and CCA strategies and actions. The choice to adopt imaginary VTB is mainly dictated by the need to avoid sensitivity problems that could arise when modelling real communities and by the willingness to create a VTB that could be a reference for geographic areas and type of urban settlements with similar characteristics. However, even if not real, the VTB should be realistic, avoiding over-simplification that could impair results significance when translated to real-world situations. In fact, although it is possible to fictitiously reproduce the urban pattern starting from the study of town planning of the different types of contexts, the complexity of urban forms and the interrelationship between the different components and networks constituting the system is extremely difficult to reproduce. Moreover, some characteristics such as the street paths, urban greenery, the distribution and percentage of urban voids (e.g. squares and open spaces) with respect to the built volumes, may have a significant impact on the effects of some hazards such as heat waves or extreme winds, particularly relevant as weather related events in connection to climate change; the fictitious attribution of certain characteristics may not find a counterpart in the different existing realities.

While the examples of Centerville and Benchmark city provide useful platforms for testing and calibrating resilience assessment algorithms in the respective countries, they are not deemed adequate to mimic urban morphology and patterns characterized by stratified historic development as often is the case for European cities. Even if procedural modelling could be used to enhance the spatial details of urban plans along with suitably informed data generation algorithms to create buildings layouts, as done for Tomorrowville, this urban design process can hardly reproduce the complex urban development that is typically found in cities that include an historical center and a long history of urban development and expansion.

For this reason, inspired by the Collage City concept [24], in which the urban form is understood as the result of processes of stratification and juxtaposition of different elements rather than as the product of a unitary design, the structural foundation of the VTBs created in RETURN have been conceived as a union of urban parts of real cities. This is an innovative approach for the design of a VTB, requiring the selection of suitable urban parts to form the assembled city, for which the basilar census data on population and buildings are retrieved along with the information on the road network and building footprints. A further novelty is the fact that the designed VTBs are imagined to be located in RETURNLAND, an imaginary land also re-created by assembling real portions of the Italian territory [25], suitably ensuring that the digital elevation model of the virtual cities, inherited from the original ones and with some minor adjustments, can fit on the land. The resulting digital eco-system allows to instantiate realistic multi-hazard process simulations on the territory that can hit the areas where the virtual cities are located, allowing to investigate multiple and cascading impacts on the built infrastructures.

This paper presents the structural foundation, including exposure (GIS) data as operational backend for simulation, for two imaginary VTBs created in RETURN to represent typical urban settlements in Italy. The first VTB, named coastal RETURNVILLE (briefly RV1) represents a town developed along the coast, while the second, inland RETURNVILLE (briefly RV2) represents a town laying in an intra-mountainous plane. Sections 2, 3 and 4 introduce the concepts underlying the VTB development and the resulting proposal.

The paper also presents methodological approach developed to deal with multi-risk assessment for complex urban environments that is based on the use of risk-storylines and impact chains, and the potential for applications based on what-if scenarios. By using risk

storylines, a narrative structure can be used to describe complex multi-risk- scenarios instantiated on the virtual models, allowing to initiate discussion and interaction with relevant stakeholders involved in scenario analysis. Impact chains complement the risk-storylines, providing conceptual models that describe risk-related impacts in terms of cause–effect relationships and focusing on identifying and describing important linkages between the different components of risks, including hazard, vulnerability and exposure. Section 3 and 4 illustrate the multi-risk assessment framework relying on a bottom-up approach based on risk storylines and impact chains.

2. Building the coastal and inland RETURNVILLES

According to the proposed approach conceiving the VTB as a union of urban parts of real cities, the creation of the structural foundation for the RETURN VTBs involves selecting portions of existing geographic areas in Italy and merging them to construct a virtual environment that mirrors real urban settlements. Considering the numerosity and diversity of urban settlements in Italy, comprising more than 8000 municipalities located in regions of extremely variable geographic characteristics (from coastal areas to hilly or mountainous ones) and history, the choice of urban settlements from which to extract urban parts is not trivial.

Each urban sector used to build the RETURNVILLES preserves the internal spatial configuration of the original area, including street layout, building footprints, and census data. The synthetic characteristics of the VTB lie in the assemblage of these real urban portions within a single virtual environment. To ensure spatial continuity between adjacent fragments, limited geometric adjustments are introduced at their boundaries, including partial modification of census tract contours. Spatial consistency is further ensured through the prior selection of municipalities belonging to the same urban archetype, the identification of compatible urban fabrics, and the preservation of census-based exposure data within each fragment, while enforcing continuity of the road network across the assembled system.

Both RV1 and RV2 were conceived to be densely populated municipalities (classified as cities by Eurostat, [26]) functioning as hubs or intermunicipal hubs, defined as service-providing centers with extensive educational, health, and rail transport services, located respectively in coastal (RV1) and inland (RV2) regions. As representative of Italian coastal and inland urban settlements, RV1 and RV2 are assumed to be exposed to the most common hazards affecting these contexts. Thus, RV1 is assumed primarily exposed to volcanic, coastal flooding, landslide and heatwave risks, while RV2 is characterized by high exposed to seismic, river flooding and heatwave risks.

The construction of the VTBs is based on a two-level conceptual approach, combining urban settlement archetypes and urban-morphological types, which play distinct and complementary roles. Urban settlement archetypes (Section 2.1) are used to identify and select municipalities with comparable demographic and geographic characteristics, which are then further filtered based on their level of exposure to relevant hazards. In contrast, urban-morphological types (Section 2.2) are used to decompose selected municipalities into representative urban portions (e.g., historic center, consolidated city, suburban area, urban sprawl), which are then assembled to construct the VTBs.

Paragraph 2.1 explains how such urban settlements were selected while paragraph 2.2 describes the process that guided in the extraction of relevant urban parts based on suitable urban patterns and fabric. Next, section 2.3 describes the different systems introduced to create the digital model of the community according to risk oriented urban modeling.

2.1. Urban settlement typology

Urban areas are inherently complex systems, where physical elements (buildings, infrastructure, and the natural environment) interact with social dynamics (demographics, socioeconomic inequalities) and institutional capacities (planning, governance, and emergency management). This interplay makes urban risk assessment particularly challenging, as hazards rarely act in isolation but are mediated by vulnerabilities and resilience capacities embedded in the urban fabric [27], [28]. Past events confirm that vulnerability to hazardous events and disasters varies significantly across communities depending on their physical, demographic, socioeconomic, and institutional conditions [27], [29]. For instance, elevation and topography can hinder service accessibility and evacuation in mountain regions [30], while population size and density affect exposure levels, evacuation complexity, and infrastructure stress [31], [32]. In this context, building VTBs requires a careful selection process to ensure that the chosen areas share key characteristics shaping urban vulnerability and resilience.

Traditionally, urban settlements have been classified using only a limited set of characteristics, such as population density, land use, or service accessibility [26], [33]. While useful, such simplified approaches overlook the multidimensional nature of cities. Tocchi et al. [34] proposed a more comprehensive approach by clustering urban settlements into archetypes defined by shared vulnerability and exposure characteristics. This clustering relies on a wide set of demographic, geographic, and socioeconomic indicators, including: (i) altimetric zone, describing elevation and topographical features; (ii) degree of urbanization, classifying municipalities by population density, concentration of activities, and extent of the built environment; (iii) degree of urban centeredness, reflecting service availability and spatial connectedness through distance and travel time to major service centers; (iv) residential population, representing exposure levels; and (v) social vulnerability, capturing the heightened susceptibility of certain groups to natural hazards due to limited coping and adaptive capacities.

Building on this framework, a two-steps process was adopted to identify the municipalities contributing to the VTBs. First, a set of candidate municipalities was defined based on urban archetypes proposed in Ref. [34], selecting all municipalities sharing the same degree of urbanization (i.e., cities), degree of urban centeredness (i.e., hubs or intermunicipal hubs) and altimetric zone (coastal municipalities for RV1; hilly or mountainous municipalities for RV2). Residential population was not used as an explicit selection

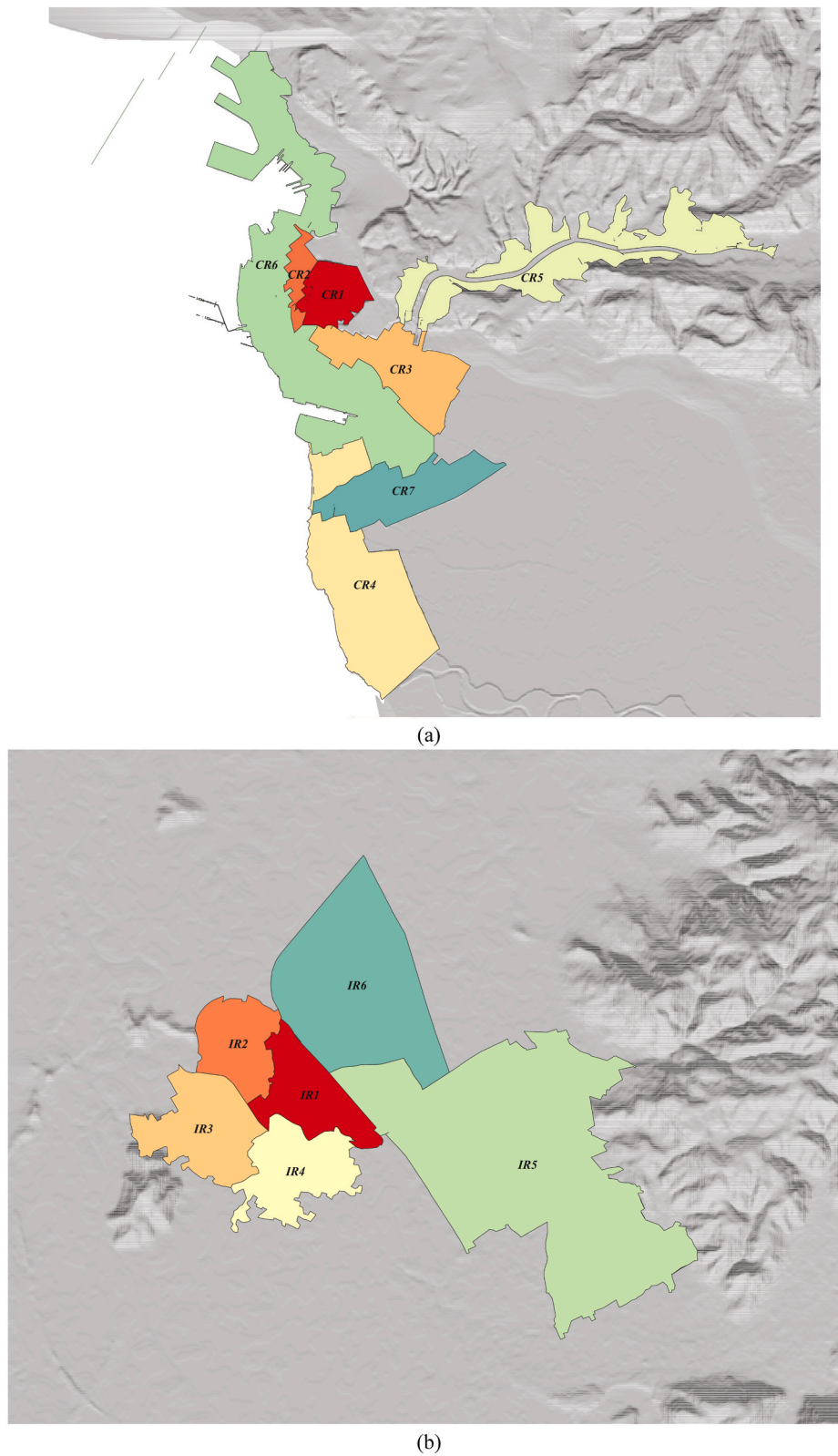


Fig. 1. Coastal RETURNVILLE (a) and Inland RETURNVILLE (b). Colored areas indicate the different portions of each VTBs: CR1, CR2, etc. for the Coastal RETURNVILLE, and IR1, IR2, etc. for the Inland RETURNVILLE.

criterion, since it is indirectly captured by the degree of urbanization and is less relevant when only portions of municipalities are selected for the construction of the VTBs. In this context, ensuring consistency in the degree of urbanization - which reflects both population size and density - was deemed more appropriate. Moreover, by selecting only portions of municipalities, socioeconomic diversity is preserved, allowing the VTBs to capture the heterogeneity that typically characterizes real urban areas.

From this set of candidates, municipalities showing the highest level of exposure to more relevant natural hazards in each context were shortlisted. To this end, results from a GIS-based national hazard assessment [35] were used. Hazard scores were assigned to municipalities by normalizing intensity indicators related to worst-case scenarios: for example, Peak Ground Acceleration (PGA) for a 2500-year return period as an earthquake indicator, and inundation extent for a 300-year return period as a flood indicator. The resulting hazard maps assigned each municipality a score between 0 and 1, with 1 representing the highest exposure. These scores were then used to refine the choice of municipalities included in each VTB. Thus, RV1 incorporates municipalities highly exposed to volcanic, flood, landslide or heatwave risks, while RV2 includes those with high exposure to seismic, flood, or heatwave hazards. The selected municipalities (archetype-consistent) are then decomposed into urban-morphological components, which constitute the building blocks of the VTBs. The specific portions of these municipalities to be merged into the VTBs were identified based on their urban morphology, in order to represent the distinct evolutionary phases of a real city (i.e., historic center, consolidated city, planned city, and urban sprawl), as detailed in the following section.

2.2. Identification of urban patterns and fabrics for VTB urban morphology definition

The configurations of the RETURNVILLES virtual cities are inspired by the Aldo Rossi's model of the "Analogous city" presented at

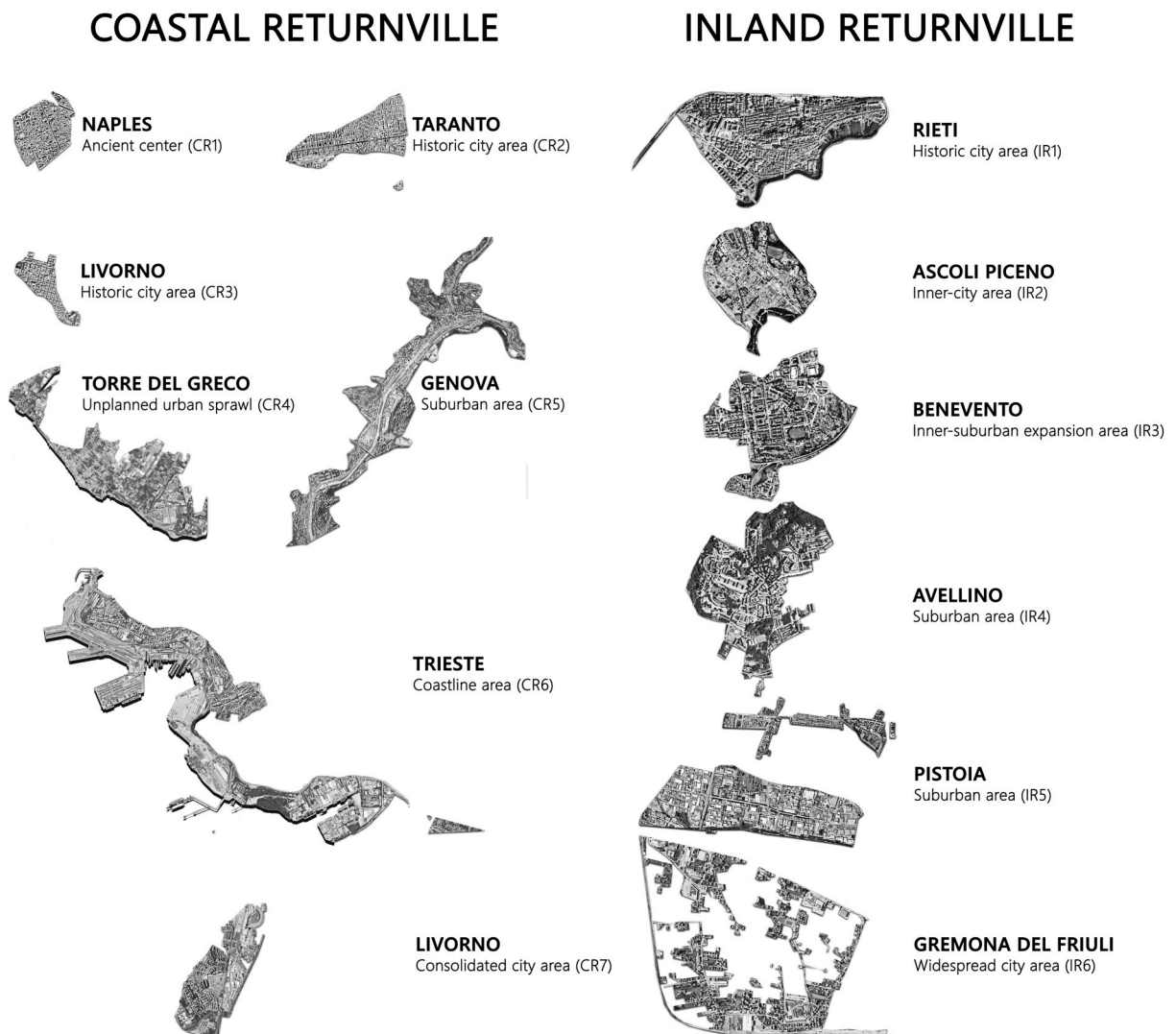


Fig. 2. Urban parts as real city extracts.

the 1976 Venice Architecture Biennale as a collage of an imagined territory. The model of Aldo Rossi introduced the meaning of urban elements and parts in the typological-morphological analysis that was conceptualized as a representation of factors relating to the identity and homogeneity of building types, patterns and urban areas [36], [37]. The proposed VTBs should be able to convey the complexity of Italian urban settlements in relation to the multi-hazard conditions and to the specificities of settlements. Therefore, according to the urban settlement typologies selection (Section 2) a study on urban morphologies was conducted to investigate recurrent physical urban forms.

The study of urban morphologies investigates the urban forms, the urban fabrics parts and their relationship [38], [39]. Settlements are studied to select real cities fragments representative of specific characteristics concerning the location, the consistency of the built environment and of urban fabric, the characteristics of open spaces and urban voids, and other features concerning the geological, geo-morphological, functional, and socioeconomic aspects [40], [41]. The fragments are identified based on the urban physical system taxonomy proposal [42].

RV1 was conceptualized as a coastal inter-municipal hub or hub subject to volcanic, heatwave, flood and landslide risks. RV1 design is based on the identification of different urban-morphological types selected across the Italian territory to represent a specific evolutionary phase: historic center, consolidated city, planned city and urban sprawl. The fragments of cities, with an average of 20,000 inhabitants each, have been identified in urban and metropolitan settlements along the Tyrrhenian coast with the aim of preserving the orientation and relationship with the natural system, which are constituent factors of settlement patterns. Accordingly, the cities of Naples, Taranto, Trapani, Genoa, Livorno, Trieste and Torre del Greco were considered; Fig. 1(a) represents RV1 as assemblage of the selected urban parts. The historic city area of Taranto and Trapani (CR2 and CR3) were selected according to the cultural and historic value and combined with the ancient center of Naples (CR1) representing the oldest part of RV1. The suburban area of Genoa (CR5) was selected as example of widespread city – i.e. an area characterized by uncontrolled and low-density expansion in a large suburban area – partly due to its complex mountainous coastal geomorphology. In addition, part of the city of Torre del Greco (NA) (CR4) was selected for the unplanned urban sprawl. Finally, the industrial area of Livorno (CR7) was selected for the consolidated urban area with industrial function and the coastline of Trieste (CR6) for the coastal industrial/commercial area (see Fig. 1(a)). For each part natural, infrastructural and facilities were also considered.

RV2 was developed following the same methodological approach, representing an inland inter-municipal hub or hub subject to seismic, flood, and heatwave risks. The historic city of Rieti was selected to represent the oldest part of RV2 (IR1); for the consolidated city part of Ascoli Piceno was selected as inner-city area (IR2), part of Benevento as inner-suburban expansion area (IR3), and part of Avellino (IR4) and part of Pistoia (IR5) as suburban area; finally, Gemona del Friuli (IR6) were selected to represent the widespread city (IR5) (see Fig. 1(b)). In the case of RV2, the river was considered as a natural element and the railway track as an anthropogenic element, both of which represent generative and characteristic elements of the urban form.

The spatial extent of each urban portion was not predefined but derives from the intrinsic characteristics of the selected morphological type (e.g., historic centre, consolidated city, suburban area, urban sprawl). Consequently, different components have varying sizes and population densities. Portions representing historic centers (e.g., IR1) tend to be compact and densely populated, while suburban areas (e.g., IR5) are more extensive low-density areas (see also section 2.3.1). This variability reflects real urban conditions and inherently influences exposure and socio-economic patterns within the VTBs. Alternative configurations - based on different selections or proportions of morphological components - could lead to variations in the resulting risk patterns; however, the

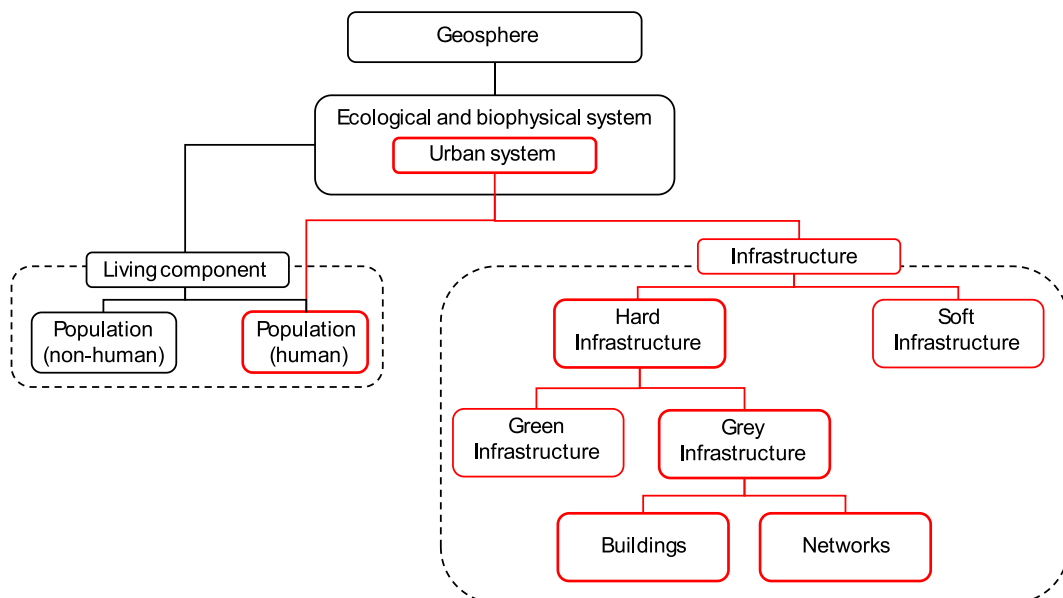


Fig. 3. Conceptual model of urban system and corresponding subsystems (adapted after [46]).

adopted approach prioritizes morphological representativeness over geometric standardization to better capture the heterogeneity of real urban systems.

Fig. 2 shows the images of the different urban parts selected for RV1 and RV2 as extract from the real cities.

The assemblage of the various urban parts of the mentioned cities provides a composite settlement of about 115000 inhabitants for RV1 and about 38,000 inhabitants for RV2 that are capable of representing the complexity of Italian settlements and reporting the co-presence of potential risks – environmental, natural and anthropogenic – derived from real conditions in the urban and metropolitan contexts of reference.

2.3. Risk-oriented urban modeling

The development of a virtual testbed requires the creation of a digital model of the community, ideally representing geospatially the multiple interconnected social, economic, and physical systems forming the urban settlement, as well as one or more hazard modules enabling to instantiate hazard related simulations [11].

A typical categorization of the systems forming the community encompasses the physical system, including buildings and infrastructural assets (e.g. transportation network, water network, electricity network etc.), social system and economic system [43]. In the City Anatomy approach proposed by the City Protocol Society [44] the city is defined starting from the analogy between the city and the body; accordingly the systems considered as basic and common to every city are the *Built Domain*, *Society*, and *Environment* as well as six infrastructure layers that enable flows from/to and within a city (*Communication Network*, *Water Cycle*, *Energy Cycle*, *Matter Cycle*, *Mobility Network* and *Nature*). This latter approach is clearly shaped around urbanistic domain in view of favoring simulation of urban processes to be schematized for urban planning and policies development, generally included in the so-called urban metabolism.

The systems categorization adopted for the VTBs developed in RETURN follow the Risk-oriented Urban Taxonomy developed within the RETURN framework. Fig. 3 presents the risk-oriented taxonomy of the urban system proposed in Ref. [45], in which the system is organized into subsystems and elements according to their role in risk assessment. A taxonomy is intended as a structured classification that identifies and groups the main components of the urban system (e.g., geosphere, infrastructure, population) relevant for risk analysis, without explicitly representing all possible interactions or feedback mechanisms among them. The representation of relationships, interactions, and mutual influences among system elements – e.g., potential reverse influences of population and infrastructure on the geosphere – is instead addressed through an ontology, which can be defined as a formal representation of a set of concepts within a domain and the relationships between those concepts, allowing for a more comprehensive and explicit modelling of system interdependencies and processes [45], [46].

As it can be seen in Fig. 3, Urban systems are seen as part of Ecological and Biophysical system which are part of the factors interacting with hazard, vulnerability and exposure in the environmental and anthropic risks. Fig. 3 also stresses the role of the geosphere, that represents the foundation layer where the population and infrastructure develop so that the geosphere elements influence them; in turn, population and infrastructure can also modify the geosphere, for example, urban development and even risk mitigation often involve excavation which interact and often modify the underlying geology. The geosphere can be represented by means of descriptive elements such as geologic substratum, the soil, the topography and the hydrology [45]. The susceptibility of urban settlements to natural hazards is significantly influenced by the underlying geological conditions, the topography, the hydrology etc. Hence, a consistent definition of an urban settlement should consider those factors in a context specific description. Adopting a holistic approach, the structural foundation of the VTBs of urban settlements in RETURN are defined by taking into account the territorial features of the virtual land where the VTBs are imagined to be developed, including the topography, geology and river basins. Such virtual land, defined as RETURNLAND, was specifically created inspired by the same principles of RETURNVILLE, i.e. to create a VTB to allow instantiating simulations and multi-risk workflows for assessing multi-risk at the territorial level, and is described in Ref. [25].

The Ecological and Biophysical system consist of two primary components: the first representing the ‘living’ component of the biophysical system underlying the urban system, formed by the human (the social component) as well as the non-human population, and one indicated generally as the ‘infrastructure’ to include all non-population elements to be found in an urban system. This component is further divided into hard infrastructure, which includes all physical components such as roads, metros, railways, buildings, and utilities, and soft infrastructure, encompassing the set of relevant functions necessary for the ordinary and extraordinary management of the urban system, for instance, health, emergency, law enforcement, mid-term services (e.g., waste management), and long-term services including educational and recreational.

This paper introduces the grey infrastructures as well as (human) population layers employed for preliminary definition of RV1 and RV2, contoured with red bold boxes in Fig. 3, as detailed in the next subsections. The resulting exposure model and data are available and published within the digital ecosystem of RETURNLAND and the RETURNVILLEs on a public repository [47].

Note that, while not explicitly considering organizational/functional aspects of the city life, such as Business activity or Public services - conceptually included within the soft infrastructure, the proposed conceptual/taxonomic approach allows to represent the parts of the urban system that are related to the operationalization of those services/functions; hence, the disruptive effects or impacts on those functions can be assessed based on the impact produced by an hazardous event on the relevant elements of the urban system. As example, impact on business activity depends on the impact on buildings where those business activities are performed.

Conversely, other aspects of social and community level organization, including institutional and risk governance framework as well as cultural identity, are not captured in this representation. Those aspects, that are relevant in shaping the response and institutional capacity of a community, can be considered through a so-called Cultural Infrastructure dimension, whose characteristics may vary across different contexts and that can be explicitly considered in the production of Context-based risk storylines to be applied in

the first phase of multi-risk assessment for the VTB (see section 3).

2.3.1. Population

As previously mentioned, the foundational structures of the VTBs are constructed from real geographic areas, meaning that actual data can be utilized for these zones. The careful selection of urban portions to be merged (see Sections 2.1 and 2.2) enables the integration of real datasets - where available - that reflect the key urban characteristics used to define the area, such as urban density and typo-morphological features. For Italian municipalities, census data on buildings and population are publicly available at the census tract level. Consequently, each component area merged to create the VTBs corresponds to a group of census tracts, and the spatial resolution of the population exposure model is therefore defined at the census tract scale.

For each census tract, ISTAT (the national institute for statistics in Italy) provides detailed demographic and socioeconomic data, including the number of residents and families, household composition, population age structure, education level, commuting patterns, and employment characteristics (e.g., total and female employment rates). These variables are essential for assessing social vulnerability, defined as the tendency of certain social groups to experience adverse effects from natural hazards due to limited adaptive and coping capacities [27], [48]. Quantifying and mapping social vulnerability helps identifying areas where impacts may be particularly severe and supports the design of preventive and mitigation measures. Among existing approaches, indicator-based methods are the most widely applied [27], [49], [50], as they enable the aggregation and comparison of diverse variables. However, the calculation of a Social vulnerability index (SoVI) requires careful selection of indicators to ensure that it reflects the specific local and regional context (e.g., Refs. [27], [51]). In the Italian context, studies typically include parameters such as age, family structure, educational attainment, ethnicity, population growth, household composition, socioeconomic status, and employment levels (e.g., Refs. [50], [52]). All these variables are available from ISTAT at the census tract level and have been identified for each zone within the VTBs, as reported in Tables 1 and 2. Such data are crucial for integrating social vulnerability into comprehensive risk analyses (e.g., Ref. [52]).

In particular, the Coastal RETURNVILLE (RV1) has 114607 inhabitants and 8150 residential buildings, covering an area of approximately 20 km². It is constructed by merging: (i) the ancient centre of Naples (CR1); (ii) the historic urban areas of Taranto (CR2) and Trapani (CR3); (iii) the suburban areas of Torre del Greco (CR4) and Genoa (CR5); and (iv) the industrial/commercial zones of Trieste (CR6) and Livorno (CR7). Resident population data for each component, derived from ISTAT and organized according to proxies that are relevant to social vulnerability, is reported in Table 1.

CR5 is the most populated zone, with 34701 inhabitants. A high percentage of elderly residents (over 65) is observed in CR6 (33%), CR7 (28%), and CR5 (27%). CR4 records the highest incidence of large families (14% of households with more than five members), the lowest employment rate, and the highest share of commuters (38% and 16% of the working-age population, respectively). The most densely populated area is CR1, with 25375 inhabitants per km², followed by CR2 (18174 inh./km²), CR3 (10918 inh./km²), CR5 (9480 inh./km²), CR7 (4617 inh./km²), CR4 (2385 inh./km²), and CR6 (1353 inh./km²). Fig. 4 shows the spatial distribution of residential population of RV1.

Concerning the Inland RETURNVILLE (RV2), it has 38060 inhabitants and 3905 residential buildings, covering an area of approximately 14 km². It is constructed by merging: (i) the historic city of Rieti (IR1); (ii) the inner-city area of Ascoli Piceno (IR2); (iii) the inner suburban expansion area of Benevento (IR3); (iv) the suburban area of Avellino (IR4) and Pistoia (IR5); and (v) the peripheral area of Gemona del Friuli (IR5). Resident population data for each part of Inland RETURNVILLE is derived from ISTAT and reported in Table 2.

IR3 has the largest residential population (11679 inhabitants) and the highest population density with 9322 inhabitants per km². High population densities are also observed in IR1 (6864 inhabitants per km²) and IR2 (7062 inhabitants per km²), compared with much lower values in IR4, IR5 and IR6 (2566, 445, and 1777 inhabitants per km², respectively). IR2, IR5 and IR1 exhibit the highest proportion of elderly residents (31%, 27% and 25% respectively), while IR3 and IR5 show the highest share of population under 15 aged (15% and 14% respectively). IR3 also records the largest number of families and the highest percentage of families with more than 5 members (11%). IR5 and IR6 show high employment rates among the working-age population (67% and 69% respectively), while also recording the highest proportion of commuters (20% and 37% respectively). The lowest employment rates are observed in IR3 (45%) and IR4 (50%). Fig. 5 shows the spatial distribution of residential population of RV2.

Table 1
Residential population for Coastal RETURNVILLE (RV1).

Residential population/attributes	CR1	CR2	CR3	CR4	CR5	CR6	CR7
Population aged under 15	3383	943	3023	1693	3790	983	1040
Population aged over 65	3803	1723	4817	1313	9452	3169	2525
People which achieved at most a secondary school diploma	15288	4672	14898	6536	27108	6851	6587
Number of families	9061	3436	8952	3164	17347	5002	3856
Number of families with more than 5 components	843	129	497	443	313	92	115
Foreign residents	1624	193	490	68	2764	551	233
Employed	6070	2331	6630	2526	13773	3437	3242
Female employed	2386	955	2593	675	6220	1567	1429
Commuters	597	198	1673	1090	491	319	673
People x dwelling	0.39	0.46	0.41	0.33	0.48	0.52	0.43
Total number of residents	22913	7395	21764	9605	34701	9488	8741

Table 2
Residential population for Inland RETURNVILLE (RV2).

Residential population attributes	IR1	IR2	IR3	IR4	IR5	IR6
Population aged under 15	681	828	1739	1039	393	235
Population aged over 65	1476	2497	2112	1717	792	389
People which achieved at most a secondary school diploma	3498	5330	8250	5382	2159	1269
Number of families	2731	3358	4225	2907	1229	731
Number of families with more than 5 components	89	174	459	199	67	33
Foreign residents	373	448	187	129	127	100
Employed	2432	2811	3534	2560	1196	759
Female employed	1165	1284	1345	1061	508	340
Commuters	466	482	520	851	355	414
People x dwelling	0.46	0.41	0.36	0.37	0.40	0.41
Total number of residents	5862	7948	11679	7883	2957	1731

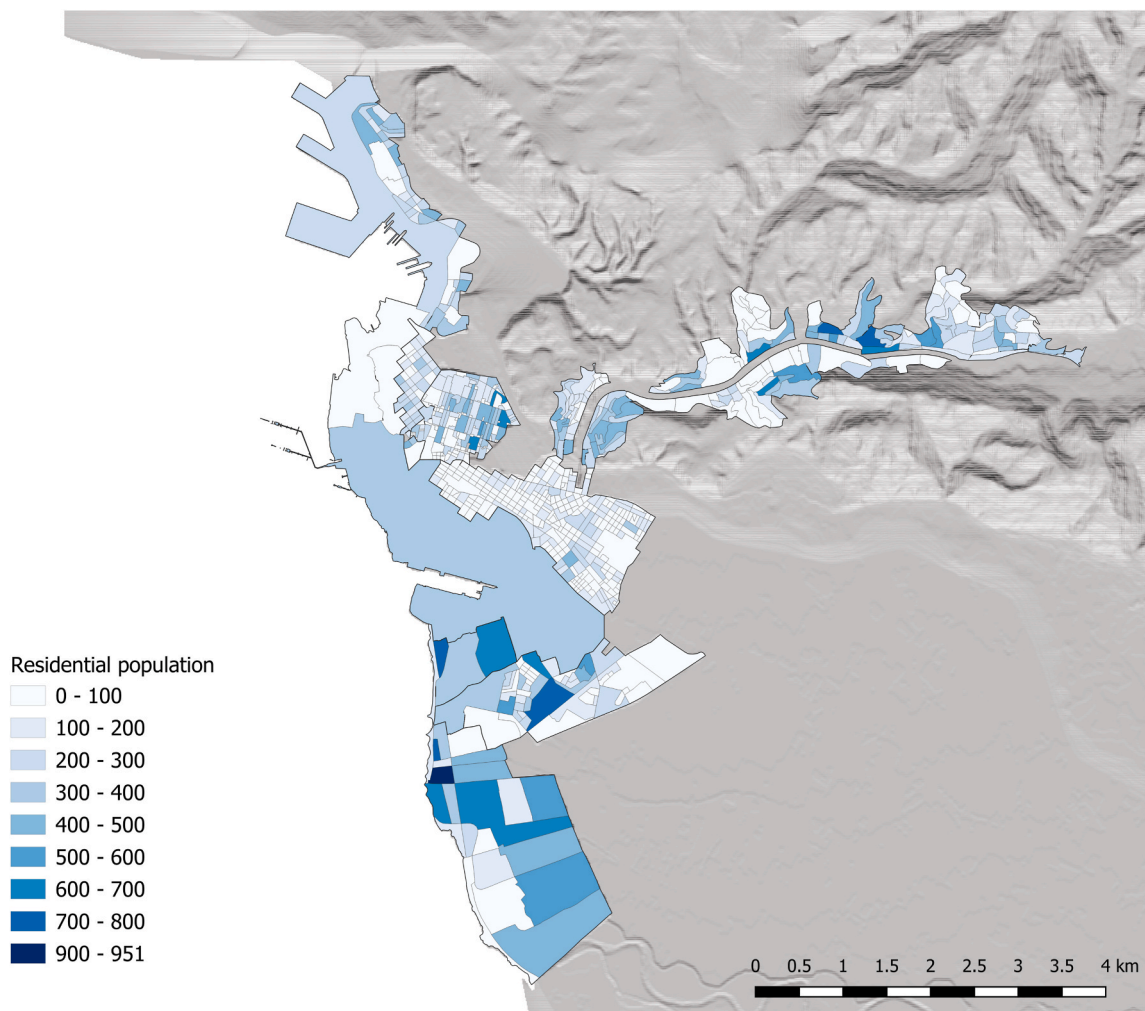


Fig. 4. Residential population maps for the Coastal RETURNVILLE (RV1). Data are derived from ISTAT and mapped at the census tract level.

2.3.2. Buildings and open spaces

Buildings can be classified according to their occupancy (e.g., residential, commercial, public use or cultural heritage building), their typological characteristics (e.g., construction age, height), and, when available, more detailed attributes such as the vertical load-bearing system, horizontal diaphragms, and external technical components. A comprehensive set of attributes adopted for building classification is provided in the *Risk-Oriented Urban Taxonomy* [45].

As detailed in Section 4.1, basic information on buildings is obtained from the national census [53]. For each census tract, ISTAT

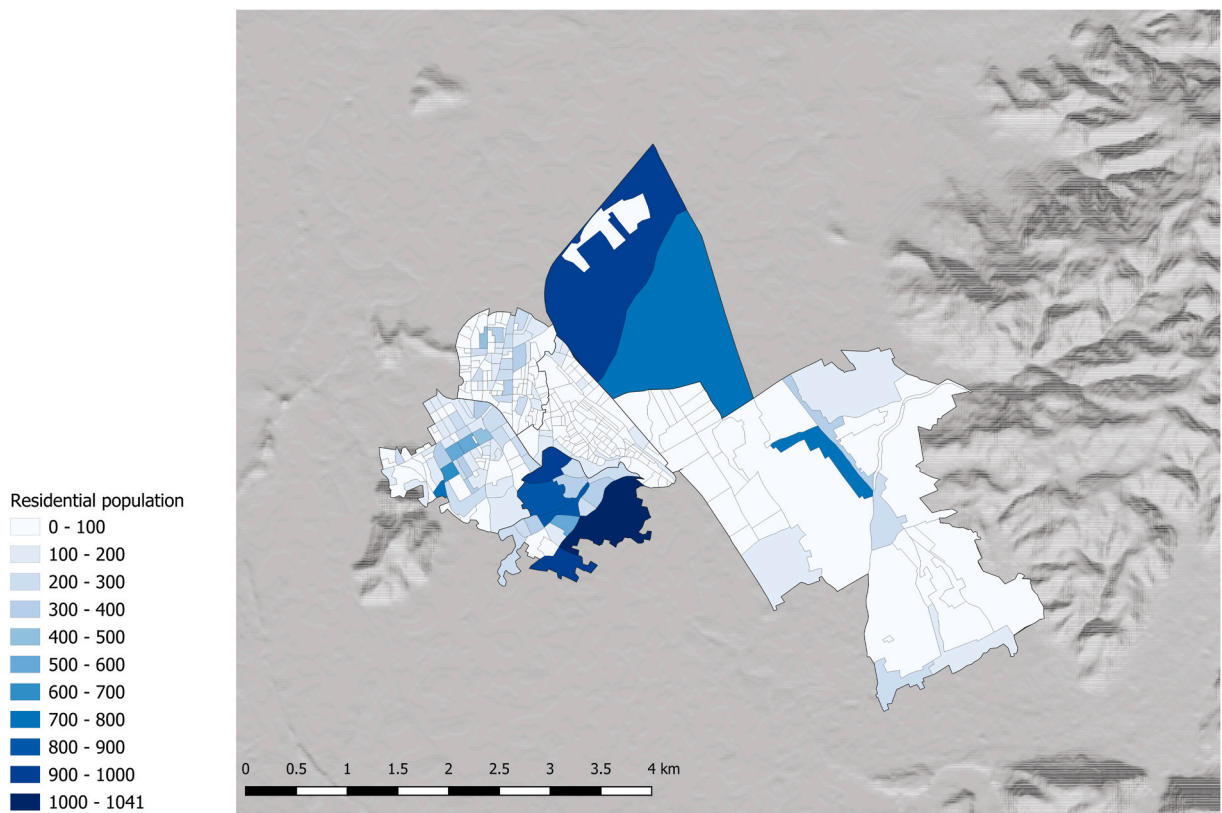


Fig. 5. Residential population maps for the Inland RETURNVILLE (RV2). Data are derived from ISTAT and mapped at the census tract level.

provides data on building occupancy - specifically, the number of residential and non-residential buildings - while more detailed typological information is available only for residential structures.

Note that, while as observed in previous section the Business activity or Public services are not modeled explicitly in the urban system, the National Census of Industries and Services (2012) also provides the number of activities and employees organized according to specific NACE (Nomenclature statistique des activités économiques dans la Communauté européenne - Statistical

Table 3
Residential buildings for Coastal RETURNVILLE (RV1).

Buildings' attribute		CR1	CR2	CR3	CR4	CR5	CR6	CR7
RES	Masonry	787	455	2464	954	902	224	234
	Reinforced concrete	23	28	759	217	479	213	198
	Other material	7	11	3	5	78	108	1
	YBET: <1919	588	135	35	54	504	69	34
	YBET ^a : 1919-1945	193	199	60	49	417	130	46
	YBET: 1946-1960	15	73	252	334	241	217	151
	YBET: 1961-1970	0	51	1671	473	187	83	129
	YBET: 1971-1980	1	26	741	188	69	10	25
	YBET: 1981-1990	0	3	259	70	17	20	11
	YBET: 1991-2000	3	0	128	8	8	4	15
	YBET: 2000-2005	2	1	35	0	10	5	5
	YBET: >2005	15	6	45	0	6	7	17
	1 story buildings	64	2	377	432	180	27	55
	2 stories buildings	73	56	1407	583	370	96	168
	3 stories buildings	53	124	820	101	282	42	47
	4 or more stories buildings	627	312	622	60	627	380	163
	Good state of preservation	355	352	2431	743	1185	465	416
	Bad state of preservation	462	142	795	433	274	80	17
	Total number of buildings	817	494	3226	1176	1459	545	433

^a YBET: date of construction upper/lower bound.

Classification of Economic Activities in the European Community) codes at census tract level. This information can be supplemented with data on the gross stock value of structures and contents, which is provided at a national level by ISTAT as part of the “National Accounts” (Conti Nazionali) to inform studies on economic activities and potential losses to the Business sector.

2.3.2.1. Residential buildings. Similarly to the population, the spatial resolution of exposure model for residential buildings is the census tract scale. Data on residential buildings - retrieved from ISTAT - includes construction material (masonry, reinforced concrete, other construction material), period of construction (<1919, 1919-1945, 1946-1960, 1961-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2005, >2005), and number of stories (1,2,3, 4 or more). The census-based information on residential buildings for the VTBs is summarized in [Tables 3 and 4](#) for RV1 and RV2 respectively.

In RV1, CR1, CR2 and CR4 exhibit the highest proportions of masonry buildings (96%, 92% and 81% respectively). CR1 and CR2 are also characterized by a predominance of older buildings, with 96% and 68% built before 1945, respectively. In contrast, CR4 represents a more recent expansion area, with the majority of buildings (56%) built between 1961 and 1980. CR3 and CR5 also show high proportion of masonry structures (76% and 62%), with CR5 having a significant share of older buildings (63% built before 1645), while CR3 predominantly consists of buildings built between 1961 and 1980 (75%). Reinforced concrete (RC) buildings are more common in CR6 and CR7 (39% and 46% respectively), which correspond to suburban zones developed during the post-war expansion, with 55% and 65% of buildings constructed between 1946 and 1970. Regarding building height, low-rise structures are predominant in CR4 (86% of buildings with 1–2 stories), whereas CR1, CR2, and CR6 are dominated by medium-to high-rise buildings with four or more stories (77%, 63%, and 70%, respectively). CR5 also shows a notable proportion of medium-to high-rise buildings (43%), while in CR3 and CR7 a large share of buildings are two-story structures (44% and 39%, respectively).

In RV2, IR1 exhibits a notably higher proportion of masonry buildings (82%) compared to the other zones, whereas IR2 and IR4 have the highest shares of RC buildings (86% and 75% respectively). In IR3 and IR5 show nearly equal proportions of masonry and RC structures (47% masonry and 50% RC in IR3; 52% masonry and 48% RC in IR5), while in IR6 49% of buildings are RC, 43% are constructed with other material, and only 8% are masonry. The highest proportions of older buildings are observed in IR1 (77%) and IR5 (38%), while in other zones most buildings were built between 1961 and 1980 (66%, 58%, 46%, 58% for IR2, IR3, IR4 and IR6 respectively). IR5 is also characterized by low-rise buildings, with 84% of buildings being two-story structures. Medium-rise buildings (2- stories) are common in IR1 (74%), IR3 (53%) and IR6 (86%), while medium-to-high-rise buildings (4 or more stories) are pre-dominant in IR2 (57%) and IR4 (52%).

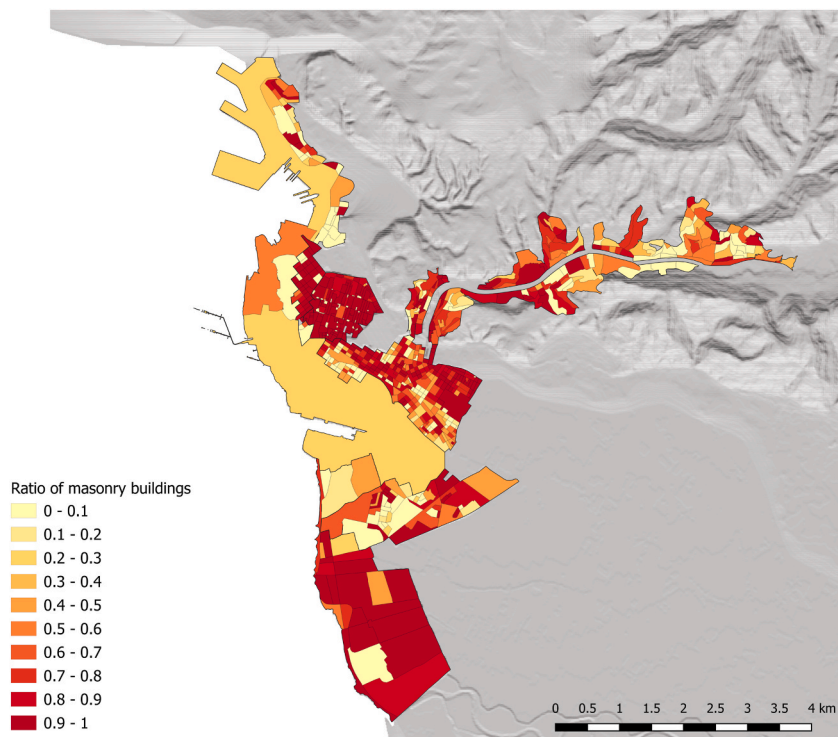
[Figs. 6 and 7](#) show the distribution of some relevant building typologies in the census tracts for RV1 and RV2, respectively.

Census data are provided in aggregated form, meaning it is not possible to determine, for instance, how many masonry buildings with two stories or RC buildings constructed before 1980 exist within a census tract. Therefore, when a higher level of detail is required for risk evaluation, assumptions or downscaling procedures must be applied to disaggregate the available data (e.g., Refs. [\[54\]](#), [\[55\]](#)). In Refs. [\[56\]](#) and [\[57\]](#), a disaggregation approach aimed at developing exposure models for seismic and multi-risk analyses is adopted, based on statistics on construction material and building age available at the municipal level. The number of buildings by construction period is derived from census-tract-level data, while construction material and building height classes (1, 2, 3, 4 or more storeys) are assigned using percentage distributions available at municipal scale. In other words, the distribution of construction materials and building heights by construction period (e.g., percentage of two-storey masonry buildings built between 1961 and 1970) is uniformly applied to the buildings within each census tract belonging to the same age class. This procedure enables the estimation of the number of buildings associated with each relevant building typology at census tract level.

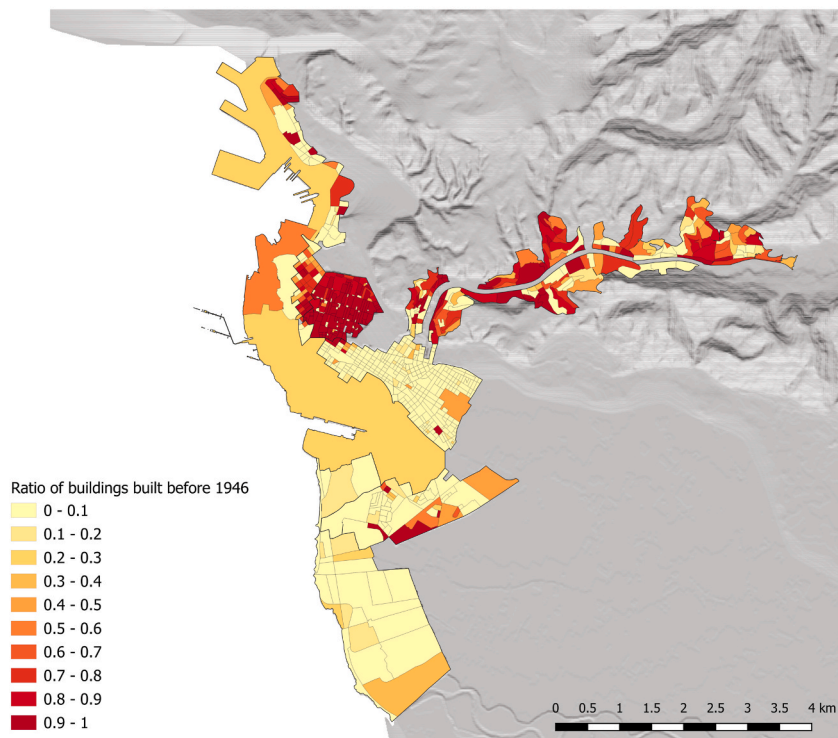
Table 4

Residential buildings for Inland RETURNVILLE (RV2).

Buildings' attribute		IR1	IR2	IR3	IR4	IR5	IR6
RES	Masonry	936	66	300	46	395	48
	Reinforced Concrete	96	447	322	202	361	281
	Other material	110	5	18	20	4	248
	YBET: <1919	783	11	30	1	136	7
	YBET*: 1919-1945	98	19	3	7	152	13
	YBET: 1946-1960	111	71	148	27	193	60
	YBET: 1961-1970	72	244	253	98	87	96
	YBET: 1971-1980	35	99	117	25	161	237
	YBET: 1981-1990	12	44	36	41	25	84
	YBET: 1991-2000	14	22	24	45	5	16
	YBET: 2000-2005	13	5	14	12	0	28
	YBET: >2005	4	3	15	12	1	36
	1 story buildings	6	8	51	5	27	66
	2 stories buildings	251	74	192	104	638	287
	3 stories buildings	596	142	145	20	87	212
	4 or more stories buildings	289	294	252	139	8	12
	Good state of preservation	933	495	521	209	735	558
	Bad state of preservation	209	23	119	59	25	19
	Total number of buildings	1142	518	640	268	760	577

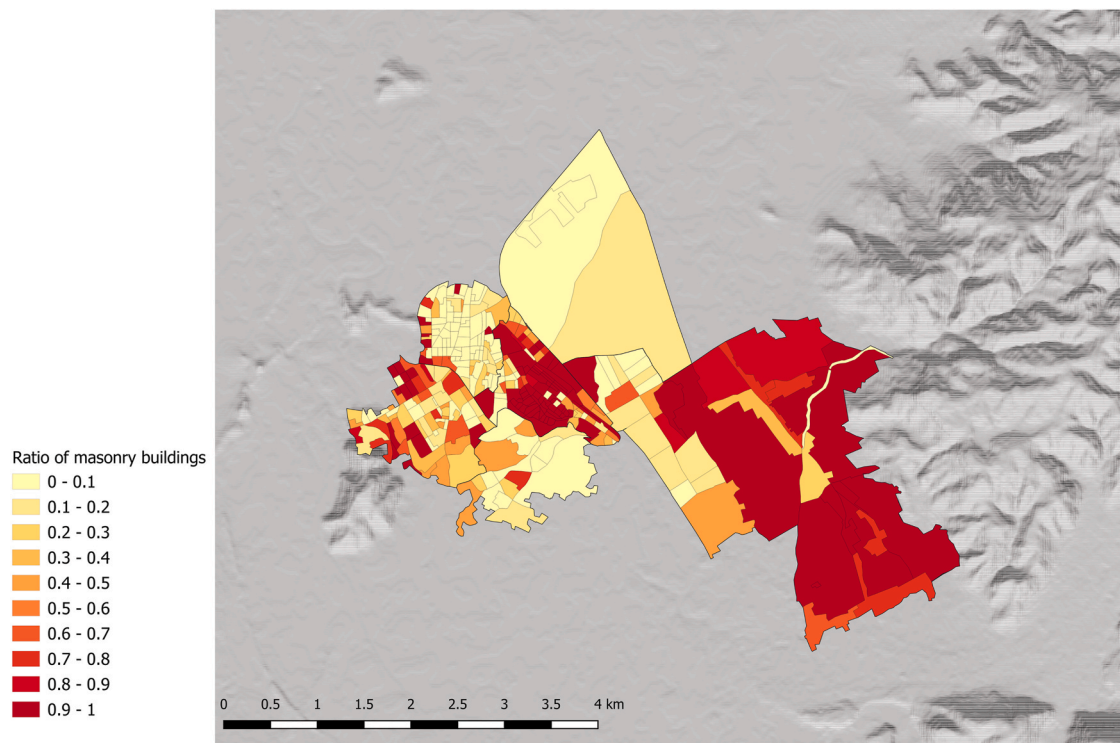


(a)

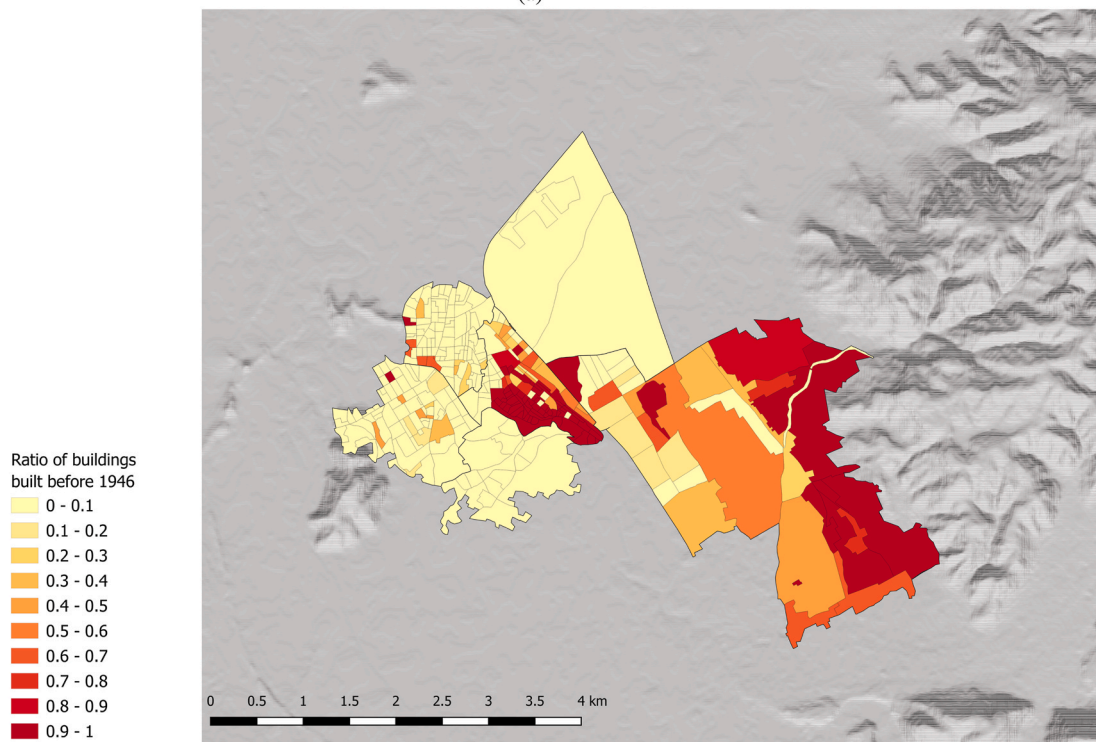


(b)

Fig. 6. Distribution of masonry buildings (a) and older buildings (b) for Coastal RETURNVILLE (RV1). Data are derived from ISTAT and mapped at the census tract level.

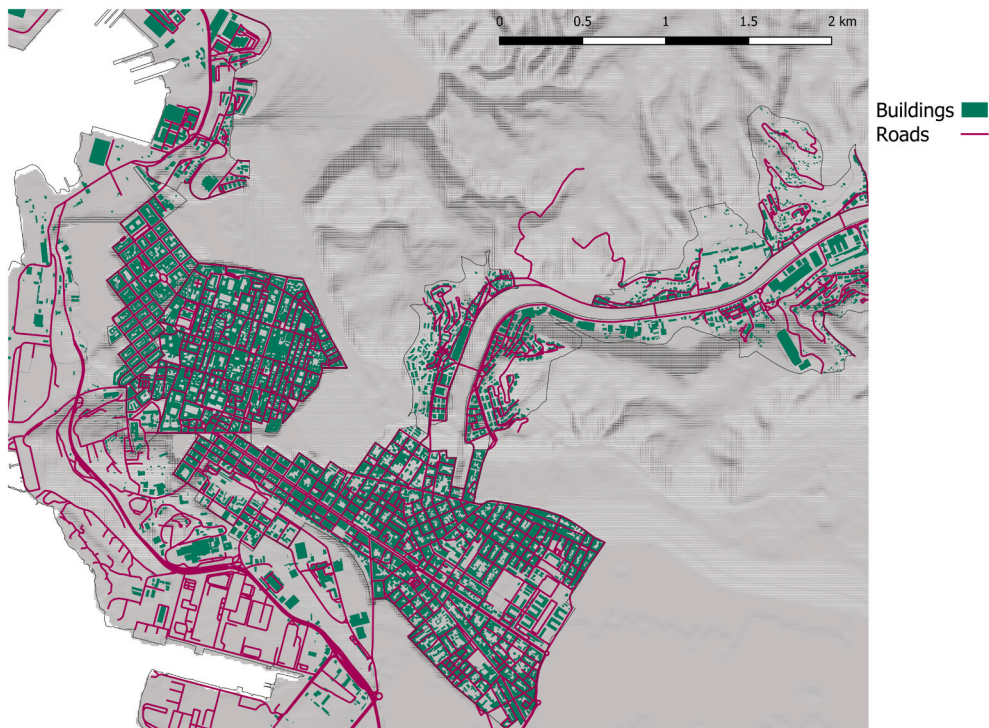


(a)



(b)

Fig. 7. Distribution of masonry buildings (a) and older buildings (b) for Inland RETURNVILLE (RV2). Data are derived from ISTAT and mapped at the census tract level.

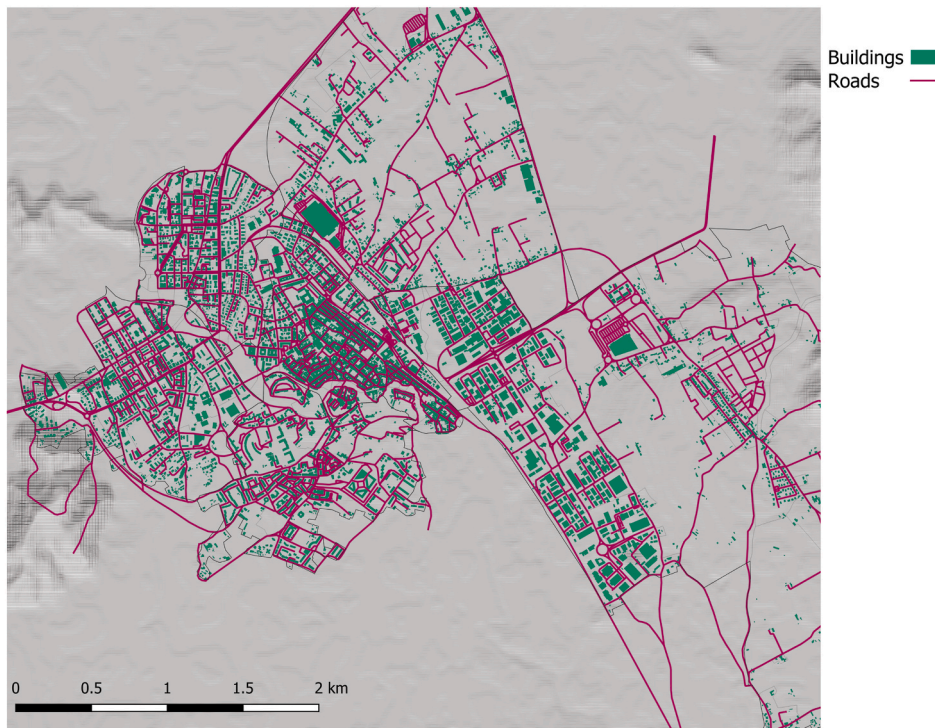


(a)



(b)

Fig. 8. Excerpt of the ordinary buildings, roads (a), educational buildings and Hospitals (b) for the Coastal RETURNVILLE. Building footprints and road network layer are collected from Ref. [59] and OSM.



(a)



(b)

Fig. 9. Excerpt of the ordinary buildings, roads (a), educational buildings and Hospitals (b) for the Inland RETURNVILLE. Building footprints and road network layer are collected from Ref. [59] and OSM.

Building data available at the census tract level allows to perform risk analyses at this spatial resolution. Despite in aggregated form, using real census and open-source data ensures that the VTBs remain realistic and representative of actual urban conditions, reducing uncertainty compared to purely synthetic or simulated datasets. This, in turn, enhances the reliability and transferability of simulation results to real-world contexts. Additionally, several methodologies for refining census data are available in the literature and can be readily implemented (e.g. Ref. [58]). Therefore, for each census tract, the VTBs include the full set of variables available from ISTAT, including population counts, building counts, and aggregated building characteristics. The census-based population and residential buildings dataset used for the construction of the VTBs has been made available in an open-access repository [47].

The spatial dimension of census tracts varies according to population density. In densely populated areas (e.g., historic city centers), census tracts are typically very small and may include only a limited number of buildings, whereas in low-density areas (e.g., suburban or peri-urban contexts), they can be significantly larger despite containing relatively few buildings (e.g., Figs. 6 and 7). While the assumption of a uniform distribution of building characteristics within each census tract is commonly adopted when working with aggregated data, it may introduce limitations in risk assessment, particularly in contexts where building characteristics are highly heterogeneous within the same tract. This effect is more pronounced in low-density areas, where larger census tracts may mask local variability, and in the case of highly localized hazards (e.g., flooding), where spatial heterogeneity plays a significant role. Thus, even after disaggregation, the resulting information may still lack the granularity needed for certain analyses.

For this reason, building footprints are collected from available cartographic databases for both VTBs (i.e., [59], OSM - OpenStreetMap(R)). These buildings footprints may support more detailed analysis in case of higher resolution, building-by-building information is required. From these footprints, rapid image-based or machine learning techniques can be applied to infer spatial building features - such as shape, location, and height (e.g., Refs. [60], [61]); while none of these elaboration is performed in this study, a suitable procedure to improve building exposure characterization towards a high-resolution, georeferenced typological distribution of the building stock, relying on availability of building footprint location, is proposed in Ref. [57]. Nonetheless, key attributes that are critical for vulnerability assessment, such as construction material and building age, cannot be reliably derived from remote sensing alone. For this reason, the integration of census data remains essential to complement remotely sensed information and enhance the accuracy of vulnerability evaluations [62].

Building footprints relative to the urban parts forming each VTB are shown in Figs. 8(a) and 9(a) for excerpts of RV1 and RV2 respectively. Note that building footprints are not associated with specific functions (e.g., residential, commercial, or educational). In the figures, the term ‘ordinary buildings’ is used solely to distinguish the general building stock from buildings with identified public functions (see Section 2.3.2.2).

2.3.2.2. Public buildings – schools and hospitals. As for public buildings, only schools and hospitals were considered. Differently from the approach adopted for residential buildings, the schools and hospitals in RV1 and RV2 were not defined considering the public buildings already existing in the chosen urban parts; indeed, the public buildings may serve a population that goes beyond the dimensional limit chosen for each urban part forming each VTB and referring to public buildings really existing in the selected urban parts may lead to inconsistencies with respect to the final dimension of each VTB (in terms of population and size). Hence, new ad hoc building layers were developed for schools and hospitals adopting the methodology here described. For each VTB (RV1 and RV2) six Italian cities were selected belonging to the same urban archetypes as the VTBs (according to the approach from Ref. [63]) and having a comparable number of inhabitants to RV1 or RV2 respectively, see Table 5. The number and type of schools and hospitals - along with the corresponding numbers of students and hospital beds - to be located within each VTB were then estimated based on the average figures observed in the six reference cities. Table 6 resumes the average estimated values based on the calculation performed for RV1 and RV2. For example, the number of high schools that should be present in a city comparable to RV1 is 16 (to host approximately 8000 students) and for RV2 is 11 (for almost 3800 students). Institutional data on schools were obtained from the “Portale Unico dei Dati della Scuola” and “Scuola in Chiaro”. By consulting the Open Data section of the former (<https://dati.istruzione.it/opendata/opendata/>), it is possible to download, for each school within the city of interest, information on location, school type, and the number of enrolled students, disaggregated by age and gender. Comparable information is also available from Scuola in Chiaro

Table 5

Number, type and capacity of hospitals and schools in the reference cities, along with population data (2018). The number of hospital beds and students are reported in parentheses, respectively.

RV	Reference cities	Population (2018) [Nr]	Hospital	Kindergarten	Primary school	Middle school	High school
RV1	Ancona	100924	4 (1497)	31 (1992)	22 (3827)	10 (2527)	15 (6530)
	Latina	126470	3 (839)	37 (2448)	28 (5562)	12 (3881)	22 (9760)
	Pescara	119217	2 (834)	36 (2650)	27 (5604)	12 (3891)	21 (10111)
	Salerno	133970	3 (1173)	47 (2686)	32 (4959)	15 (3531)	24 (10837)
	Sassari	126769	2 (922)	39 (2083)	27 (4059)	9 (2954)	19 (7217)
	Siracusa	121605	7 (561)	36 (2393)	29 (4912)	16 (3392)	18 (6353)
RV2	Belluno	35710	1 (271)	15 (702)	13 (1336)	4 (1033)	12 (3931)
	Cassino	36497	4 (539)	9 (869)	8 (1701)	4 (1217)	13 (5212)
	Fabriano	30809	1 (160)	8 (490)	6 (1093)	3 (809)	7 (1957)
	Gorizia	34411	1 (176)	13 (571)	11 (1173)	4 (1022)	14 (3137)
	Gubbio	31736	1 (138)	14 (565)	11 (1137)	1 (776)	5 (2020)
	Nola	34467	1 (117)	18 (986)	9 (1917)	3 (1375)	16 (3905)

Table 6

Number, type and capacity of schools and hospitals. Number of students and hospital beds are shown in parentheses.

Public buildings	Type of facilities	RV1	RV2
School	Kindergarten	30 (2239)	12 (779)
	Primary school	23 (4552)	11 (1560)
	Middle school	11 (3170)	3 (1165)
	High school	16 (7990)	11 (3769)
Hospital	Hospital	3 (916)	2 (262)

(<https://unica.istruzione.gov.it/portale/it/scuola-in-chiaro>), which was consulted to complement the dataset in cases where information was missing from the first source. For hospitals the “Ministero della Salute” website can be used. Through the website, it is possible to access the ‘Open Data for Public Health’ section (<https://www.dati.salute.gov.it/>), which makes available numerous datasets containing publicly relevant health-related information. The Hospitals section was considered, in particular the data related to hospital bed capacity (number of beds, type of beds, departments available, etc.).

Once the number of Schools and Hospitals were determined, it was necessary to position them in the VTBs. To geolocate schools and hospitals within each VTB, the estimated number of required facilities was converted into the corresponding floor area using design criteria defined by national regulations (i.e., 6 m² per student and 32 m² per hospital bed), as established by the building standards on national school (D.M. 29/175) and the national and regional law on sanitary buildings requirements (L.R. 36/1990 – Calabria Region, DM 70/2015).

Subsequently, considering the building footprints available for each VTB (see e.g. Figs. 8(a) and 9(a)), a set of buildings with a total floor area equal to the required area for schools and hospitals, respectively, was identified. In particular, based on data of the six reference cities for each VTB, an average floor area for each facility was estimated. This value was used as a reference to identify buildings for which the combination of footprint area and number of floors were compatible with the expected size, while allowing some variability to reflect the natural differences among real facilities. The number of floors was assigned to each building based on the distribution of building heights reported in the ISTAT census for each census section. In the case of schools, building selection was guided not only by floor area requirements but also by the spatial location of the building (i.e., a higher number of schools was allocated to census tracks with higher number of inhabitants, see section 2.3.1) and the accessibility to the road network.

The resulting Schools and Hospitals are represented in Figs. 8(b) and 9(b) for RV1 and RV2, respectively.

2.3.2.3. Cultural heritage buildings. Although cultural heritage encompasses both tangible and intangible assets, the VTB primarily focuses on tangible heritage, such as monuments and buildings. Geospatial information on cultural heritage buildings is derived from the national database of the Italian Ministry of Culture (<http://vincoliinrete.beniculturali.it/vir/vir/vir.html?listaBeniImmobili=392733>) [64]. This database consists of point coordinates associated with three textual attributes: (i) the name of the asset; (ii) the class (i.e., architecture, archaeology, or open space); and (iii) the typology (e.g., abbey), comprising approximately 400 individual types.

Starting from the original database, several processing steps were undertaken to create the heritage building component of the VTB. First, for each portion of the assembled urban area, new polygonal footprints of cultural heritage buildings were manually delineated

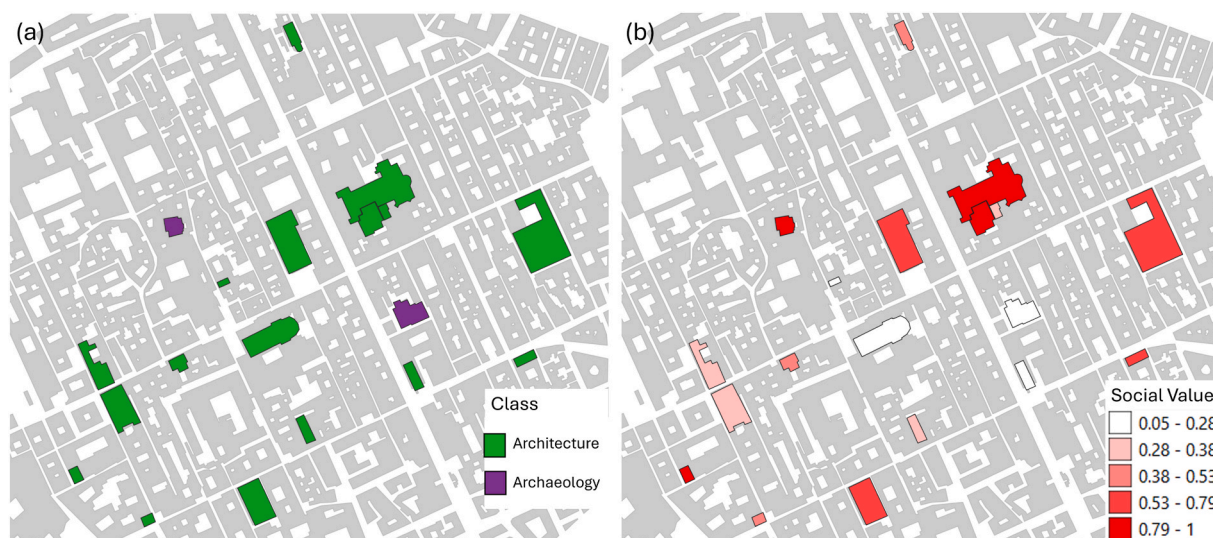


Fig. 10. A close-up view of cultural heritage buildings classified by type (a) and by social value (b) in a portion of Coastal RETURNVILLE. Building locations were derived from the Italian Ministry of Culture national cultural heritage database.

based on the corresponding point features from the Ministry of Culture database, preserving the original locations and enriching the dataset with relevant key attributes.

The resulting polygon shapefile includes various typologies belonging to the architectural and archaeological classes (Fig. 10(a)), such as churches, noble palaces, museums, and towers. Each record was then enriched with an ad hoc taxonomy [65], developed specifically for multi-risk analysis, which is based on the most common geometric characteristics of the buildings (e.g., tall and slender for towers, equidimensional for churches) and their broad category (six classes).

This taxonomic classification enables the assignment of a hazard-specific vulnerability class (five classes, ranging from very low to very high), based on expert judgment. Finally, to complement information on location, geometry, and vulnerability with aspects related to heritage value, two additional attributes were included: the annual number of visitors, used as a proxy for tourism revenue and indirect losses [66], and the social value of heritage (Fig. 10(b)), intended to capture intangible components and role in community identity [67].

2.3.2.4. Open spaces. Information on open spaces may be essential for analyzing certain types of urban risk, as well. Open spaces within a city - such as parks, plazas, courtyards, gardens, and undeveloped land - are areas not occupied by buildings or infrastructure and are typically accessible for public or ecological purposes. They play a vital role in the urban system, both functionally and environmentally. From a risk assessment perspective, open spaces are key for several reasons. They not only influence exposure and vulnerability conditions but may also affect hazard processes. For example, in the case of pluvial flooding, open spaces enhance water infiltration, temporary storage, and runoff regulation, thereby reducing surface water accumulation in densely built environments. During heatwaves, they help mitigate urban heat island effects by enhancing natural ventilation, evapotranspiration, and shading, thereby lowering ambient temperatures. Thus, incorporating open-space information into urban risk models improves the representation of hazard dynamics, exposure and vulnerability and help to identify areas with limited adaptive capacity or restricted space for evacuation, cooling, or water absorption.

In the present study, however, open spaces are not explicitly modeled within the VTBs. Nevertheless, information on open spaces can be indirectly inferred through urban morphology characteristics (e.g., built-up density, coverage ratio, and block configuration), which are considered in the definition of urban portions of VTBs. In addition, if a detailed representation is required, since the VTBs are constructed by merging portions of existing urban areas, information on open spaces can be derived from open-source geospatial data, such as satellite imagery (e.g., imperviousness or land cover products) or local spatial datasets. The integration of such data represents a potential extension of the framework for analyses where open spaces play a more explicit role in risk assessment.

2.3.3. Networks

The network system component within the conceptual model proposed may be further decomposed in Transportation network and Utility network, see Fig. 11.

At the present stage, the structural foundation of the two VTBs RV1 and RV2 comprises the road network, the water distribution network and the urban drainage system.

2.3.3.1. Road network. Road Networks (RNs) represent a critical component of urban infrastructure and serve as a primary lifeline for communities. Under normal conditions, they form the backbone of economic development, enabling the daily movement of goods, services, and people. Their role becomes even more strategic in the aftermath of natural disasters, when road networks function as evacuation routes, support emergency operations by ensuring the passage of rescue vehicles, and provide access to vital facilities such as hospitals, fire brigades, and external supply routes [68].

Roadway systems are complex networks composed of various elements such as roads, bridges, and tunnels. Some of these components are highly vulnerable and often require lengthy repair times or involve rerouting difficulties. Their disruptions can severely affect emergency efforts immediately after an earthquake and hinder rebuilding and business activities in the following period. Damage may occur due to direct effects (e.g., fault rupture, settlement, landslides) or indirect effects (e.g., debris from collapsed buildings, flooding, tsunami deposits, or damage to underlying pipelines). Bridges, in particular, are recognized as the most fragile elements of the system; their failure can lead to severe traffic delays and service interruptions, amplifying indirect losses across the

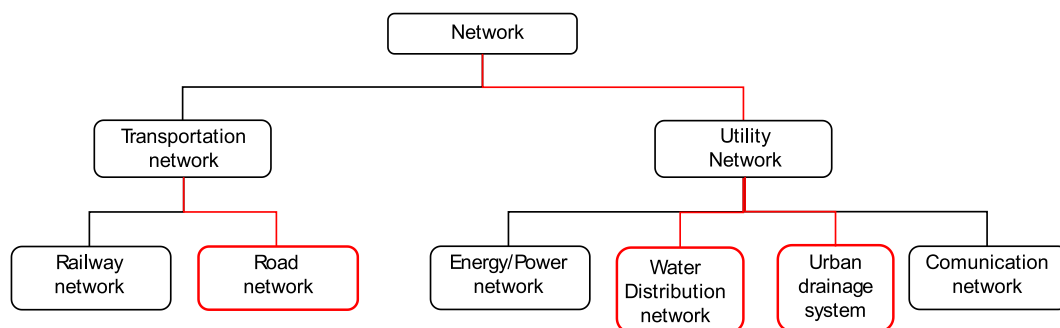


Fig. 11. Taxonomy of networks (adapted from (adapted from Pittore et al., 2023)).

affected region.

Within the present structural foundation of the VTBs, bridges are included as part of the road-network graph and are therefore represented as connectivity-relevant infrastructure elements. However, the current model does not yet assign bridge-specific structural attributes such as construction class, age, material, span configuration, or condition state, nor does it include bridge-specific fragility relationships. Accordingly, the present paper captures the functional role of bridges in the transportation network, while detailed bridge vulnerability modeling is left to future developments.

The road network was assembled via a simple but consistent preprocessing and harmonization workflow. OpenStreetMap (OSM) data were first filtered to include only roads and bridges relevant for vehicular traffic and emergency operations. The resulting network was then represented as a graph, with road segments as edges and intersections as nodes. For both VTBs, the road graphs extracted from the selected urban fragments were merged and connected through interface checks aimed at preserving continuity between adjacent fragments, thus ensuring a coherent accessibility pattern across the assembled virtual environment without introducing unnecessary complexities. In the present version of the VTB, the road network represents the simplified geometry and connectivity of roads and bridges relevant for vehicular traffic and emergency operations. The network is modeled as a graph, with road segments as edges and intersections as nodes. The VTB does not include a full segment-level transportation inventory with attributes such as lane count, traffic capacity, operational speed, or pavement condition, which may be introduced in future applications.

The selected roads correspond to actual layouts from the reference cities, reflecting the evolution of the built environment (from historical centers to modern districts). When merging different urban portions, roads were carefully connected to maintain continuity between neighborhoods and ensure realistic accessibility. The same criteria were applied for both inland and coastal virtual environments. Fig. 8 (a) and 9(a) show excerpts of the resulting road network for RV1 and RV2 respectively.

Beyond their primary role in transportation, the road network also serves as a foundation for other infrastructure layers within the testbed, such as water distribution (section 2.3.3.2) and drainage systems (section 2.3.3.3). This integrated approach reflects the interdependence of lifelines in modern cities, where the functionality of one system often relies on the accessibility provided by another.

2.3.3.2. Water distribution network. Water Distribution Networks (WDNs) are the backbone of thriving communities, safeguarding health and driving social and economic progress. Their architecture is strongly shaped by the environmental, social, and economic context, as well as by the location and availability of water resources. The systemic nature of a water distribution network, whose primary objective is to convey water resources to end users through a pressurized system, does not allow for the direct integration of portions of existing real-world infrastructures within portions of real urban contexts, in line with the approach adopted for the conceptualization of the VTB.

Hence, two complementary strategies were adopted to construct the WDNs in the RETURNVILLE testbeds. For the inland RETURNVILLE (RV2), the WDN was obtained by adapting a real-world network to the configuration and population distribution of the virtual city. For the coastal RETURNVILLE (RV1), instead, the network was designed from scratch using engineering design procedures based on urban morphology, population distribution, and hydraulic design criteria. This dual approach reflects the different morphology of the two RETURNVILLES and their likely supply configurations, which make the direct adaptation of the reference real-world network unsuitable for RV1. At the same time, it allows the testbeds to combine infrastructure realism (RV2) with full transparency and reproducibility of the design process (RV1), as further discussed at the end of this section.

2.3.3.2.1. Water distribution network for inland RETURNVILLE. The first strategy is applied to the inland RETURNVILLE (RV2). It consists of adapting a complete real-world network, previously analyzed within the RETURN project, to the entire RV2. This network presented a layout, supply scheme, and topographic variability compatible with the virtual city under study, thus achieving a realistic yet depersonalized representation that preserves confidentiality while enabling the elicitation of general design insights and operational guidelines. This approach involved two subsequent steps, as described in the following.

The initial placement of the network was defined by analysing the compatibility between RV2's most populated census tracts and analogous areas in the original city, as well as by identifying a suitable area within RV2 to host the cluster of wells constituting the main water source of the system. In particular, historic city centers were aligned with their counterparts in the reference city, residential districts with residential districts, and well fields were positioned in areas consistent with the configuration of the reference network (i.e., outside the most densely populated zones but still within the inhabited territory). Key demand nodes, including high-demand facilities such as hospitals, were also used as anchor points for the alignment. The road network was deliberately not used as a matching criterion: although aligning the network with RV2 roads would have been feasible, it would have introduced a spurious geometric constraint without improving hydraulic realism and could have made the reference city more easily identifiable. The overlap between the real and virtual networks was performed through a rigid geometric transformation (translation and rotation, with no scaling), which preserves all metric properties of the original network such as pipe lengths and spatial relationships between nodes. The resulting alignment was validated through both visual inspection and quantitative checks, verifying that the number of demand nodes and their spatial distribution remained consistent with the structure of the reference network and compatible with the urban layout of the virtual city.

Subsequently, demand nodes, wells, pumping stations, fire hydrants, and isolation valves of the final network were obtained by extracting the elements located within the RV2 boundary. The extraction buffer for pipes was extended by 500 m to include alternative paths connecting peripheral nodes. Each building was connected to its nearest demand node, and unconnected nodes were removed to avoid excessive fragmentation of the demand and to simplify visualization. This simplification does not compromise generality, as higher demand node density typically corresponds to areas with greater building density.

In the absence of more detailed data, residential demand was estimated by assigning the inhabitants of each census tract to buildings proportionally to their floor area, assuming an average domestic consumption of 183 L per person per day. This value is consistent with operational data associated with the reference real-world network. Because RV2 derives from an existing infrastructure system, local consumption values were retained to preserve consistency with the original hydraulic configuration, rather than adopting the national average value (204 L per capita per day) reported by ARERA (2023). The difference between these values is relatively small and would not significantly affect the hydraulic behaviour of the network; however, the original value was maintained to reflect the modelling approach adopted for this testbed.

Commercial, institutional, and industrial demands were estimated based on the corresponding values from the original network.

Finally, during the network refinement phase, all elements were adjusted to the Digital Elevation Model (DEM) and pumping station settings were fine-tuned to satisfy the validation criterion for water pressure, maintaining values within the $[z + 20 \text{ m}, z + 30 \text{ m}]$ range, where z is the ground elevation at each node. This pressure range – confirmed by the network operator – is a standard operational criterion for Italian urban water distribution systems, ensuring adequate service pressure at user nodes while avoiding excessive pressure levels that may increase leakage and pipe stress.

The final configuration of the RV2 WDN hydraulic model comprises 1,326 demand nodes (including 4 high-demand ones), 14 wells, 17 pumping stations, 661 hydrants, and 6,228 pipe segments for a total network length of 188 km. Fig. 12 shows the demand nodes (in yellow) and a subset of the wells (in red) geographically located in RV2. The position of the demand nodes with respect to the buildings highlights that demand nodes do not represent individual users or buildings, but aggregates of multiple buildings.

This configuration ensures that the RV2 WDN preserves the robustness, redundancy patterns, vulnerability characteristics, and topological complexity of the original network. Because real-world hydraulic parameters (e.g., pipe diameter, length, material, and pump characteristics) are retained for all components, the resulting WDN includes a credible mix of pipe materials – such as cast iron, asbestos cement, steel, and polyethylene (PE) – and a realistic range of diameters. This composition reflects the historical development of the infrastructure and the progressive replacement of older assets with larger diameters and more suitable materials over time, consistent with the evolution of the reference cities used to construct RV2. This approach is potentially scalable to larger urban settlements.

Due to confidentiality and security considerations, the real city on which the RV2 WDN is based on, as long as the files containing

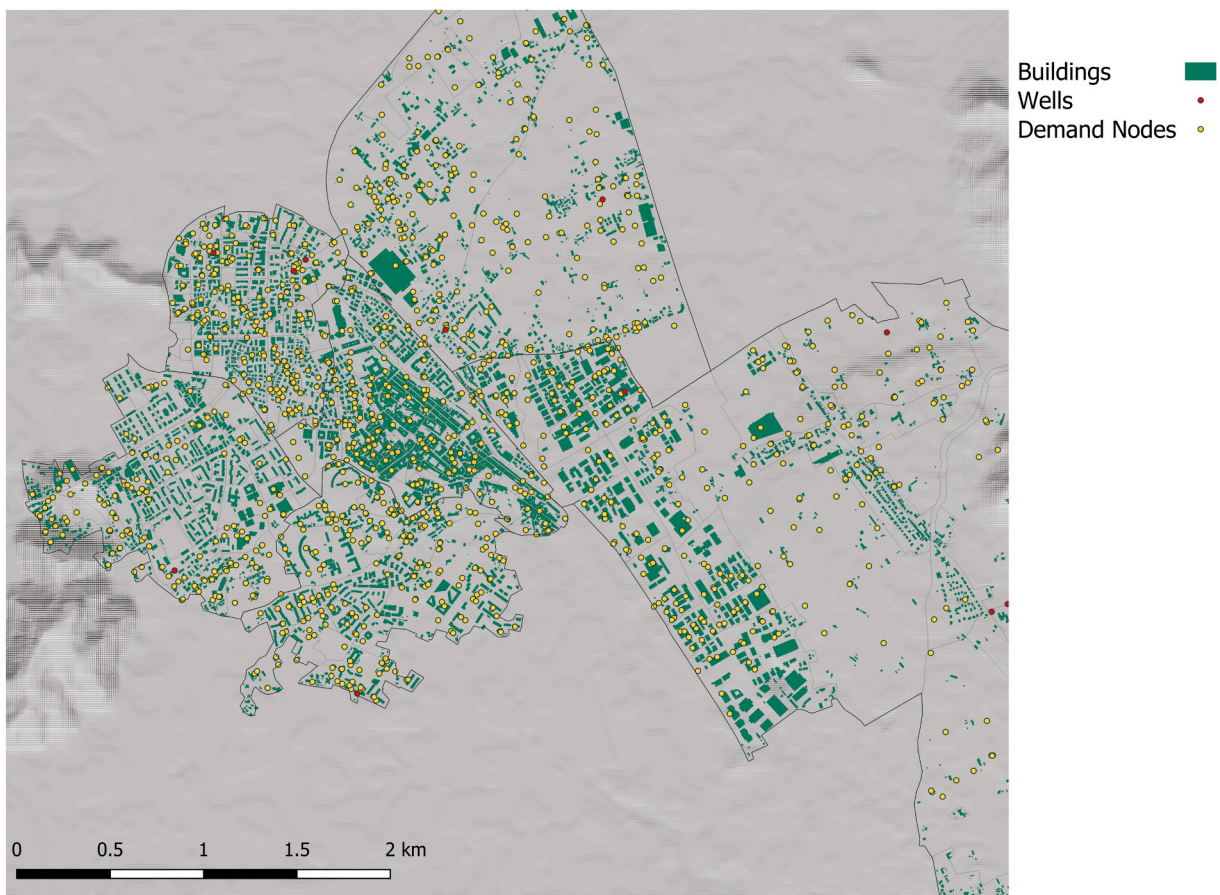
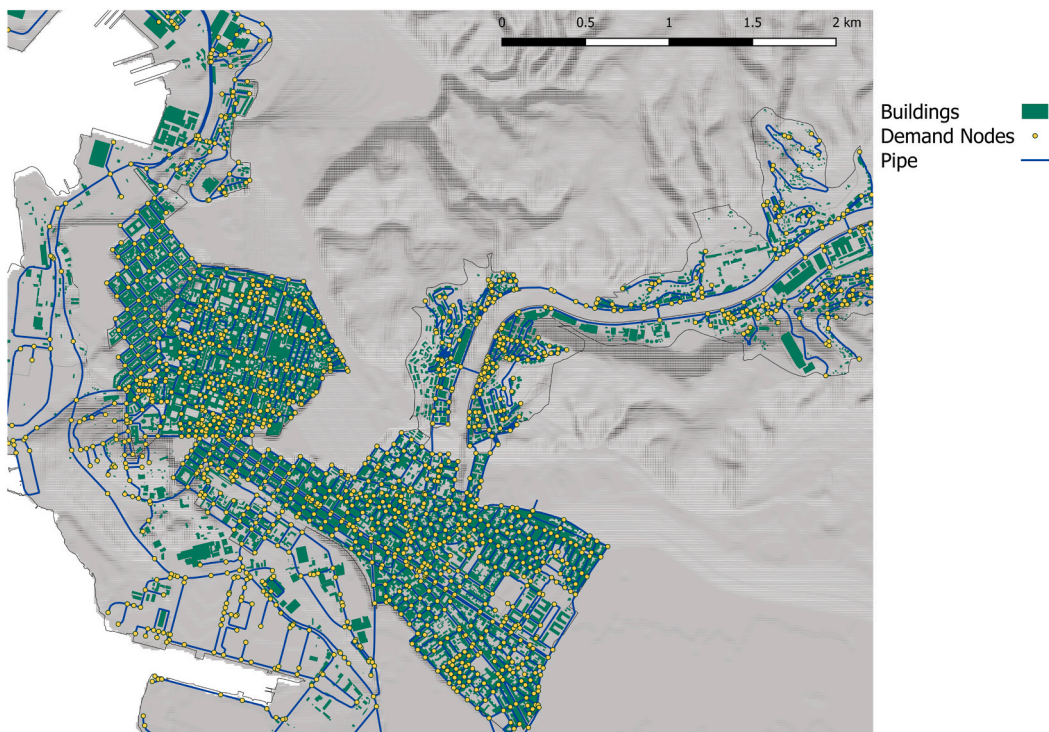
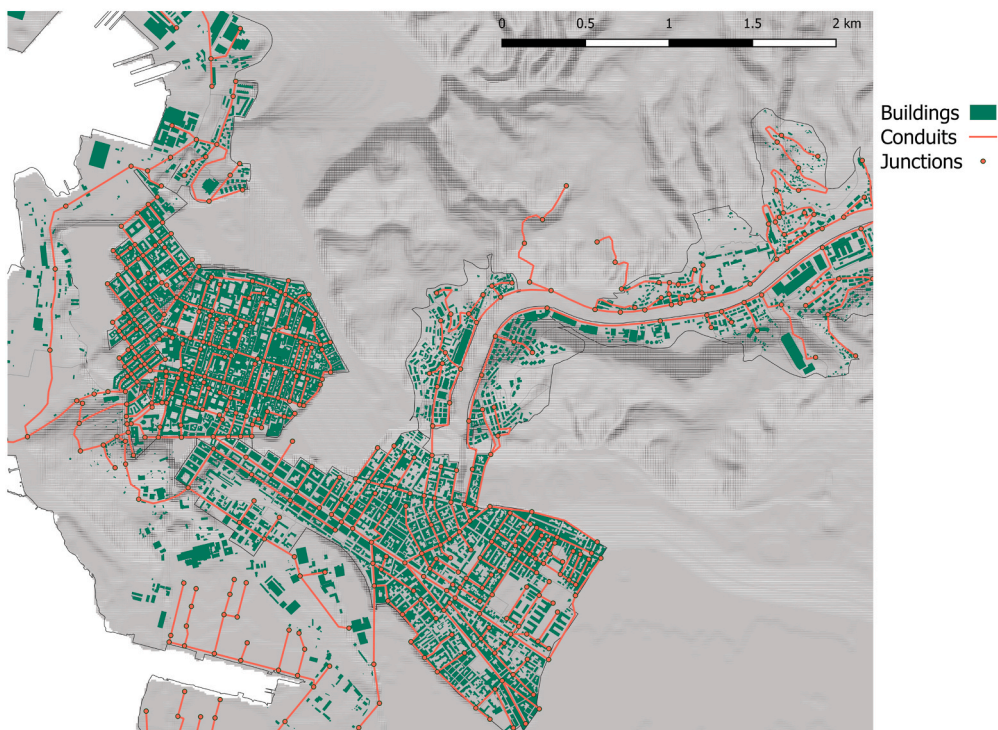


Fig. 12. Details of the water distribution network for the Inland RETURNVILLE.



(a)



(b)

Fig. 13. Details of the water distribution network (a) and the sewer network (b) for the Coastal RETURNVILLE.

hydraulic data for RV2, cannot be shared publicly. They may, however, be made available upon request to the corresponding author, subject to authorization by the network operator.

2.3.3.2.2. Water distribution network for coastal RETURNVILLE. The WDN of Coastal RETURNVILLE (RV1) was designed based on key input data, including the road network, the spatial distribution and footprint area of buildings, and population data at the census section level. RV1 extends mainly along the coastline, with a part that develops in an internal valley whose stream flows into the sea, partially crossing the urban area. RV1 WDN was designed starting from the roads map and its configuration reflects this spatial layout, ensuring service coverage across both the coastal and inland sectors while accounting for variations in population density and building distribution (see Fig. 13(a)).

Concerning water resources, it has been considered a well field that extracts water from the alluvial deposits of the valley floor, with pumping restricted by groundwater levels to mitigate saltwater intrusion. Furthermore, water resource is also supplied jointly by exploiting two springs. Due to the gravity-fed spring supply and the topographic variability, pressure control must be differentiated, with the installation of pressure reducing valves where necessary.

The daily water supply and linear water losses were based on the average values reported for Italy by ARERA (2023), equal to 204 L per capita per day and 17.9 m³/km/day, respectively. Likewise, the material composition of the network pipes was assumed following the percentage distribution as overall observed in Italian water distribution pipes (ARERA, 2023).

RV1 WDN was designed through a methodological framework that replicates the typical engineering steps followed in the construction of WDNs. The advanced hydraulic (physically-based) model of a real-world water supply network has been implemented in WNTR Python package [69] able to perform multiple analysis using the pressure-driven model Epanet 2.2 as hydraulic model.

In the methodological framework the first module focuses on the potentially most suitable paths for transferring water resources using a graph theory based – algorithmic approach to identify a connected subgraph named Primary Network (PN) [70]. Furthermore, the PN constitutes the supporting infrastructure for implementing WDS sectorization, which is necessary due to the elevation variability present in RV1. The sectorizing process evolves by a Tabu Search algorithm [70] to optimize objective functions tailored in this case on the topology of the WDN. Finally, pipe diameters were assigned based on design criteria ensuring proper hydraulic performance and cost minimization [71].

The final configuration of the RV1 WDN hydraulic model comprises 2.650 nodes (including 5 wells, 2 springs and 2 tanks) and 3.293 links (3281 pipes, 7 control valves and 5 pumps) for a total network length of 277 km.

2.3.3.2.3. Exposure model characteristics and transferability. The adoption of two different approaches for developing of the WDNs in RV1 and RV2 allows the virtual testbed to represent two complementary modelling strategies commonly encountered in risk and infrastructure studies, as well as different potential use cases.

The network implemented in RV1 – designed from scratch using standard engineering procedures – ensures full transparency and reproducibility of the modelling process and allows the network model to be openly shared with the research community and directly reused to extend analyses or test alternative methodologies. In this sense, RV1 offers greater transferability at the methodological and data-sharing level.

By contrast, the network implemented in RV2 derives from a real-world infrastructure system and therefore preserves infrastructure heterogeneity (pipe materials, diameters, age distribution), redundancy patterns, and operational parameters. Although this approach limits data sharing due to confidentiality constraints, it provides exposure assessments that can be more easily extended to, or validated against, other real-world systems with similar characteristics, making the results more directly relevant to infrastructure operators. Furthermore, it demonstrates the feasibility and value of integrating realistic, operator-informed infrastructure configurations within the virtual testbed framework. In fact, this enables infrastructure operators to analyse how their networks may respond to extreme natural events, while providing emergency management authorities with more credible infrastructure constraints and response scenarios for emergency planning.

Together, these two approaches allow the virtual testbed to balance methodological openness with operational realism, emphasizing its value as a tool for both the research and practitioner communities.

2.3.3.3. Urban drainage system for coastal RETURNVILLE. The urban drainage system was designed based on key input data, following the layout of roads, buildings, and elevation changes based on EPA Storm Water Management Model (SWMM). The procedure was developed starting from the road graph, the buildings' layout and the elevation map. The network was built considering a combined use (sanitary + pluvial sewers), following as much as possible the natural slope of the urban context. To address this task, recent methods use GIS data – notably road networks, building footprints, and elevation maps – to infer urban drainage networks automatically. This approach rests on the observed correlation between street layouts and underground sewer lines: sewer pipelines frequently run beneath or alongside roads.

In particular, the applied approach in Coastal RETURNVILLE uses *street layouts*, *topography*, and *land cover (including buildings)* to estimate belowground stormwater pipes. The method operates as follows:

Step 1: Data Acquisition. Relevant spatial data layers are gathered for the region of interest. Including the road network (graph of streets), high-resolution DEM for terrain, land use/land cover data to identify impervious surfaces and building footprint maps to locate structures. Data are preliminarily verified for consistency, interconnection and possible simplification by automatic routines typical of river trees analysis.

Step 2: Preprocessing and Attribute Extraction. Raw data are processed to enrich each road segment with hydrologically relevant attributes. The main operations include: (a) DEM conditioning and slope calculation; (b) estimation of road width based on distances between building footprints, used to assign an approximate number of lanes and the right-of-way (ROW), with a buffer equal to half the

ROW on each side of the road centerline; and (c) assessment of land use and building density, where a high building footprint area within the buffer indicates greater imperviousness and runoff potential. At the end of this phase, each road segment is characterized by length, slope, road category, estimated width, predominant land cover, and building footprint area.

Step 3: Graph Weighting for Water Transport Significance. The method evaluates the likelihood that a road conveys stormwater. To this end [72], introduce the Integrated Weighted Betweenness Centrality (IWBC) applied to the street network. IWBC integrates four main factors: (1) road type, (2) land use/land cover, (3) building footprint density, and (4) estimated flow capacity of a hypothetical pipe beneath the road. These factors are converted into numerical weights through classification into classes, assigning lower weights to more critical streets to increase their prominence in the graph. Betweenness centrality analysis then identifies road segments that most frequently occur along shortest paths between runoff source locations and drainage outlets, highlighting streets that are most relevant for urban drainage.

Step 4: Extracting the Drainage Network. Road segments with very low IWBC values are progressively removed, while those with high values are retained. Because IWBC values are highly skewed, the Drainage Adequacy Classifier Index (DACI) is introduced as a threshold parameter [72]. IWBC values are classified (e.g., using the Fisher–Jenks method), and the DACI (ranging from 0 to 1) controls the proportion of low-importance roads to be removed. Higher DACI values result in more complete networks, whereas lower values produce more parsimonious ones. After thresholding, any isolated subnetworks are eliminated. The result is a predicted urban drainage network, with assigned flow directions and preliminary estimates of pipe slopes and sizes.

In this study, we consider four street attributes, namely, land cover type, road type, the discharge capacity of its associated storm drain pipe, and the building footprint, using integer, string, float, and float data types, respectively. First, we normalise each attribute using data binning (i.e., dividing the values into 5 categories and assigning each category an integer from 1 to 5). These integer values correspond to different levels of relative importance, starting from very high (1) to very low (5). After transforming all of the attributes into edge weights by normalizing them to the range [1,5], we compute the integrated weight of edges (IWBC) by taking the average of four weights in order to consider all the criteria equally important for the classification of roads with respect to drainage importance. Only 5% of the streets were classified in the highest class of relevance (0-1). The DACI was used as a threshold to apply to IWBC to remove less important streets from the main drainage system. A preliminary analysis showed that assuming DACI lower than or equal to 3.2, thus removing 64% of the streets, produces fragmented drainage systems, losing system continuity. In the coastal testbed, DACI was set to 4.3, with a drainage pipe installed on 80% of the streets.

The final network comprised approximately 970 nodes, 920 pipes, 8 pumping stations, 9 outlets, and 680 urban catchments (see Fig. 13(b)).

While the above methodology is automated, human expertise can be integrated at several points to improve results. One obvious role for user input is in choosing the DACI threshold or adjusting weighting factors to reflect local knowledge. Human supervision is also crucial for defining inputs such as the location of outfalls or catchment boundaries - as in Reyes-Silva et al.'s tool [73], where the user determines the sewer outlet and area of interest.

The Urban Drainage System was not designed for the RV2 because the inland testbed is characterized by a complex morphology with several hills and sinks. In this situation, natural slopes direct surface and underground drainage flows towards different concentration points, breaking the underground drainage system into several sub-systems and requiring a large number of underground pumping stations. In the real world, such conditions would have been addressed alongside urban evolution by filling sinks and adapting urban morphology to allow wastewater to be removed from urban areas and discharged naturally to the final receiver. Such an issue was not present in the coastal testbed due to the higher slopes and the natural degradation of elevations toward the coast, making the urban drainage layout much more realistic.

3. Multi-risk assessment: a bottom-up approach

Virtual city models must be able to solve problems related to the integration of different layers in a consistent simulation process. In this sense, the VTBs created in RETURN have the ambition to allow the simulation of the whole management processes of multi-hazard conditions with a holistic approach (from prevention to contrast), allowing to test and exemplify the simulation tools of different hazards and risks developed, among others, by researchers in RETURN. In particular, the RETURNVILLEs as digital models of the VTBs developed in RETURN, should enable to visualize all the relevant factors of risk, including the hazard intensity distribution, exposed elements characterized by their vulnerabilities, as well as the hazard impacts and the effect of applying mitigation and adaptation strategies, e.g. through the application of what-if scenarios.

However, the extreme complexity of the problem hinders the feasibility of seamless modeling encompassing all elements and risks in a single process.

To enable holistic simulations, in the CityPhysiology approach Meta et al. [10] propose a conceptual framework to facilitate the integration of different layers of the urban system. In this approach they refer to a conceptual modeling of the urban system that is based on the City Anatomy proposed by the City Protocol Society. The City Anatomy also contains a proposal for Foundation Ontology linked to the conceptual model of the city that is the basis of the description of the processes that can be activated in it [74].

Multihazard processes, which take into account the hazards, exposures and vulnerabilities of different relevant elements and systems as well as their functional relationships, can be described by ontologies appropriately constructed to explain relationships and hierarchies; these ontologies differ from the basic ones constructed for the explanation of the urban system, e.g. those introduced in it [74], in that they are risk-oriented. Griffo and Pittore [46] propose an ontology-based model enabling to represent Multi-Hazard Events in Urban Systems.

However, the extreme complexity of the problem of modeling multi-risk in complex urban environments does not allow for

modeling that encompasses all risks in a single process.

In this perspective, risk-storylines and impact chains, defined in specific contexts, are useful tools that support simplification with a pragmatic approach; this way, the simulation activities can effectively aid decision makers to test strategies and actions to reduce risk in urban areas.

In this paper, we propose a conceptual framework for the multi-risk assessment in urban VTBs that is based on an adapted version of the pipeline process presented in Ref. [10]. In such a scheme, presented in Fig. 14, the problem definition starts from suitable Risk Storylines (box 1) that are built for the context under investigation. The risk storylines [75] are complemented by impact chains allowing to identify the relevant layers underlying the system representation (box 2) as well as their relationship (box 3). Risk domain specific simulations are applied depending on the specific scope of the analysis; for example, suitable hazard dependent fragility or vulnerability curves are employed to derive expected impact on the relevant exposed assets such as building stock or population (box 4). Finally, the coupling strategy refers to the choice of common or synthetic indicators (e.g. direct economic losses) and scale (e.g. census tract level) used to represent the results (box 5).

The next subsection elaborates on the use of risk storylines and impact chains within the conceptual framework. The applications presented in Refs. [56] and [57], propose a focus on risk-domain specific simulations and coupling strategy. Section 3.2 presents some of the results from Ref. [56] to exemplify main aspects of multi-risk assessment according to the conceptual framework.

3.1. Risk storylines and impact chains

Climate and disaster risk storylines offer a powerful framework that can foster a comprehensive and holistic understanding of systemic risks and associated uncertainties, which in turn can improve decision-making processes across diverse sectors and scales. This approach is deeply rooted in scenario-oriented DRR practices but has been recently increasingly employed in the disciplinary context of climate science, recognizing its value to describe and explore the intricacy of climate-related processes [75], [76], [77]. Climate and risk storylines can be used to investigate and describe impacts from multi-hazard events and to stress-test emergency protocols and preparedness and prevention actions [75]. The latter, as possible CCA or DRM actions to be put in place in an area to manage and reduce the risk and/or adapt to worsening climate conditions, are largely dependent on the social/-institutional/governmental context for which they should be applied, often being conditioned on the culture or propensity to intervene as well as by social or economic barriers. Hence, risk storylines are more representative if co-developed with relevant stakeholders, including scientific advisors, local administrators, and population, for the specific context under investigation. Sub-section 3.1.1 offers a proposal towards the typification of the so called cultural infrastructure (as analogy to hard and soft infrastructure of the urban system) informed by political/social science perspective; being at a very preliminary stage of definition, such classification is not applied to the definition of the VTB, but can be used to investigate on the different cultural infrastructure between urban contexts belonging to different regions and urban archetypes.

In the context of RETURNVILLE risk storylines suitably developed in relevant urban contexts can complement virtual models to generate complex scenarios with narrative structure.

Impact Chains (ICs) have been developed as analytical tool to better understand, systemize and prioritize the factors that drive impact-related risks in a specific system of concern and have served as backbone for an operational climate risk assessment [78] and more recently in the context of disaster risk analysis (e.g., Ref. [79]). Impact chains are conceptual models that describe risk-related impacts in terms of cause–effect relationships within a socioecological system, focusing on identifying and describing important linkages between the different components of risks. ICs innovatively provide a conceptual description of risk that is consistent with the most recent interpretation (e.g., by the IPCC, Intergovernmental Panel on Climate Change) as well as the more historical DRR perspective. Additionally, they explicitly include and highlight the role of impacts in this conceptual representation. Impact chains have been used also in the framework of disaster risk reduction. In both applicational frameworks the main purpose is to:

- *co-develop a common knowledge* and understanding between experts and stakeholders of key risks, their underlying drivers and interactions for the specific context and specific risks,
- *structure the description and analysis of key risks* and their risk drivers for the current situation and potential future situations making use of the best quantitative and qualitative knowledge and evidence available,
- *identify key vulnerabilities*, gaps in risk management and entry points for risk mitigation and adaptation planning.

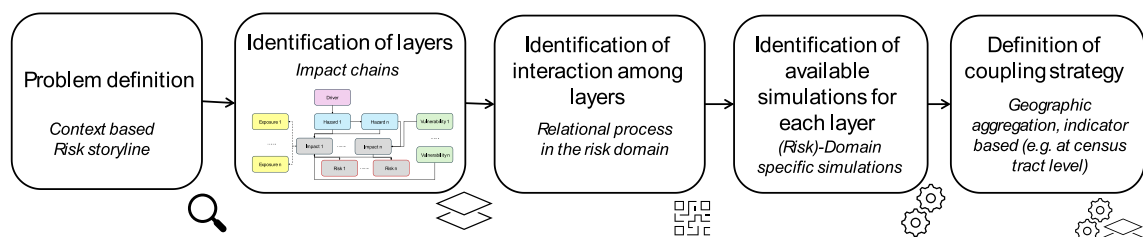


Fig. 14. Conceptual framework for the multi-risk assessment in urban VTBs.

Table 7
Fields of action in the Cultural Infrastructure.

Field of action	Action	Actor
<i>Risk understanding</i>	Updating, extending and deepening scientific knowledge relating to natural hazards through scientific research	A group of collective actors, formalized, active, and with recognized scientific expertise (e.g. university research groups, public and private research institutes).
<i>Risk government</i>	Development of strategies aimed at prevention, intervention, and reconstruction through the adoption of administrative measures with regulatory content.	A group of collective and individual actors with formal responsibilities and legitimate decision-making powers (e.g. municipal councilors responsible for civil protection, municipal officials and technicians, mayors, civil protection area managers).
<i>Risk learning</i>	Updating, disseminating, and consolidating the culture of vulnerability by involving the population in a broad or targeted manner to specific segments.	A group of collective (and individual) actors, formalized, active, and with recognized authority (e.g. local associations active in the field of civil protection, institutional actors such as the Chamber of Commerce, workers' and employers' associations).

3.1.1. Socio-political context and cultural dimension

The cultural infrastructure can be understood as the ensemble of operative models, relationships and interactions between people and organizations that can influence the prioritization between issues to be addressed, as well as impact operational decisions along with the outputs and outcomes of the actions taken. Therefore, the cultural infrastructure, in a broad sense, is relevant to ensure that DRR and CCA are operationalized and effective.

Cultural infrastructure is a long-term outcome of the specific context of reference and is linked to events of various kinds that have taken place within the community, to the specific characteristics of the economic groups in the area, and to the socio-political resources and traditions of the social fabric. This is an extremely complex intertwining, specific to each urban or metropolitan reality, with a partial but noticeable dynamism and, therefore, mostly elusive to any attempts at typification. The embeddedness of cultural infrastructures in social contexts requires the use of bottom-up approaches to grasp the possible link with DRR strategies. To promote an intersectoral and interdisciplinary approach in the modelling cultural infrastructures, it is possible to propose a working framework that moves towards the identification of certain factors with a certain degree of typification.

Firstly, the factors influencing and relevant for the cultural infrastructure in the context of DRR were defined by referring to the Sendai Framework (in particular in relation to Priorities 1, 2 and 4 respectively: Understanding Disaster Risk, Strengthening disaster risk governance to manage disaster risk and Enhancing disaster preparedness for effective response) and to Sustainable Development Goals (SDGs; in particular in relation to Goal 11 – Sustainable cities and communities). This led to the identification of three fields of action: a) Risk understanding; b) Risk government; c) Risk learning. Table 7 describes the actions associated with each identified field of action as well as the actors involved.

With the scope to investigate the specific characteristics of the three fields of action and the forms of interaction between them and possible risk management models, a specific investigation has been carried out as part of the activities in RETURN. In particular, three Territorial Processing Units (TPUs) were identified in which to conduct the analysis: 1) Genoa, 2) the IX Municipality of Naples (Soccavo and Pianura districts), 3) the Friuli Venezia Giulia coastline including Trieste, Lignano, Grado and Monfalcone. The TPUs were selected according to the following criteria: a) different territorial and administrative extent, b) different risk scenarios, c) different socio-demographic, socioeconomic and socio-political characteristics. The lack of homogeneity is explicitly aimed at facilitating the identification of variables whose salience may be independent of the differences between the territories. Within each TPU, mixed techniques (including interviews, workshops etc.) were used to identify the specific characteristics of the three fields of action and their interaction; the collected information and material is being analyzed with the scope to investigate the hypothesis on correlations, interactions or connections between specific configurations of the three fields of action and DRR models.

The outcome of this analysis can help characterizing the Virtual Testbeds in terms of the so-called cultural infrastructure context, also in order to hypothesize and simulate intervention scenarios in light of the characteristics of the three fields of action and the ecosystem they generate. This would help to identify the possibilities for implementing certain actions rather than others, or to establish whether the action is compatible with the system of relationships defined by the actors in the three fields of action.

3.2. Example application of the framework

To exemplify the framework, we briefly describe some features for one of the applications proposed in Ref. [56]. A multi-risk storyline scenario is considered for which a moderate volcanic event produces tephra fallout covering part of the inland RETURN-VILLE, followed shortly in time (within few days) by a moderate earthquake. In Fig. 15, showing a portion of the Impact chain developed in Ref. [56], it is possible to recognize the different components of risk, including hazard (light blue boxes), vulnerability (green boxes), exposure (yellow boxes), and impacts (grey boxes). In this simplified version of the impact chain only the impact on residential buildings is considered (physical damage to buildings), which are the sole element of exposure. Distinct building vulnerabilities can be considered with reference to the considered hazards, namely earthquakes or ash fall cover [80]. However, ash fall cover may affect the building seismic vulnerability due to larger mass temporarily present on the roof; this aspect may be explicitly considered in the modeling of combined vulnerability due to earthquake and ash fall cover and is formally indicated by the arrow “affects” linking the ash fall hazard with the seismic vulnerability.

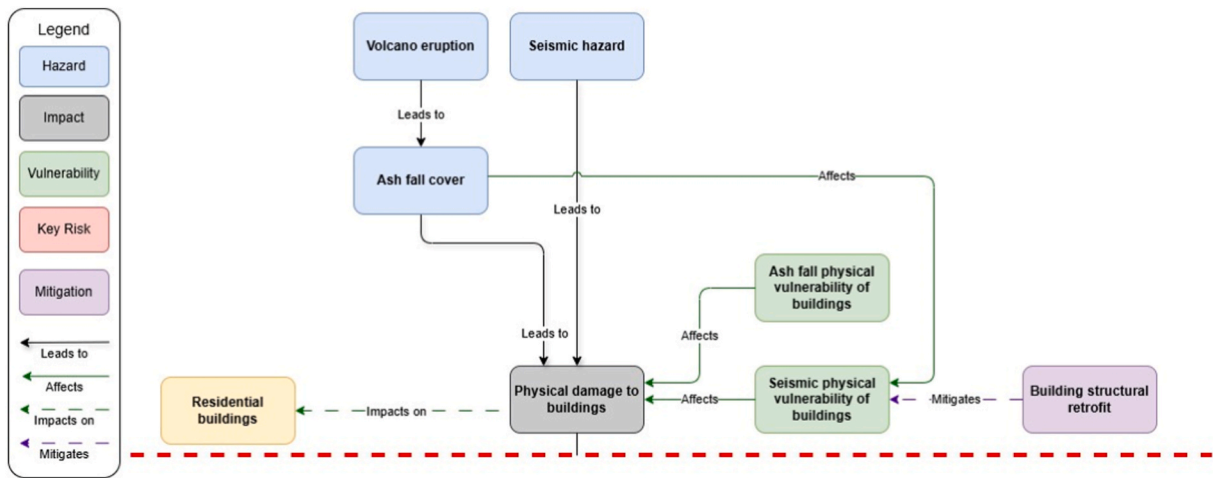


Fig. 15. Part of the impact chain considering seismic and ash fall cover hazards developed for RV2 (adapted from Ref. [56]).

Risk domain calculations are performed consistently to the geographic reference considered for exposure. Referring to census tracts as minimum geographic unit, this means that the hazard intensity should be evaluated for each census tract (e.g. peak ground acceleration - PGA - for the considered seismic hazard scenario or the thickness of ash fall cover), along with the percental incidence of each vulnerability class for the exposed elements (in this case buildings) in the same area. Within the VTb, hazard conditions are defined according to its spatial location within RETURNLAND. In particular, hazard intensity distributions are derived from numerical simulations carried out on the virtual territory, as presented in Refs. [81] and [25], with the resulting datasets also made available through dedicated online repositories [82], [83]. Vulnerability information for buildings - specifically vertical structural types and roof typologies - is instead assigned to census-based building classes stored in the VTb through classification rules. These rules define structural and roofing characteristics based on construction material and period of construction, following the approach described in Tocchi et al. [56].

The combination of hazard, exposure and vulnerability allows to evaluate the impact in the chosen representative metric for each census tract. For example, let us consider the (mean expected) number of collapsed buildings as representative impact in terms of physical damage to buildings generated by the sole seismic hazard (other metrics can be considered as discussed in Refs. [56], [84]); such impact can be determined evaluating, for each vulnerability class present in each census tract, the percentage of buildings in highest damage state (e.g., D5 according to the EMS-98 damage scale; [85]) for the given PGA according to the class-dependent fragility curve, and then multiplying such percentage by the total number of buildings in the census tract. In case of a combined scenario of ashfall followed by earthquake the interaction between ashfall and seismic action can be considered through the adoption of multi-hazard fragility function that suitably consider the critical role of ash-induced vertical loads in modifying baseline seismic vulnerability. As shown in Ref. [56], when accounting for the interaction between ashfall and seismic action a significant increase in building collapses with respect to the case of earthquake only may be observed.

The RETURNVILLE exposure model for residential buildings (see Table 4 for RV2) gives the distribution of buildings in relevant typologies; suitable vulnerability/exposure models (e.g. Refs. [86], [87]) can then be applied to assign vulnerability classes and corresponding vulnerability functions.

The multi-risk storyline scenario can be modified considering possible DRM actions put in place to reduce the risks. For example, suitable structural retrofit interventions can be put in place to reduce the seismic physical vulnerability; the purple box in Fig. 15 is added to represent the option of applying this kind of mitigation strategy. In the modelling process, the introduction of building structural retrofit has the effect of changing (reducing) the building's seismic vulnerability and eventually the physical damage (impact) to buildings.

It should be noted that effective implementation of DRM action depends on the socio-political context underlying the urban system. As observed in section 3.1.1, different cultural infrastructure may influence alternative choices among mitigation strategies, and this aspect can be captured in different risk storylines. The cultural infrastructure is shaped by the different fields of action; among the three considered, the risk government one has a major influence on the selection among alternative mitigation strategies. However, depending the urban context, also the other fields of action can be relevant, for example in contexts where the Risk learning field of action is very well developed, the culture of risk is more widespread and the population can be more inclined to adopt mitigation interventions with respect to other contexts. Accordingly, the storyline may be changed hypothesizing different mitigation alternatives such as a) building structural retrofit for all the buildings having high vulnerability; b) building structural retrofit for 50% of the buildings having high vulnerability. The residential building exposure is modified accordingly by changing the percental incidence of highly vulnerable constructions in the building stock.

4. Development of what-if scenarios to support risk adaptation and mitigation

The development of the two virtual cities can support decision-makers in the implementation of what-if scenarios for the transition towards more resilient and livable urban settlements. *What-if* scenarios are decision-making support tools based on the methodological approach of Scenario Planning (SP) for risk management.

The SP approach emerged after the Second World War as a strategic approach to support decision-making in imagining future scenarios in the military field. It then expanded into many other fields of knowledge, including urban and territorial planning and design for risk management [88]. Scenarios can be developed starting from the construction of risk storylines and impact chains, also taking into account interaction with stakeholders [75], [89]. Furthermore, considering climate change-related factors, international organizations have already developed the Shared Socioeconomic Pathways (SSPs), i.e. future climate scenarios based on different levels of greenhouse gas concentration in the atmosphere according to different socioeconomic scenarios that consider the introduction or not of measures to contain emissions [90].

In the field of decision support for environmental, natural, and anthropogenic risk mitigation and adaptation design, what-if scenarios are hypothetical scenarios used to verify the impact of design actions, supporting stakeholders through the systemic variation of different variables and parameters [91]. In what-if scenarios, it is possible to perform simulations with/without mitigation and adaptation interventions and verify the results by introducing specific indices or indicators, quantitative or qualitative, for the status of ex-ante and ex-post scenario assessment [92], [93].

Built on real case studies and therefore using real and no non-simulated data, the what-if scenarios applied to the two RETURNVILLE cities allow realistic scenarios to be developed, highlighting certain conditions of hazard, vulnerability and exposure in order to understand the response of the urban system in all its complexity. The systemic construction of the virtual cities based on a holistic approach and on the identification of urban taxonomies and ontologies allows the application of design intervention categories, verifying their resilient effectiveness even in terms of aggregate, cascade or compound impacts. As example, the application of different building retrofit solutions (e.g. the alternatives a) and b) introduced in section 3.2) can be seen as *what-if* scenarios producing a measurable variation of potential impact on the exposed elements. The objective is to support decision-makers not in identifying the best scenario but in assessing the potential impacts of actions in multiple sectors or systems according to the proposed alternative design scenarios [94]. In this perspective, *what-if* scenarios enable strategic decision-making, also facilitating interaction between different stakeholders through impact assessment.

Another possible use of the *what-if* scenario approach is in foresight analysis, where the future hazard or exposure components can be varied. For hazards, we may expect an exacerbation in intensity and frequency of meteo-climatic phenomena and perils due to climate change, while for exposure it is possible to consider its variation due to population flows associated to migration or a contraction due to lower birth rate.

5. Conclusions

The foundational structures of two VTBs developed to represent realistic urban systems in Italy is presented, along with a methodological approach for multi-risk assessment in VTB representing complex urban environments based on the use of risk-storylines and the associated impact chains.

The two VTBs are: a coastal RETURNVILLE (RV1) that represents a typical town of about 115000 inhabitants developed along the Italian west coast and an inland RETURNVILLE (RV2) that represents a town of about 38'000 inhabitants laying in an intra-mountainous plane.

With the aim to develop realistic VTB, even if not referring to real existing communities, both urban systems are conceived as union of urban parts of real cities. Differently from previous examples of VTB, where the urban systems were designed based on urban planning principles and considering data generation algorithms, the innovative approach adopted herein for designing the urban configuration of a VTB allows to create a digital model that is fed by real data, even if the assemblage itself is a fictitious collage albeit using carefully selected and merged urban parts. Moreover, both towns are imagined to be localized in RETURNLAND, an imaginary virtual land including the topography, geology and river basins that was specifically created to allow instantiating simulations and multi-risk workflows for assessing multi-risk at the territorial level [25]. The RV1 represents a town prone to flood, landslide or heatwave risks as well as to coastal flooding while RV2 is mainly exposed to seismic, flood and heatwave hazards. Both the towns can suffer the effects of volcanic eruption, due the presence of an active volcano in RETURNLAND.

The digital eco-system formed by RETURNLAND and the two RETURNVILLES is the first example of integrated territory and city imaginary VTB environment allowing to instantiate multi-risk scenarios with a coherent seamless simulation-based approach.

The foundational structure of the RETURNVILLES is based on the Conceptual model of urban system and corresponding subsystems proposed in Ref. [45], considering the human living component as well as grey infrastructures for the system's description. In particular, the data on residential population and buildings are retrieved from census data available for the urban parts forming the RETURNVILLES. Census based data allow a first level definition of exposure enabling the instantiation of simulation and consequence models consistent with this scale of analysis. In addition to census data, the VTB is equipped with building footprints retrieved from available cartographic databases relative to the urban parts forming each VTB (i.e., [59], OpenStreetMap(R)). The visualization of building footprints allows the recognition of urban patterns and fabrics as well as open spaces that are relevant for the urban morphology characterization. School buildings and hospitals do not correspond to the real ones existing in the cities originating the urban parts used in the assemblage of the RETURNVILLES, while they are inserted as a new layer and assigned to selected shapes among available building footprints. To establish the number and type of schools and hospitals to be located within each VTB — along

with the corresponding number of students and hospital beds as well as the required area in m^2 —a procedure based on analogy with urban settlements belonging to the same urban archetype of the RETURNVILLES was implemented. On the other hand, the footprints for cultural heritage buildings and monuments were retrieved for each portion of the assembled urban area based on the corresponding point features from the Ministry of Culture database. The polygonal footprints of cultural heritage buildings were manually delineated creating a new polygon shapefile including various typologies belonging to the architectural and archaeological classes such as churches, noble palaces, museums, and towers.

Concerning the networks, the road network RN was the only one explicitly considered for transportation network, while for utility networks the water distribution network WDN and the urban drainage system were considered. The RN was built assembling the road network graphs derived from OpenStreetMap (OSM) data relative to the urban parts forming the two villes and carefully connecting them to maintain continuity between neighborhoods and ensure realistic accessibility.

To insert the WDN in the RETURNVILLES two different strategies were adopted: the first one, adopted for the inland RETURNVILLE consists in adapting an existing real-world network to the configuration and population distribution of the VTB, while the second strategy, applied to the coastal RETURNVILLE, consists in ad-hoc design based on key input data such as the road network, the spatial distribution and footprint area of buildings, and population data at the census section level. An analogous design-based procedure was adopted to establish the Urban drainage system of the coastal RETURNVILLE, considering as input parameters the street layouts, topography, and land cover (including buildings).

The two RETURNVILLE VTBs can be used as exposure models to test multi-risk impact assessment and the effectiveness of DRM and CCA strategies to reduce expected impacts. Following the methodologic approach for multi-risk assessment proposed in this study, the risk scenarios to be instantiated in each of the VTBs can be selected according to risk storylines and impact chains suitably developed in relevant urban contexts. A preliminary application dealing with multi-hazard risk planning considering coastal flooding and the effects of pyroclastic density currents generated by volcanic eruption is presented in Ref. [57] for the coastal RETURNVILLE. Concerning the inland RETURNVILLE [56], propose an application investigating on the effects of road blockages due to seismic event and also on the exacerbating effect that volcanic ash fall can determine on the impacts on the built environment if it is followed by a seismic event affecting the same area. Both the applications are the starting point for application of what-if scenarios allowing to investigate the effect of preventative mitigation actions oriented to reduce the impacts in a multi-risk framework.

Some limitations of the imaginary VTBs represented by the two RETURNVILLES should be acknowledged. Firstly, the selection of urban portions to form the final configuration of the imaginary VTBs may influence the resulting exposure and risk patterns; however, this approach was adopted to prioritize morphological representativeness over geometric standardization to better capture the heterogeneity of urban systems that is observed in reality.

Moreover, the exposure models for buildings and network components of the grey infrastructures forming the RETURNVILLES can be improved. For example, referring to census data and adopting uniform distribution of building characteristics within each census tract may be an inadequate approach in case of highly localized hazards (e.g., flooding, or pyroclastic density currents after a volcanic eruption), where spatial heterogeneity plays a significant role. Indeed, although the VTBs are equipped also with building footprints, this level of information may still be insufficient when accurate characterization of the building stock at fine spatial resolution is needed. In such cases suitable downscaling procedures should be employed, allowing to disaggregate available data into building-level information, as proposed in Ref. [57]. As for the networks, the power distribution network, that is an essential lifeline in cities whose malfunctioning can have cascading impacts also on other networks (e.g. water distribution network and telecommunications) should be added, along with other relevant transportation networks such as train or metro line networks if relevant.

Although Gaetani d'Aragona et al. in Ref. [57] and Tocchi et al. [56] propose some improvements of the exposure model presented in this paper, still several advancements can be considered and should be implemented for more exhaustive representativeness of the VTBs.

CRedit authorship contribution statement

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Declaration of competing interest

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

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Data availability

Dataset used for the construction of the VTBs has been made available in an open-access repository (<https://doi.org/10.5281/zenodo.18987490>)

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