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multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

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1. Technical references

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2. ABSTRACT

After presenting the Risk-Oriented Taxonomy and Ontology of Urban Subsystems and Functional Models (DV 5.2.1), the multi-criteria metrics and methodology for integrated exposure assessment (DV 5.2.2), relevant indicators and example algorithms for risk assessment (DV 5.2.3), this Deliverable aims at the identification of relevant data sources, characteristics of datasets and development of smart data models for risk assessment. As this Deliverable is the natural following building block after the identification of indicators and algorithms conducted in DV 5.2.3, we follow up on it utilizing the same methodology and in particular the same approach based on event risk storylines. In particular, here we leverage on results from the previous Deliverables and we describe example data sources along with data characteristics in terms of format, attributes and metadata for risk assessment and management in urban and metropolitan environments, again for the same subset of event storylines described and presented in DV 5.2.3. After that, examples for smart data models in terms of algorithms and risk calculation methods are presented. While this Deliverable, similar to DV 5.2.3, does not aim to be fully exhaustive as it does not provide a complete definition of data models for all data categories, it aims to initiate the path and showcase the methodology for some selected and more mature examples. Indeed and as demonstrated in DV 5.2.3, one of the reasons to adopt an approach based on event storylines was the fact that it is intrinsically flexible and modular, with a great capability of being further integrated or modified during the development of the project. In order to demonstrate and present the approach, firstly we recall the main relevant and selected indicators for the subset of risk components and risk storylines; after that, also based on recommendations and constraints on data presented in DV 5.2.3, relevant data sources for the calculation of the indicators are described along with their characteristics, and finally example smart data models for risk calculation are presented. In this way, the Deliverable fully demonstrates the capabilities and advantages of the approach chosen, driven by the modularity of the event storylines and impact chains. Thus, in spite the gaps still not covered by this Deliverable, it constitutes a fundamental building block for the further developments within the project activities and in particular for the development of the data platform in WP5.5 and the development of risk models in WP5.3. As such, although the data sources coverage and description are still not complete, and the smart data models are presented only for a small subset of risk components, the Deliverable successfully demonstrates the approach and drives the next steps in other Deliverable and WPs.

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4. Introduction

The process of data modeling is of crucial and increasing importance when creating or improving a Data Governance program. Indeed, Data Governance is becoming increasingly complex because of the expanding use of data analytics and the need for compliance with existing laws and regulations. In this context, the availability of widely adopted (de facto standard) information models is crucial for creating interoperable and replicable smart solutions in multiple domains, including risk management and smart cities for instance. As a rule, data models define the harmonized representation formats and semantics that will be used in applications to ingest and to publish data. Data governance is used to set internal standards – data policies – for determining how the data is collected, saved, processed and eliminated. It also restricts the access to certain types of data (e.g., sensitive or personal) and ensures the compliance with regulations set by government agencies (e.g., GDPR). Overall, data governance ensures the data adheres to the FAIR data principle of being Findable - Accessible - Interoperable – Reusable. It can also be used to:

- Gather high quality data from a variety of sources;
- Make fast and good decisions;
- Enhance regulatory compliance respecting people's privacy;
- Reduce costs with an efficient resource management.

All these elements are extremely important in the context of RETURN and specifically in TS1, which in particular deals with multi-risks in the urban environment i.e. in an environment where exposure and vulnerability components are intimately interrelated, vulnerability is particularly enhanced by poor local governance, environmental degradation, and the overstretching of resources and where compound risk events are more probable to occur with a recognized probability of "risk accumulation" (UNDP, 2010). As fully outlined in DV 5.2.3, to overcome these challenges and in order to develop a modular methodological framework, we have adopted an approach based on risk storylines and impact chains (cf. DV 5.2.1 and 5.2.3). Thus, leveraging on the results from DV 5.2.3 and based on the event storyline approach, this Deliverable aims to describe relevant example data sources (along with relevant data characteristics, attributes and metadata) for risk management in the urban environment and setting up and showcasing examples for smart data models in terms of algorithms and calculation methods.

While the complete definition of a data model for all data categories is premature at this stage of the project and is beyond the scope of this Deliverable, it thus aims to conceptualize and set the path for the development of the data platform and its derivatives (WP5.5) where multiple and heterogenous sources will be fully merged and the data models will be fully developed and schematized. In addition, results from this Deliverable will be instrumental to WP5.3 and specifically to develop conceptual models and simulations in the Urban Labs. Indeed and similar to DV 5.2.3, while this Deliverable does not pretend to be fully exhaustive, thanks to the fact of being based on a flexible and modular approach (the risk storylines and impact chains), it has the capability to being integrated and taken further along the project development and further. To this aim, the Deliverable is structured as follows: Section 5 describes the goals and the adopted methodology; Section 6 describes the selected indicators for a subset of risk components and risk storylines; Section 7 identifies relevant data sources and Section 8 further illustrates the relevant data sources along with their attributes and characteristics; Section 9 describes and shows schematics for example smart data models; finally, Section 9 draws the main conclusions.

5. Goal and methodology

As stated in the Introduction, the aim of this Deliverable is to describe relevant data sources and conceptualize algorithms for the calculation of risks, with a specific focus on the multiple and cascade events occurring in the urban environment. The aim of this Deliverable is thus to initiate and setup a working methodology whereby to ingest data in the RETURN platform (WP5), calculate risk(s) (WP3), and finally provide useful outputs in terms of data and visualizations (WP5). In order to tackle the challenges of assessing and managing risks in the urban environment, which by nature is subjected to multiple cascade and compound risks, in DV 5.2.3 we have decided to adopt an approach based on risk storylines (cfr. Sec 5 of DV 5.2.3). This approach has multiple advantages, including most of all the capability of being modular and possibly extended or integrated at a later stage of the project, yet defining a common standard for integrating multiple heterogenous data sources, thus enabling to address risk in a very pragmatic way. In particular, here we take further what we have initiated in DV 5.2.3 where we have selected a relevant subset of risk storylines and described indicators for each risk component (hazard, vulnerability and exposure) along with variables needed for their calculation; in addition, there we have also illustrated algorithms for risk calculation with a focus on uncertainty and constraints posed on data. Here, we will follow this path, in particular following these logical steps:

a) Selection of the indicators that will be utilized and calculated in RETURN, also based on their complexity and data constraints;
b) Identification of relevant data sources (for input data);
c) Description of data sources and data characteristics;
d) Provision and description of example smart data models for calculation of risk.

As such, this Deliverable constitutes a building block and exemplification of the concrete methodology for risk calculation for the aims of RETURN.

6. Selection of indicators

This section is focused on the explanation of the first step of the methodology, namely the selection of the indicators for the characterization and description of risk components in the subset of risk storylines previously detailed in DV 5.2.3 and based on their level of complexity and data constraints therein explained.

6.1 Risk storyline 1

- **Hazards**
  - *Heatwave*

As concerns the heatwave hazard, relevant indicators were presented in the DV 5.3.2. In this section, specifically some indicators are identified and selected to characterise heat waves under specific conditions:

1. The availability of variables for the index calculation in the datasets: for instance, indicators requiring peculiar variables such as "clothing insulation" which are difficult to retrieve from available datasets, are excluded.
2. The temporal availability of variables in a specific period in the past. Indeed, some indicators may measure not only the severity of the phenomenon, but also provide a climatic insight about heat waves and their increasing frequency with respect to the reference climate period. Similar considerations can be made also in the case of weather forecasts and climate projections, which are usually available for some indicators only while others may be potentially and eventually computed on the basis of forecasted variables.
3. The possibility to characterise heat waves both in a statistical way, through indicators which investigate climatic series, and as a health issue, through indicators which consider the health stress these events may pose on human health.
4. The ease of indicators' computation.

Therefore, following the previous considerations, the following indicators for heat waves and heat stress have been selected (Table 1).

Table 1. Selected indicators for heat wave characterization, variables needed in their computation, recommended and minimum temporal availability in the past (1 - It may be retrieved through the other variables; 2 - Ancillary indicators).

Indicator	Variables	Recommended availability	Minimum Availability
Warm Spell Duration Index (WSDI)	Daily maximum temperature (°C)	1970-Present	1990-Present
Excess Heat Factor (EHF)	Daily mean temperature (°C) OR Daily maximum temperature (°C), Daily minimum temperature (°C)	1970-Present	1990-Present
Heat Index (HI)	Air temperature (°F or °C), Relative Humidity (%)	Latest year	-
Thom Discomfort Index(TDI)	Wet bulb temperature[1] (°C), Air temperature (°C), Relative Humidity (%)	Latest year	-
Humidex[2]	Air temperature (°C), Water vapor pressure (hPa), Wind speed at 10 m (m/s), Net radiation absorbed (W/m^2)	Latest year	-
Apparent Temperature[2] (AT)	Temperature (°C), Vapor tension (hPa)	Latest year	-

In this selection, the WSDI and the EHF are indicators which consider the climatic relevance of a heat wave event (so called holistic indicators), with some insight on its magnitude (through the second one), whereas the HI, TDI, Humidex and AT are indicators measuring the heat stress and discomfort posed by such events on population (so called biometeorological indices). Their use is therefore complementary and enables the characterization of heat wave characteristics and associated level of risk posed on human health.

- *Compound riverine and urban flood*

Similar to heatwaves, also in the case of compound riverine and urban flood a list of indicators was presented in DV 5.2.3. As commented therein, the description of riverine and urban flood hazard is based on groups of indicators depicting different characteristics of flood intensity and local characteristics such as slope angle, lithology, land cover. Indeed, the general approach in flood management is to group indicators considering that the hazard is inherently dependent not only on rainfall but also on the morphological and geological characteristics. In this case, the selection of indicators therefore relies directly and solely upon the temporal availability of the variables and their spatial resolution. Unlike the heatwaves, indicators for flood management are quite simple to calculate and are often directly available from observations or forecasts.

- **Exposure**

The exposed assets in the urban and metropolitan settlements are the population, the buildings and their characteristics, and the presence of other infrastructural elements such as rails, roadways, type and characteristics of green and blue infrastructure. Although in specific cases and especially if it is planned to provide a model for the sub-urban scale, it may be optimal to have data at very high spatial resolution most often these data are available at census or at district level in aggregated forms. As for the built-up area, the census data may be integrated with topographic information from Digital Elevation Models and from open repositories such as OSM or Google Maps.

- **Vulnerability**
    - *Fuel poverty*

As reported in DV5.2.3, the fuel poverty refers to the fuel poverty population density (non-income earners, unemployed and households with more than five members) by census area. This indicator was already described in terms of advantages and disadvantages in the previous Deliverable, providing also possible alternative indicators. In all cases, the computation of these indicators requires data at least from the demand side, potentially integrated also with data on the supply side. Socio-demographic variables are usually available at census level, so as in the case of exposure, also in this case the spatial resolution of the indicators may be the unique constraint for the development of the smart data model.

- *Flood vulnerability*

In DV 5.2.3 we have already provided a final choice on indicators for flood vulnerability based on based on a preliminary expert opinion survey form conducted on all the potential indicators obtained from the literature review (Usman Kaoje et al., 2021). In the following Table, we report the final list of indicators.

Table 2. Flood vulnerability indicators chosen based on expert opinion survey from Usman Kaoje et al. (2021).

Description	Indicators
Characteristics of buildings	Construction type and material
	Number of floors
	Stilts/Elevated buildings
	Ground floor foundation material
Flood hazard intensity (I)	Flood water depth
	Flood duration
	Flood water Velocity
Surrounding environment (E)	Distance from main river

As previously described, while data on flood hazard intensity are usually available as direct observations, details on building characteristics may be available only at census or district level, and specific data on single buildings may be absent. As such, the choice of indicators may be limited by the availability of the required variables at the required resolution.

- *Socioeconomic vulnerability*

The indicators proposed in DV 5.2.3 to describe socioeconomic vulnerability to extreme heat are the deprivation index and the Townsend score. Both of them consider mostly variables generally available at census level, and can therefore computed quite easily without further complications and constraints. However, as pointed out in DV 5.2.3, the Townsend score also considers health status and related variables such as hospitality admissions, mortality by cause and number of accesses to emergency districts, which are often available at municipal level and may be subjected to privacy and ethical constraints. This may pose potential limitations to their application, also in terms of latency or readiness for the computation of the indicators and their consideration into the model.

- **Risks**
  - *Short-term health issues*

Extreme heat is associated with several risks, including many on human health and especially on Non-Communicable Diseases depending in particular on the timing, intensity and duration of the event. In particular, heat waves are associated with a worsening of health risks from chronic conditions (cardiovascular, mental, respiratory and diabetes related conditions) and acute kidney injury[1]. Associated with these, relevant indicators include the short-term increase in mortality and morbidity conditions.

  - *Injuries & loss of human lives*
  - *Physical damage of buildings*
  - *Physical loss of buildings*
  - *Socio-economic damage to households*

6.2 Risk storyline 2

- **Hazards**
  - *Earthquake*

In this section, detailed information on useful variables to represent seismic hazards indicator (already presented in DV 5.3.2) is provided. The most common measures of ground shaking used are Peak Ground Acceleration (PGA) and spectral acceleration at reference elastic periods (Sa(T)), corresponding to an exceedance probability in a given period of time or, equally, to an assigned return period. In Italy the official reference is the MPS04 model proposed by Stucchi et al. (2004; 2011). Seismic hazard is presented in terms of maps showing the value of PGA and Sa(T) corresponding to an exceedance probability in a given period of time or, equally, to an assigned return period. The maps report the value of ground motion intensity measure over a grid of more than 16,000 points across the Italian territory. Table 2 shows the probability of exceedance in 50 years for which the hazard maps (both in terms of PGA and Sa(T)) were released. Seismic hazard maps in terms of spectral acceleration have been released for 10 spectral periods ranging between 0.1 and 2 seconds.

[1] https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health

Table 3. Variables available for evaluating seismic hazard indicator at referred return periods. Seismic hazard variables are provided for each point of a 5x5 km mesh covering the whole Italian territory.

Indicator	Variable	Return Periods (years)								
Seismic Hazard	PGA	30	50	72	101	140	201	475	975	2475
	S(T=0.1 sec)	30	50	72	101	140	201	475	975	2475
	S(T=0.15 sec)	30	50	72	101	140	201	475	975	2475
	S(T=0.20 sec)	30	50	72	101	140	201	475	975	2475
	S(T=0.30 sec)	30	50	72	101	140	201	475	975	2475
	S(T=0.40 sec)	30	50	72	101	140	201	475	975	2475
	S(T=0.50 sec)	30	50	72	101	140	201	475	975	2475
	S(T=0.75 sec)	30	50	72	101	140	201	475	975	2475
	S(T=1 sec)	30	50	72	101	140	201	475	975	2475
	S(T=1.5 sec)	30	50	72	101	140	201	475	975	2475
	S(T=2 sec)	30	50	72	101	140	201	475	975	2475

The official hazard model is elaborated on rock or stiff soil category (soil type A). Soil effects may be considered via an amplification map containing Vs30 values. Five soil categories are identified (A, B, C, D, E), based on topographic characterization and corresponding Vs30 values, and for each category soil amplification factors of the ground shaking intensity are defined.

- *Extreme precipitation*

As described in DV 5.3.2, the ETTCDI (Expert Team on Climate Change Detection and Indices) has defined a list of indicators for describing extreme precipitation and in particular duration, frequency, and intensity. These indicators are all based on the availability of rainfall data, and therefore can all be computed and selected. Their calculation poses only particular constraints in terms of temporal availability for calculations in the past (as in the case of heatwave, it is suggested to compute them in a reference baseline period and in the current climate to make also insights into changes in the nature of extreme events) and on the temporal resolution of the observations, which should be at least daily for some of the indicators.

- *Pluvial flood*

See risk storyline 1.

- **Exposure**
  - *Built-up area*

The number of buildings and surface area/living area at census tract level (or aggregated at larger scale) are the built-up area indicator selected (see also DV 5.3.2). The specific construction material (i.e., masonry, reinforced concrete, other), number of floors and period of construction of buildings is also required to describe the exposure to seismic hazard. As a matter of fact, such characteristics (i.e., material of construction, number of storeys and period of construction) are close related to seismic physical vulnerability of buildings. More detailed information on earthquake vulnerability is provided in the dedicated paragraph.

Census data are publicly available, homogeneous and widespread across the entire national territory, which is why they are widely used in exposure assessment for risk analysis. For privacy reason, disaggregated data on buildings are available only at municipality level. This means that the combined data on material, period of construction and number of storeys are not available at census tract level. Construction materials information, years of construction ranges and number of storeys included in last available census in Italy (ISTAT 2011) are provided in Table 4.

Table 4. Buildings' information provided by ISTAT.

MATERIAL	Masonry
	Reinforced Concrete (RC)
	Other (e.g., Wood, Steel, Mixed)
STOREYS	1
	2
	3
	>=4
PERIOD	< 1919
	1919 - 1945
	1946 - 1960
	1961 - 1970
	1971 - 1980
	1981 - 1990
	1991 - 2000
	2001 - 2005
	2005 - 2011

  - *Inhabitants*

The number of inhabitants at census tract level from last census (ISTAT, 2011).

  - *Households*
  - *Socioeconomic wellbeing*
- **Vulnerability**
  - *Compact, old historical center // earthquake vulnerability*

To describe the seismic physical vulnerability of buildings, suitable matrices, functions or curves, representing the propensity of a building class to sustain different levels of damage varying the seismic intensity, can be used. Index-based approaches are also available to evaluate seismic vulnerability. These straightforward approaches consist in clustering buildings into vulnerability classes based on the values of a Vulnerability Index (VI). This VI is typically calculated based on the features of buildings that most affect their seismic performance: a different score assigned to each feature, and the final VI is obtained through the aggregation of such scores. Then, for each building class a different set of fragility functions is adopted to describe their propensity to damage under seismic actions. An example of a widely used index-based approach is the Risk-UE proposed by Lagomarsino & Giovinazzi (2006).

The VI for buildings is derived from basic information on construction material (e.g., masonry, RC), structural system (e.g., simple stone, massive stone, adobe, for masonry structures; frame or walls for RC) and additional information on vulnerability factors, such as the height of the structure, the type of horizontal structures for masonry buildings and the level of earthquake resistant design in the case of RC. An initial value of the VI is defined as a function of the sole construction material/structural system, which can then be modified based on further information, if available. For example, a value of 0.87 is assigned to masonry buildings with irregular layout, and this value could increase if vaults (+0.08) or flexible slabs (+0.02) characterise the lateral structural system. Specifically, the VI ranges between 0 and 1, with values close to 1 indicating the most vulnerable buildings and close to 0 indicating buildings with superior seismic performance. Intervals of VI values for the vulnerability classes are defined so that, given the VI value for a building or a building typology, the vulnerability class of belonging can be assigned. Based on VI values, buildings are clustered into the six vulnerability classes of the EMS-98 (Grunthal, 1998), i.e., A, B, C, D, E, F. Table 5 provides the parameters needed to define VI according to Risk-UE.

Table 5. Parameters used in the calculation of VI, according to Risk-UE approach (Lagomarsino & Giovinazzi, 2006).

Vulnerability Factor	Description
Masonry type	Rubble stone; Adobe (earth bricks); Simple stone; Massive stone; Unreinforced Masonry (URM) - old bricks; URM with RC floors; reinforced/Confined masonry
Slab type	wood; vaults; composite steel and masonry; reinforced concrete slabs
Roof type	thrusting; not thrusting
Presence of horizontal connection	Tie roads; Tie beams
Plan and elevation regularity	Regular geometry/Irregular geometry
Building position in a block aggregate	Isolated; corner; end; central
Retrofitting interventions	Retrofitted/not retrofitted
State of preservation	Good/Bad
RC type	Moment Frame; Concrete Shear Walls; Dual System
Steel	Steel structures
Timber	Timber structures
Design level	without Earthquake Resistant Design (E.R.D); moderate E.R.D.; high E.R.D.
Storey number	L= 1/2, M=3/5, H≥6 for Masonry L= 1/3, M=4/7, H≥8 for RC

- *Soil sealing*
- *Poor sewage system*
- *Flood vulnerability*
- *Lack of MH design in recovery*
- *Socioeconomic vulnerability*

In research literature, different socio-economic and demographic factors have been identified as social vulnerability components. The main parameters adopted to assess social vulnerability are gender, age, education, socioeconomic status, public health condition, employment status, and access to resources (Cutter et al., 2003). To measure social vulnerability, indicator-based approach are the most used methods (Yoon, 2012). In Cutter et al. (2003) a Social Vulnerability index (SoVI) was formulated to measure the social vulnerability of U.S. counties to natural hazards. In Frigerio et al. (2018) SoVI index was suitably fitted in order to apply the same methodology to the Italian context. Based on a literature review and taking into account also the data availability, the authors selected 16 variables for quantifying social vulnerability in Italy (see also Table 14 of DV 5.2.3). These variables are representative of 7 demographic and socio-economic indicators relevant to the specific context, that can increase or decrease social vulnerability, i.e., family structure, education, socioeconomic status, employment, age, population growth, race/ethnicity, as also shown in Table 6.

Table 6. Indicators and variables derived from ISTAT and their impact on social vulnerability.

Variables	Indicators	Impact on social vulnerability
Under 14 aged	Age	+
Over 65 aged		+
Aging index		+
Dependency ratio		+
Families with more than 6 components	Family structure	+
High educational index	Education	-
Low educational index		+
Buildings with very bad or bad state of preservation	Socio-economic status	+
Commuting rate		+
Unemployed	Employment	+
Employed		-
Female employed		-
Population density	Population growth	+
Crowding index		+
Foreign resident	Race/Ethnicity	+

Age indicator involves variable such as rate of children (i.e., population under 14), rate of elderly (i.e., population over 65), aging index and dependency ratio. The aging index refers to the number of elders compared to persons younger than 15 years old in a specific population (Preedy & Watson, 2010). The dependency ratio is the ratio of persons of nonworking age to persons of working age (Simon, et al., 2012). Considering the information on population provided by census (ISTAT 2011), people of working age can be calculated considering those under 15 and over 65.

The education indicator is represented by two variables: low educational index and high educational index. ISTAT provides data on education levels, including the number of people with various educational qualifications and those who are illiterate. The BES report (ISTAT, 2016) focuses on key indicators such as the percentage of 25–64 year-old with a high school diploma, the percentage of 30-34 year-old with a degree, and the percentage of 18-24 year-old who left the education system early. The high educational index can be calculated as the ratio of people with degrees to the population over 30, while the low educational index as the ratio of people with only secondary school diplomas to the population over 15. The suggested age thresholds are based on the population age ranges in the census database.

As representative of socio-economic status, the commuting rate and the quality of buildings are the variables considered. The commuting rate is calculated as ratio of commuters and people in working age, defined as over 15 aged (in line with census definitions). The quality of buildings can be expressed considering the number of buildings with a bad or very bad state of preservation, derived from census. The unemployment rate, employed and female employed can be calculated as ratio of unemployed, employed, female employed and people in working age respectively.

Concerning family structure, in Frigerio et al. (2018) the number of family with more than 6 members is considered as variable. However, families with more than 6 members represent only the 0.05% of families in Italy, so it may be not relevant data for SoVI calculation. Also, ISTAT provides the value of the average annual income of family in Italy, classifying families based on their number of components as families with 1, 2, 3, 4, 5 or more components (www.istat.it/it/dati-analisi-e-prodotti/banche-dati/statbase). Therefore, percentage of families with more than 5 components is suggested as family structure indicator for social vulnerability calculation (Tocchi et al., 2023).

Population density can be determined using a GIS software by relating the residential population to the surface area (km^2) at the selected scale of analysis (e.g., census tract or municipal scale). Additionally, the crowding index is included as a variable for population growth. This index typically represents the number of people per room, but since such detailed information is unavailable, the number of people per flat is used instead, calculated by comparing the number of dwellings to the residential population (both available from ISTAT).

It is important to note that the "Built-up area" variable, included in the study by Frigerio et al. (2018), is not considered here. This is because it cannot be determined solely from census data and requires information on building footprints to calculate the covered area of buildings. Additionally, this variable could be seen as a representation of population density, a factor already included in the SoVI calculation.

Finally, the percentage of foreign residents, that is the proposed variable for race/ethnicity indicator, can be derived from ISTAT as well.

- **Impact**
    - *Physical damage of buildings*

Seismic vulnerability for buildings indicates their likelihood of experiencing a certain level of damage when subjected to specific ground motion intensity. To describe the susceptibility of buildings to sustain damage from earthquakes of specified intensity, it is necessary to:

a) Define a damage scale describing the severity of damage
b) Adopt a vulnerability model that defines appropriate fragility functions representing the propensity of a building (or a building class) to sustain different levels of damage varying the seismic intensity.

A damage scale commonly adopted in Europe is the EMS98 scale (Grünthal, 1998). It identifies five damage grades Dk (k = 1/5), that are defined based on the observed damage for both structural and non-structural components; also, the absence of damage D0 (no damage) is introduced. The vulnerability can be represented in terms of either Damage Probability Matrices (DPM) or Fragility Curves. While DPM describe the probability of the occurrence of a specific damage level at specified intensity measure through a discrete relationship (Braga, et al., 1982; Di Pasquale, et al., 2005; Lagomarsino & Giovinazzi, 2006) fragility curves do it in a continuous way (Del Gaudio et al., 2019; Lagomarsino, et al., 2021).

Thus, as indicator of physical damage, the number of buildings reaching a specific damage level can be adopted. Note that such fragility functions are usually specifically developed for certain types of structures, identified by parameters such as the construction material, the later load resisting system, the design level and the number of storeys. Therefore, to evaluate the number of damaged buildings in a given area using fragility functions, it is also necessary to compile the building inventory, that provides the distribution of buildings having certain structural/non-structural features at territorial scale. For instance, according to Risk-UE approach (Lagomarsino & Giovinazzi, 2006) buildings are clustered into 6 vulnerability classes based on vulnerability index (VI) value e for each class a different DPM is defined. Therefore, the evaluation of the number of buildings reaching a given damage grade (e.g., D3) at census tract level require also the knowledge of the number of buildings belonging to each building class for the considered census tract. As physical damage indicator, also the mean damage value can be adopted, which considers the damage distribution for a given intensity level (Lagomarsino & Giovinazzi, 2006).

An alternative or supplementary indicator of physical impact is building usability, which determines whether people can return to their homes or need temporary shelter, and whether buildings can be partially or fully occupied. Building usability is often evaluated based on the damage attained by structural and non-structural elements (Dolce et al., 2021; Tocchi et al., 2022). Thus, the number of buildings that are temporarily unusable (requiring short-term measures to ensure safety) and the number of buildings that are long-term unusable (needing significant structural repairs or even demolition) may be adopted as physical damage indicator as well.

- **Risk**
  - *Physical loss of buildings*

Generally, physical losses refer to expected costs for the repair or replacement of damaged or collapsed buildings. The computation of economic losses requires the definition of the building replacement cost and a damage ratio, that expresses for each damage state the percentage of the building replacement value (Dolce et al., 2021). In Italy, the reconstruction cost for buildings is estimated taking into account the demolition and the reconstruction cost, including technical expenses and VAT; it is assumed equal to 1350 (€/m^2) for residential buildings (Dolce et al., 2021), regardless of the structural type (e.g., masonry or RC). The percentage cost of repair or replacement (with respect to reconstruction cost) is usually defined for each structural damage grades (e.g., in Dolce et al., 2021 such percentages are equal to 0.02, 0.1, 0.3, 0.6 and 1 from EMS-98 damage level from D1 to D5). As the cost for repair or replacement is expressed as euro per square meters (€/m^2), its calculation also required the knowledge of the living areas (m^2) of damaged buildings (for each damage grades considered).

- *Injuries and loss of human lives*

The number of injuries and deaths due to earthquakes is usually evaluated as function of damaged and collapsed buildings, i.e., it is assumed that people occupying buildings are potentially affected. Similarly to the physical losses' evaluation, consequence functions that provides the percentages of expected injured people and deaths are generally defined (see for instance, Dolce et al., 2021).

- *Loss of productive systems*

Damages and risks for commercial and industrial activities consider both the building structure and its content. In particular, the indicators consider the number of employees and the unitary net capital, further integrated by information on building structure which was already investigated as part of the vulnerability assessment. Most of the information derives from census aggregated data at district level.

- *Socio-economic damage to households*
- *Temporary increase of urbanization*

7. Identification of relevant data sources

This section details the relevant data sources available for the determination of the indicators selected and detailed in the previous section.

7.1 Risk storyline 1

- **Hazards**
  - *Heatwave*

The choice of sources has to be made on the basis of the variables they can provide and their availability. In particular, also the particular scope of risk (or hazard) calculation, either for the proper assessment of past events either for the forecast of future ones somehow drives the choice and the selection of data sources. Indeed, in the case of assessment of past events, we need to rely on measured data from a range of diverse sources, eventually combined with simulations at different time scales, while in the case of forecasted events, we need to base our calculations on modelled data only. However, in this second case, choices of the proper modeling tools are based on the range of temporal scales of interest, with very and intrinsically different data sources for weather forecasts on time scales of days or weeks, for climatic projections on time scales of multiple decades or centuries, passing through the range of seasonal or decadal predictions.

In the case of weather variables as those needed for the calculation of heat wave hazard indicators, they are routinely measured in real time from survey regional networks (in Italy, often, these networks are managed by the Regional Environmental Protection Agencies) and from "synoptic" stations operated by the Italian Air Force Meteorological Service and National Agency for Flight Assistance (ENAV). These are included in the World Meteorological Organisation international telecommunication system. Ground station networks are also further integrated by data offered by amateur networks, which represent an important additional source of information covering also regions where other sources are missing or sparse. Examples of this type of data sources include the Wunderground network (https://www.wunderground.com/), the Meteonetwork (https://www.meteonetwork.it/rete/livemap/), and others. Nowadays, also low cost sensors for measuring weather variables are spreading and offering relevant opportunities to complement data from ground weather stations. In particular, in this category we can cite the very recent Meteotracker sensor, which has proven particularly accurate and useful for the assessment of spatial variability of temperature and humidity parameters (Barbano et al., 2024).

For detailed assessment of past events, ground-based measurements are the best recommended to be used as in situ data best depict the local conditions. However, these datasets may not be fully available for the period considered or for the geographical region investigated: in this case and for the purpose of extending the coverage of past events, reanalysis datasets (e.g., ERA5) or gridded datasets (e.g., E-OBS) can be useful to cover these gaps. In particular, climate reanalysis is a numerical description of the recent climate, produced by combining observations with climate models. Climate reanalysis contains estimates of all atmospheric parameters including air temperature, pressure and wind at different altitudes, and surface parameters such as rainfall, soil moisture content, and sea-surface temperature. Estimates are produced for all locations on earth, for long time periods back several decades. Examples of climate reanalysis often utilized are ERA5 from ECMWF (European Centre for Medium-Range Weather Forecasts) (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5), but also MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2; https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/) from NASA. Other possibilities include the use of gridded observational datasets such as E-OBS (https://www.ecad.eu/download/ensembles/download.php), an ensemble dataset available on a 0.1 and 0.25 degree regular grid for the elements daily mean temperature, daily minimum temperature, daily maximum temperature, daily precipitation sum, daily mean sea level pressure, daily mean wind speed, daily mean relative humidity and global radiation.

Lastly, remote sensing (and in particular, satellite) datasets may be useful for integrating and complementing the previous datasets or as last chance. Remote sensing refers to the science of obtaining information about objects or areas from a distance, typically from aircraft or satellites, but also, in the case of temperature, by thermal cameras. In particular, satellite remote sensing provides the best way to measure Land Surface Temperature (LST) and generate various LST products at regional and global scales (Li et al., 2023). LST is an indicator of the energy and water exchange between the land surface and atmosphere and has been applied in various fields to study various subjects, for example, the surface energy balance, the urban heat island effect, surface soil moisture (SM) and evapotranspiration (ET) estimations, and climate change (Li et al., 2023 and references therein). Retrieval of air temperature and in particular of near surface air temperature is also possible, as it is strongly correlated with LST, even though it is also affected by terrain, elevation, vegetation coverage, and other factors (Wang et al., 2022). Several methods have been proposed to increase the accuracy of satellite-based Ta estimating in recent years, including statistical methods, the temperature-vegetation method, the energy balance method and machine learning algorithms (Wang et al., 2022 and references therein). In this way, global datasets of air temperature combining satellite remote sensing and weather stations have been developed (e.g., Hooker et al., 2018).

All the above description refers to the assessment and analysis of past events, while as said previously in case of forecasts we need to rely on model simulations at different time scales. This is particularly useful for better preparedness for these extreme weather events, including issuing warnings to the general population, implementing protection measures for vulnerable groups, but also actions with longer time scales such as the development of heat-health action plans and establishment of links between decision makers and meteorological and health services (monthly to yearly), urban and infrastructure planning and climate change mitigation and adaptation plans (yearly to decades). The predictability of heatwaves on timescales of days to decades depends on a range of local and remote physical mechanisms (Figure 1).

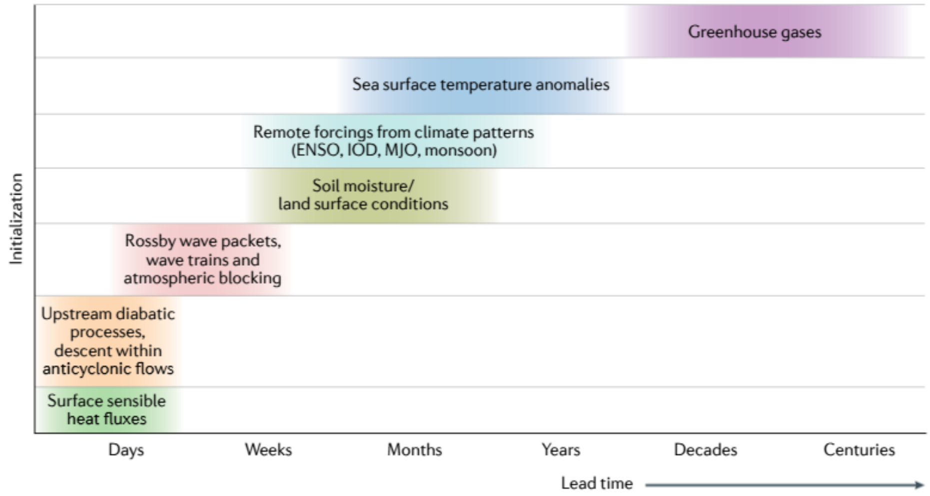

Figure 1. Predictors for heatwaves over timescales from days to centuries. The shaded horizontal range of each predictor gives an indication of the lead times for which its influence on predictability is dominant. Each timescale is associated with one or several dominant processes that allow for the prediction and projection of heatwaves. ENSO, El Nino–Southern Oscillation; IOD, Indian Ocean Dipole; MJO, Madden–Julian Oscillation. Reproduced from Domeisen et al., 2023

These processes contribute across timescales, even though the relative contribution of each process varies across the full range of lead times (Domeisen et al., 2023). Confident predictions of heatwave occurrence and amplitude are possible in weather prediction systems two to three days ahead with a traditional deterministic limit of approximately 10-15 days. This range is the one covered by weather alerts and heat warnings issued by national and regional weather services, based on weather forecasts covering ranges of days to weeks. Beyond timescales of a few weeks, heatwave prediction remains challenging (Domeisen et al., 2023). However, recently, subseasonal to seasonal predictions are also emerging (e.g., Langue et al., 2023; Prodhomme et al., 2021), which because of the chaotic nature of weather are based on probabilistic forecasting on ensemble of order 50 simulations. These systems (e.g., ECMWF's seasonal prediction system) are capable of predicting warmer-than-average summer temperatures and general information on the tendency of a season to be predisposed to heatwaves occurrence (Domeisen et al., 2023). Examples of decadal predictions also exist (e.g., the UK Met Office's Decadal Prediction System).

The setup of adequate adaptation and mitigation strategies finally calls for climate projections, which consist in the determination of trends in heatwave metrics (the number of hot days and hot nights, as well as heatwave duration, frequency, area and intensity). Generally these are available from global climate models and especially of ensembles (e.g., CMIP5 or CMIP6 (https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip6?tab=overview), generally at low spatial resolution (variable in the different models) but eventually nowadays often downscaled for some selected members of the ensemble and for specific subregions (e.g., Soares et al., 2024; Gebrechorkos et al., 2023).

- *Compound riverine and urban flood*

Similar discussions hold for the description and forecasts of floods. In this case and for the description of events occurred in the past, networks of ground stations typically can be used for measurements of river data (water level), while geological and morphological characteristics are derived from geospatial data from remote sensing (e.g., geodesy, lidar) and local field campaigns. In this particular case, indeed, measurement sources can be usefully integrated also by photographs or videos taken at the peak of the event, which include which include the flood level and / or extent against identifiable structures or locations. Such data are also collected by government or local authority staff. Recently, also web-based tools and collection of flood maps at global level are available (e.g., global flood database[2], European flood database[3], river flood hazard maps at European and global scale). Satellite data also provides one way to monitor the consequences of flood events (e.g., Europe's flood management[4]).

In the case of forecasts, weather forecasts and climate predictions are nowadays and often integrated with artificial intelligence methods (e.g., flood forecasting alerts from Google[5]).

- **Exposure**
  - *Built-up area*
  - *Inhabitants*
  - *Households*

Exposure data of the built-up area, inhabitants and households are available at census level from the ISTAT, and can be also obtained by municipality and regional authorities. Such sources, and in particular for the description of the built-up area and households, may be integrated with openly available geospatial data from OSM and from remote sensing (e.g., Longato and Maragno, 2024). In the case of Italy, for example, the Ministry of Environment (Ministero dell'Ambiente e della Tutela del Territorio e del Mare) provides such a service, named Geoportale Nazionale (http://www.pcn.minambiente. It/GN/). Furthermore, both Google and Microsoft have developed algorithms which are able to extract building footprints and heights from aerial imagery with very good results. Figueiredo and Martina (2016) have recently demonstrated that even though this data alone are not sufficient to generate exposure datasets, the integration of census data with openly available building information provides an effective description of exposed assets at suburban scale. Another useful source is the ExpoFacts (European Exposure Factors Sourcebook, https://joint-research-centre.ec.europa.eu/expofacts-european-exposure-factors-sourcebook_en) is a collection of statistics and references. It contains three parts, a database, a reference guide, and a document library, all of which publicly available and accessible at the website.

- **Vulnerability**
  - *Fuel poverty*
  - *Flood vulnerability*
  - *Socioeconomic vulnerability*

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[2] Global Flood Database (cloudtostreet.ai)
[3] European Floods Database — European Environment Agency (europa.eu)
[4] Europe's flood management: Navigating with data | data.europa.eu
[5] Flood Forecasting: AI for Information & Alerts - Google Research

Individual socioeconomic information is usually restricted to privacy and ethical constraints, thus aggregated information is often only available in most cases. Socioeconomic data in Italy are available from the Italian National Institute of Statistics (ISTAT), which is responsible for conducting Italy's decadal censuses. Such data are most often subjected to PCA analysis following normalization (e.g. Frigerio, 2018). Another useful source to integrate available information and in particular describing the economic value of the exposed assets in Italy as well as their physical characteristics in urban and rural agglomerations including estimation of population too is GAR15 Global Exposure Dataset for Italy (https://hgl.harvard.edu/catalog/stanford-mk089bq2743). Furthermore, EU SILC provides EU statistics on income and living conditions (https://ec.europa.eu/eurostat/web/microdata/european-union-statistics-on-income-and-living-conditions) and in particular comparable cross-sectional and longitudinal data on income, poverty, social exclusion, and living conditions.

- **Risks**
  - *Short-term health issues*

Data on mortality and morbidity are subjected to ethical and privacy constraints, and are available only in aggregate format and often upon specific requests to the health authorities. ISTAT, however, provides mortality monthly data at municipality level. The Italian Ministry of Health in 2007 approved the program "Guadagnare salute - rendere facili le scelte salutari", that envisages strategic actions to contrast the most important behavioral risk factors, in the context of the European strategy to tackle chronic diseases (Gaining Health). Such data are not publicly available due to specific policy of the National Institute of Health and of the Italian Ministry of Health, but it is available by the National Institute of Health upon reasonable request (Pastore et al., 2023).

  - *Injuries & loss of human lives*
  - *Physical damage of buildings*
  - *Physical loss of buildings*
  - *Socio-economic damage to households*

7.2 Risk storyline 2

- **Hazards**
  - *Earthquake*

As mentioned, information on seismic hazard variables (estimated from MPS04 – Stucchi et al., 2004;2011) are provided by INGV (http://esse1.mi.ingv.it/).

Vs30 map for Italy based on the seismic microzonation dataset proposed by Mori et al., 2020 is available at the following link: https://doi.org/10.1016/j.enggeo.2020.105745 (raster format).

- *Extreme precipitation*

Similar to heat waves and related weather variables, precipitation data are routinely measured from meteorological stations, which in Italy are operated by Regional Protection Agencies (ARPA), the Italian Meteorological Service of the Air Force. The Mistral (Meteo Italian Supercomputing Portal[6]) also provides the possibility to download data from environmental observations at weather stations and from different forecast models. Official networks are further integrated with amateur networks such as Wunderground, MeteoNetwork, already cited in the heatwave sections.

Furthermore, gridded precipitation data are available from global measurement missions such as the GPM and TRMM missions, and the Global Precipitation Climatology Project which use satellite measurements or combines raingauge measurements with satellite observations. In Italy, CNR also provides high-resolution annual climatologies for teaching and research [7], including also precipitation and temperature (Brunetti et al., 2014). Very important for the realtime estimations of precipitation type and to map precipitation patterns and movements are radar data that in Italy are usually available from regional environmental protection agencies (ARPA), but also from other national sources such as Meteologix[8] and RainViewer[9]. Recently, also estimations of precipitation data from commercial microwave links (CML) show very promising advantages even though especially for real time detection while less so for quantitative estimates (e.g., Roversi et al., 2020; Nebuloni et al., 2022; Zhang et al., 2023). As such, these data sources can usefully integrate observations from weather stations but are less useful for the quantification of the extreme precipitation indicators previously described.

All these data sources, however, provide past or real time observations useful for the assessment of past events or for issuance of upcoming weather alerts, while for the forecasts and projections of future events, we rely on national and regional weather forecasts (jointly operated by regional and national authorities together with the Civil Protection Agency), and climate predictions and projections for the longer time scales. Forecasts of precipitation are nowadays available and with good skills for time scales of 10 days, also available with mobile applications such as Windy (Windy: Wind map & weather forecast). Seasonal forecasts of precipitation are also available from, e.g., the ECMWF seasonal forecasts[10] from multi-system combinations and from individual system components. Products include deterministic and probabilistic gridded products for 1-month and 3-months means for precipitation. Last but not least, climate projection scenarios always include the precipitation variable in the form of a probabilistic gridded product. Climate prediction and projections products are most often available at coarse spatial resolution, but various downscaling methods (e.g., statistical, dynamical) and even downscaled datasets are available (e.g., GDCPIR, CORDEX) (Gergel et al., 2023; Coppola et al., 2021).

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[6] MISTRAL – Meteo Italian Supercomputing Portal (mistralportal.it)
[7] isac.cnr.it/climstor/CLIMATE_DATA/index.html
[8] Radar HD Italy | Meteologix.com
[9] Radar meteo in tempo reale - Italia | RainViewer
[10] https://charts.ecmwf.int/products/seasonal_system5_standard_rain?area=GLOB&base_time=202407010000&stats=tsum&valid_time=202408010000

- o *Pluvial flood*

See risk storyline 1.

- **Exposure**
  - o *Built-up area*

Exposure data on residential buildings (number of buildings, living area) are available at census tract level from last census (ISTAT, 2011; https://www.istat.it/notizia/basi-territoriali-e-variabili-censuarie-test/). Disaggregated information on buildings is available from ISTAT on request.

- o *Inhabitants*
- o *Households*
- o *Socioeconomic wellbeing*

For the above elements, see risk storyline 1.

- **Vulnerability**
  - o *Compact, old historical center // earthquake vulnerability*

The calculation of the seismic vulnerability index (Lagomarsino & Giovinazzi, 2006) requires detailed information on buildings that usually is not available from census. Building-by-building surveys provide detailed data for both spatial and attribute type features for single buildings in an investigated area, are generally the most complete source towards vulnerability assessment. Given the elevated costs and time, this kind of detailed survey is generally applied during post-earthquake vulnerability and damage survey campaigns. In Italy, the AeDES form (Baggio et al., 2007), which is the official form used for post-earthquake damage and usability assessments, was used to assess usability of buildings after major damaging earthquakes, by recording the main information concerning its features, such as the age and type of construction, the number of storeys, and the damage sustained. These data were retrieved from the Da.D.O. (Database of Observed Damage) web-gis platform (Dolce et al., 2019), which was conceived with the specific purpose of collecting, cataloguing, and comparing the damage data for buildings inspected after the main seismic events in the country. The access to the platform is possible after registration request.

A recent advancement towards compilation of regional scale inventories is provided by the Cartis approach (Zuccaro et al., 2015), implemented in Italy within "Territorial themes" Reluis project, financed by Civil Protection Department. The Cartis survey form allows to collect data on building typologies referring to Town Compartments (TC). These territorial units are zones in the town that are characterized by homogeneity of the building stock in terms of construction age and construction techniques and/or structural types. The Cartis survey form (one form for each town, comprising one or more TCs) is compiled by interviewing one or more technicians that are local experts with deep knowledge of the construction characteristics in the area. Interviewed technicians may be expert professionals (e.g. engineers or architects) having operated for years on the territory, or expert public employees in local technical administration offices. Although referred to a territorial unit that can be considerably larger with respect to CT, the information collected on building typologies with Cartis form are already disaggregated and include data that allow the calculation of the vulnerability indicator.

Nowadays, more than 350 municipalities were investigated with Cartis, with information on about 1,550 Town compartments and 708,100 buildings (http://cartis.plinivs.it/). Access to the platform is not free, but it is possible to send a specific request to Plinivs.

The vulnerability of the Italian municipalities exposed to seismic hazard can be analysed also through the open data offered by the Mappa dei Rischi dei Comuni Italiani provided by ISTAT, the Italian National Institute of Statistics (Didkovskyi et al., 2021) and by quick-survey data-based methodologies (Martinelli et al., 2008).

  - *Soil sealing*
  - *Poor sewage system*
  - *Flood vulnerability*
  - *Lack of MH design in recovery*
  - *Socioeconomic vulnerability*
- **Impact**
  - *Physical damage of buildings*

Physical damage of buildings can be calculated adopting appropriate vulnerability models. Many vulnerability models for residential buildings are available in literature. Information on vulnerability models officially adopted in the National risk assessment of residential buildings in Italy can be found in Dolce et al., 2021.

- **Risk**
  - *Physical loss of buildings*

Physical loss of buildings can be calculated adopting appropriate consequence functions. Many damage to impact models for the calculation of economic losses of residential buildings are available in literature. Information on functions officially adopted in the National risk assessment of residential buildings in Italy can be found in Dolce et al. (2021).

  - *Injuries and loss of human lives*

Expected number of injuries and deaths due to earthquakes can be calculated adopting appropriate consequence functions. Information on functions officially adopted in the National risk assessment of residential buildings in Italy can be found in Dolce et al. (2021).

  - *Loss of productive systems*
  - *Socio-economic damage to households*
  - *Temporary increase of urbanization*

8. Description of data characteristics

This section describes further characteristics of data available in the previously listed data sources, with a focus on their accessibility, format, spatial resolution and temporal availability. It is to note that the list of datasets is not complete but is meant to include diverse data sources, including for instance station and gridded data which are characterized by inherently different format and characteristics. As such, the list does not claim to be exhaustive while it provides a consistent picture of the heterogeneous data sources available for the assessment of risk. The final choice of the datasets utilized will be driven by the peculiar aims and characteristics of the study conducted.

8.1 Risk storyline 1

- **Hazards**
  - *Heatwave*

In the following table (Table 11), we describe some of the sources where data for heat waves identification and characterization are available. In particular, here the focus is on the characteristics of datasets such as the data source, the variables measured/reported, the resolution of data, the data spatial and temporal availability, the accessibility (i.e. if the dataset is open (O) or private (P)), the format in which data are provided, the indicators which can be computed using the dataset and where the source can be found (i.e. the link).

Please note that ground-based datasets may have different stations measuring data, hence data availability may differ from station to station and from region to region.

Table 7. Details on characteristics of specific data sources for heat wave identification and characterization (1 - Combined with temperature and pressure, it can be used to calculate the relative humidity).

Data source	Variables	Resolution	Availability	Accessibility	Format	Indicators	Link
ISPRA SCIA (in situ)	Maximum Temperature (°C) Minimum Temperature (°C)	Single station Gridded (5kmx5km) Daily	Italy 1950-2022	Open	CSV	WSDI EHF	https://scia.isprambiente.it/
Regional Meteorological Services: e.g., ARPAE Emilia	Temperature (°C) Relative Humidity (%)	Single station Hourly, daily	Selected regions 1980-Present	Open	CSV, ascii txt...	WSDI EHF HI TDI	Example links: ARPAE - dext3r (arpae.it) Liguria - https://www.regione.liguria.it/homepage-ambiente/come-

Romagna Environmental Protection Agency, Liguria region meteoclimatic archive, Friuli-Venezia Giulia meteorological observatory ... (in situ)	Air Pressure (hPa) Wind speed (m/s)						fare-per/banca-dati-meteoclimatica.htm Friuli Venezia Giulia - https://www.osmer.fvg.it/archivio.php?ln=&p=dati Toscana - SIR - DATI / Archivio storico ...
ERA5-Land (reanalysis)	2m Air Temperature (K) 10m u, v wind speed (m/s) Surface Pressure (Pa) 2m dewpoint Temperature[1] (K)	0.1°x0.1° Hourly	Global 1950-Present	Open	GRIB NetCDF	WSDI EHF HI TDI	https://doi.org/10.24381/cds.e2161bac
UERRA (reanalysis)	2m Air Temperature (K) 10m wind speed (m/s) 2m Relative Humidity (%)	11kmx11km, 5.5kmx5.5km Every 3 hours	Europe 1961-2019	Open	GRIB NetCDF	WSDI EHF HI	https://doi.org/10.24381/cds.32b04ec5
EURO-CORDEX (simulations)	Average, Maximum, Minimum Temperature (K)	30-y smoothed average of year/seasons	Europe 1985-2085	Open	NetCDF	WSDI EHF	https://doi.org/10.24381/cds.8be2c014
Heat wave days from climate	Number of heat wave days	30 year rolling means	Europe 0.1° x 0.1° 1986-2085	Open	Interactive map NetCDF 4	Heat wave days	https://cds.climate.copernicus.eu/apps/c3s/app-health-heat-waves-projections?Definitio

projections							n=Euroheat%20project
AIRS (satellite)	2m Air Temperature (K) 2m Relative Humidity (%)	50kmx50km 1 value per day	Global 2002-Present	Open	HDF	WSDI EHF HI	https://disc.gsfc.nasa.gov/datasets/AIRS2RET_006/summary

- *Compound riverine and urban flood*

In the following we report an excerpt for relevant data sources of compound riverine and urban flood (Table 8).

Table 8. Details on characteristics of specific data sources for riverine and urban flood identification and characterization.

Data source	Variables	Resolution	Availability	Accessibility	Format	Indicators	Link
Emilia-Romagna weather alert	Hydrometric level	Point sensors	Current month Every 15 minutes	Open	Map and graph	Water level	https://allertameteo.regione.emilia-romagna.it/livello-idrometrico
Hydrometric level Veneto	Hydrometric level	Point sensors	Last 48 hours Every 15 minutes	Open	Map and graph	Water level	https://www.arpa.veneto.it/dati-ambientali/dati-in-diretta/meteo-idro-nivo/livelloidrometrico
Hydrographic monitoring	Hydrometric level	Point sensors	From 1901 30 minutes	Open	Map and graph	Water level	https://www.agenziapo.it/content/monitoraggio-idrografico-0
Observed regional trends in annual river flood discharges in Europe	annual maximum of daily river discharge	Europe	1961-2010 annual maximum	open	Maps in tiff, gif, png	Flood discharge	https://www.eea.europa.eu/data-and-maps/figures/observed-regional-trends-of-annual
EEA potential flood prone area	probability of flooding is 1% assuming that flooding is unrestricted	Europe	2011-2016	open	Shapefile map	Probability of flooding	https://sdi.eea.europa.eu/data/28c36420-c31b-440e-80c5-8064696f3517
FloodHub	real-time flood forecasts and alerts based on Google's AI models and global data sources	global	up to 7 days in advance	open	Map and graph	Alert and danger level	https://sites.research.google/floods/l/45.996961618203805/8.7451171875/10/g/hybas_2120530440?layers
MISTRAL	River level	Point station	From 2002 onwards	open	JSON	Water level	https://meteohub.mistralportal.it/

Copernicus seasonal forecast	River discharge	1x1 arcminute for version 5.0, 5x5km for version 4.0 and older	November 2020 to 1 September 2023.	open	GRIB2 and NetCDF-4	Water level	https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset&keywords=((%20%22Product%20type:%20Seasonal%20forecasts%22%20))
Copernicus seasonal reforecast	River discharge	January 1993 to December 2016	5km	open	GRIB2 and NetCDF-4	Water level	https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset&keywords=((%20%22Product%20type:%20Seasonal%20forecasts%22%20))

- **Exposure**
    - *Built-up area*
    - *Inhabitants*
    - *Households*

Exposed assets to heatwaves and floods can be described on the basis of the following data sources (Table 9):

Table 9. Details on characteristics of specific data sources for exposure to heatwaves and flood calculation.

Data source	Variables	Resolution	Accessibility	Format	Link
Italian Ministry of Environment's Geoportale Nazionale	building vector data (location, area, height)	Municipality	open	map	https://gn.mase.gov.it/portale/home
ISTAT, buildings	No buildings No. Of storeys Area Other building characteristics	Census	Open	xls table	http://dati-censimentopopolazione.istat.it/Index.aspx
ExpoFacts database	Housing	Country level, Europe	Open	Xls table	https://data.jrc.ec.europa.eu/dataset/jrc-10114-10001#dataaccess
ISTAT, population	Number of people by gender, age, and civil status	From Municipality to Nation	Open	Xls, csv table	http://dati.istat.it/Index.aspx?QueryId=18560

CORINE land cover	land cover and land use inventory with 44 thematic classes	100m 1990, 2006, 2012, 2018	Open	Shape file	http://portalesgi.isprambiente.it/en/elenco-base-dati/17 https://land.copernicus.eu/en/products/corine-land-cover
ISTAT, land use	Land use (%)	Region, province, municipality 2006-2022	Open	xls	https://www.isprambiente.gov.it/it/attivita/suolo-e-territorio/suolo/il-consumo-di-suolo/i-dati-sul-consumo-di-suolo
SINANET land cover	Imperviousness, small woody features, forest, grassland, wetness, urban atlas, Natura2000	20m, national	Open	Xls and shapefile	https://groupware.sinanet.isprambiente.it/uso-copertura-e-consumo-di-suolo/library/copertura-del-suolo
Emilia-Romagna region, land use	Surfaces of urban areas, industrial areas, green areas, streets, railways	0.2 m x 0.2 m, Regional	Open	shapefile	https://geoportale.regione.emilia-romagna.it/approfondimenti/database-uso-del-suolo
Emilia-Romagna Region; Museums, monuments, buildings, and places of historical-artistic value	Latitude, Longitude	From Municipality to Region	Open	Xls table	https://dati.emilia-romagna.it/dataset/arte-e-cultura--f97ad51b
Italian open data portal	Type of school, hospital, name and coordinate (Latitude, Longitude)		Open	png	http://www.datiopen.it/it/opendata/Mappa_delle_scuole_in_Italia
GHSL - Global Human Settlement Layer	Built-up surface, built-up height, built-up volume, built-up characterist	10m to 100arcs	Open	tiff	https://ghsl.jrc.ec.europa.eu/download.php?ds=bu

	ics, Land fraction per pixel as derived from Sentinel2 data composite and OpenStreet Map (OSM) data, population grid, Settlement Model grid, Global Degree of Urbanisatio n Classificatio n of administrati ve units, Urban Centre Database, unctional Urban Areas, European Settlement Map 2015,	

- **Vulnerability**
  - *Fuel poverty*
  - *Flood vulnerability*
  - *Socioeconomic vulnerability*

Following we report the main characteristics of data sources for describing vulnerability to heatwaves and riverine floods (Table 10).

Table 10. Details on characteristics of specific data sources for vulnerability to heatwaves and flood calculation.

Data source	Variables	Resolution	Accessibility	Format	Link
GAR15 Global Exposure	economic value, number of	5x5km, country level	Open	Map in shapefile, kmz,	https://hgl.harvard.edu/catalog/stanford-mk089bq2743

Dataset for Italy	residents, and construction type of residential, commercial and industrial buildings, as well as hospitals and schools			GeoJSON	
EU statistics on income and living conditions	income, poverty, social exclusion, and living conditions	cross-sectional data over a given time or a certain period; longitudinal data on individual-level changes over time, observed periodically over a 4-year period	Open	Xls table	https://ec.europa.eu/eurostat/web/main/data/database?node_code=livcon
ISTAT	Family income, family expenses for consumption, economic disease, poverty	From 1980	Census level	Xls table	https://www.istat.it/statistiche-per-temi/popolazione/condizioni-economiche-delle-famiglie/#Tavole-di-dati

	, housing condition				
Copernicus climate simulation	Climate Index for Tourism and Holiday Climate Index	Decadal, monthly and seasonal forecasts From 1970 to 2100 0.11° x 0.11°, Europe (27°N to 72°N and 22°W to 45°E)	Open	NetCDF-4	https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-tourism-climate-suitability-indicators?tab=overview
ISTAT, air conditioning	Percentage of people	Region, season	Open	pdf	https://www.istat.it/it/files/2022/06/REPORT-CONSUMI-ENERGETICI-FAMIGLIE-2021-DEF.pdf
OECD Interviews	Disability Adjusted Life Years; Premature Deaths; Welfare Cost of Premature Deaths; Value of a Statistical Life. You can select age and gender for each variable	Nation, annual, From 1990 to 2019	open	xls	https://stats.oecd.org/Index.aspx?DataSetCode=EXP_MORSC

Daily mortality surveillance system, Ministry of Health, Italy	1. In real time, the number of daily deaths, 2. Assessment of the health impact of extreme meteorological events (heat waves, cold waves, intense rain) and other risk factors (flu epidemics, air pollution)	Daily to weekly, from 2004 on, 51 Cities (Regional Capitals and cities with over 100000 inhabitants)	Open	Graphical format and pdf	https://www.salute.gov.it/portale/caldo/dettaglioContenutiCaldo.jsp?lingua=italiano&id=4547&area=emergenzaCaldo&menu=vuoto
Heat wave bulletins	Color code warning	Every year from May to September 24, 48 and 72 hour forecasts 27 cities in Italy	Open	Graphical format	https://www.salute.gov.it/portale/caldo/dettaglioContenutiCaldo.jsp?lingua=italiano&id=4542&area=emergenzaCaldo&menu=vuoto

- **Risks**
  - *Short-term health issues*

While other health data are available upon request, ISTAT provides aggregate information on mortality at municipality level. In the following we report the main data characteristics for this data source (Table 11).

Table 11. Details on characteristics of specific data sources for risks to heatwaves.

Data source	Variables	Resolution	Accessibility	Format	Link
ISTAT	Monthly deaths for municipality, sex and age class; daily datasets for municipality, sex and age class	Municipality	From 2011	Xls table	https://www.istat.it/notizia/dati-di-mortalita-cosa-produce-listat/

  - *Injuries & loss of human lives*
  - *Physical damage of buildings*
  - *Physical loss of buildings*
  - *Socio-economic damage to households*

8.2 Risk storyline 2

- **Hazards**
  - *Earthquake*

As previously described, seismic hazard variables are provided by INGV. Following we report the main data characteristics (Table 12).

Table 12. Details on characteristics of specific data sources for seismic hazard.

Data source	Variables	Resolution	Accessibility	Format	Link
INGV seismic hazard	PGA, Sa(T)	30 seconds (~1 km2) to 10 minutes (~340 km2) 1970-2000	Open	WebGIS	http://esse1.mi.ingv.it/
INGV seismic hazard variables	PGA for exceedance probability in 50 years; spectral acceleration for various exceedance probability in 50 years	30 seconds (~1 km2) to 10 minutes (~340 km2) 1970-2000	Open	Xls table	http://esse1.mi.ingv.it/
VS30 large scale	Vs30	50 × 50 m, country	Open	Raster and ascii	https://doi.org/10.1016/j.enggeo.2020.105745

  - *Extreme precipitation*

Similar to heat waves and as previously described in Section 7, for the quantification of indicators describing extreme precipitation, data sources include mainly ground meteorological stations and amateur networks. Such data sources may be integrated with other sensors providing information on precipitation type. In particular, the MISTRAL portal provides access to various model and observation sources. Following we describe the characteristics of the main data sources available (Table 13).

Table 13. Details on characteristics of specific data sources for extreme precipitation hazard.

Data source	Variables	Resolution	Accessibility	Format	Link
MISTRAL portal	Total precipitation	Station & models with varying resolutions from 2002 onwards	Open	JSON	https://meteohub.mistralportal.it/
SCIA	Daily cumulated precipitationMaximum 1 hour precipitationMaximum daily precipitation	Point station from 1860 on	Open	Graph and csv table	https://scia.isprambiente.it/
ARPAE Dext3r	Daily, 1hour, 30 minutes and 15 minutes cumulated precipitation	Point station from 1961 on	Open	Csvor xls table	https://simc.arpae.it/dext3r/
E-obs	Daily cumulated precipitation	0.1 amd 0.25 ° regular grid	Open	NetCDF	https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php#datafiles
ECA&D	Daily cumulated precipitation	Point station	Open	ascii	https://www.ecad.eu/dailydata/index.php

Meteonetwork	Hourly cumulated precipitation	Point station	open	Graph	https://www.meteonetwork.it/rete/livemap/
Wunderground	30 minutes cumulated precipitation	Point station	Open	Json or csv	https://www.wunderground.com/wundermap
GPM	Gridded multisatellite precipitation estimates	10km/ 0.1°	Open	Visualization, GeoTIFF, HDF5, NetCDF, OPeNDAP	https://gpm.nasa.gov/data/directory
ERA5reanalysis	Maximum hourly total precipitation rate	0.25° x 0.25° from 1940 on	Open	GRIB, NetCDF	https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview
ERA-5 Land	Total hourly precipitation	0.1° x 0.1° from 1950 on	Open	GRIB, NetCDF	https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview
GLOBO BOLAM COSMO weather forecast	12 hour accumulated	19km 7 days (GLOBO) 8.3 km 3 days (BOLAM) 1.25km 2 days	Open	Graphical visualization	https://www.isac.cnr.it/dinamica/projects/forecasts/
WX maps	Total precipitation	10 day forecast	Open	Graphical visualizations	http://wxmaps.org/pix/prec4
Windy	Accumulated precipitation	5days 0forecasts	Open	Graphical visualization	https://www.windy.com/it/-Pioggia-fulmini-rain?rain,43.644,13.052,5

		9km ECMWF 2km UKV 22km GFS 2.2km ICON2D 7km ICON-EU 13km ICON4kmNEMS 2.5km AROME			
Copernicus seasonal forecast	Prob above upper tercile, median, lower third, middle third, upper third, lowest 20%, highest 20%, ensemble mean	T+744 to T+2952-	Open	Image or script	https://charts.ecmwf.int/products/seasonal_system5_standard_rain?area=GLOB&base_time=202407010000&stats=tsum&valid_time=202408010000
GCM spatial downscaled		1970-2090s 30 seconds to 20 minutes	Open	ASCII, ESRI-Grid, GeoTIFF	https://www.ccafs-climate.org/data_spatial_downscaling/
EU High Resolution Temperature and Precipitation	Daily precipitation	1981-2100	Open	NetCDF	https://data.jrc.ec.europa.eu/dataset/jrc-liscoast-10011

- *Pluvial flood*

See risk storyline 1.

- **Exposure**
  - *Built-up area*
  - *Inhabitants*
  - *Households*
  - *Socioeconomic wellbeing*

Similar to what previously depicted for the risk storyline 1, exposure datasets describing characteristics of the built-up area, households and inhabitants mostly derive from ISTAT census data. Following we describe the main characteristics (Table 14):

Table 14. Details on characteristics of specific data sources for exposure to earthquake and extreme precipitation.

Data source	Variables	Resolution	Accessibility	Format	Link
ISTAT, buildings and population	number of buildings	Census tract, 9 periods from 1900 to 2011	Open	Xls, csv	https://www.istat.it/notizia/basi-territoriali-e-variabili-censuarie-test/
ISTAT, disaggregated data on construction material, period of construction and number fo storeys for residential buildings	number of buildings	Municipality, 9 periods from 1900 to 2011	On request	Xls, csv	

- **Vulnerability**
  - *Compact, old historical center // earthquake vulnerability*

Vulnerability to earthquake can be described through data from Cartis. Following we describe the main characteristics (Table 15):

Table 15. Details on characteristics of specific data sources for exposure to earthquake.

Data source	Variables	Resolution	Accessibility	Format	Link
Cartis	# of buildings Construction material, masonry type,	Town Compartment	On request	xls, csv, shapefile	http://cartis.plinivs.it/backoffice/login.php

	slab type, roof type, presence of horizontal connection, plan and elevation irregularity, state of preservation				
Da.D.O.	data on the construction and structural characteristics, as well as on seismic damage, of ordinary buildings and churches inspected during or following seismic crises of national importance	Event-based	Open upon registration	Web-gis	[Da.D.O. (eucentre.it)]
ISTAT – Mappa dei Rischi dei Comuni Italiani	Data on seismic, hydrogeological and volcanic risk integrated with information on demographics, buildings, territory and geography	Municipality	On request	xls, csv, shapefile	[Mappa dei rischi dei Comuni italiani – Istat]

- *Soil sealing*
- *Poor sewage system*
- *Flood vulnerability*
- *Lack of MH design in recovery*
- *Socioeconomic vulnerability*

- **Impact**
  - *Physical damage of buildings*
- **Risk**
  - *Physical loss of buildings*
  - *Injuries and loss of human lives*
  - *Loss of productive systems*
  - *.3Socio-economic damage to households*
  - *Temporary increase of urbanization*

9. Examples of smart data models for risk management

Smart data models (SDAs) are useful instruments to evaluate risks and, consequently, they allow institutions to set a proper response to a potentially dangerous situation for the population. These instruments are made of algorithms which consider the different components of risk evaluation, namely hazard, vulnerability and exposure, as described in Deliverable 5.2.3. One specific algorithm is required for each component, then the results can be combined to evaluate the risks involving the specific hazard event for a specific location and time of the year. The identification of hazards requires algorithms which can define a process of identification and characterization of these events. In general, such algorithms must describe all the process, from the dataset to the results of these analysis.

As an example, a SDA for the identification of a heat wave hazard is reported in Fig.2. In the following each part of this algorithm will be described. In this example the indicators used for assessment of the heat wave hazard are WSDI (Warm Spell Duration Index), EHI (Excess Heat Index), HI (Heat Index) and TDI (Thom Discomfort Index), hence daily maximum, minimum and mean temperature (C°) and relative humidity (%) are required for their computation. Please note that this algorithm has to be integrated with algorithms dedicated to the vulnerability and exposure components, in order to obtain the complete smart data model for heat wave risk.

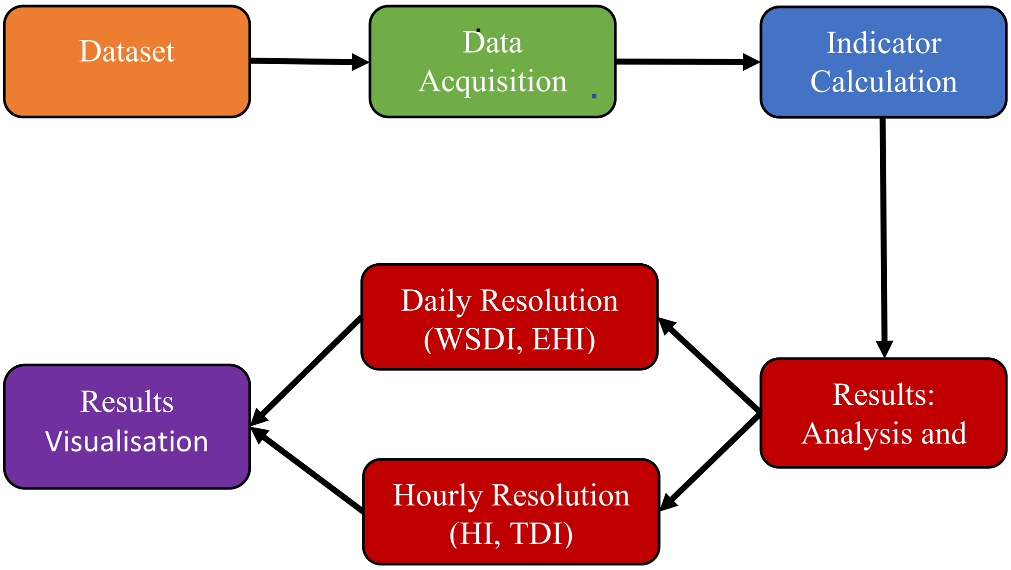

Figure 2. Example of algorithm for heat wave hazard, each block represents a step of the calculation algorithm.

The first step to identify a heat wave is to acquire data from one or more datasets (orange block), selected from those described in Sections 7 and 8 based. As described in the previous sections, datasets can be divided into different types (in situ, satellite observation, reanalysis, etc.), each having and characterized by its own characteristics including a standard format (tabular format in CSV, XLS, text, gridded format in NetCDF, GRIB, etc.). As pointed out in DV 5.2.3, the choice of the dataset is crucial in terms of spatial and temporal resolution and constraints on final uncertainty. For instance, the use of ground-based datasets may be useful for analysis at local or at most for a city scale assessment, while conversely gridded data may be applicable for regional scale analysis. As described in Section 8, furthermore, gridded datasets are characterized by widely variable spatial resolution, and the choice of the dataset drives the possibility to conduct a finer or coarser scale assessment even at regional scale. As concerns time resolution and similar constraints, one must consider that WSDI and EHI require a continuous period of at least 30 years in which measurements are available, therefore the dataset must have a long history of records. Furthermore, some datasets may provide forecasts or projections data which may be utilized to perform a forecast of the hazard itself and hence of the correlated risks (vulnerability and exposure are needed).

Once the datasets are identified, the second step is the data acquisition (green block). In this part the system will access the data from the datasets. The format of data is a crucial factor in this step since different formats require different procedures to extract the data. The model must be capable of recognizing the format of the data provided by the dataset and process it consequently, making available for computations all data needed.

Afterwards, the indicator can be computed using the extracted data (blue block). Each indicator considered (WSDI, EHI, HI and TDI) has its own method of computation (see Chapter 10 of DV 5.2.3 for more information) and the model must be able to evaluate each index for the space and time indicated.

Results of the computations must be discussed to provide indications on the heat wave hazard level (red blocks). The discussion is essential since it permits to explain the computation outcomes and to give them the proper significance in terms of magnitude. As for WSDI and EHI (holistic indicators), results may help in the identification of a heat wave and in the assessment of its magnitude. Since they both require daily temperature measurements, their results will have a daily resolution. On the other hand, as concerns HI and TDI (biometeorological indicators), results may give indications on the heat stress and discomfort posed by the heat wave event (or the peculiar meteorological situation). In this case, since these indicators require instantaneous data of temperature and relative humidity, results may be discussed and analysed at hourly resolution.

Lastly, discussion results must be elaborated and explained through an interface which could provide a proper visualisation for the user (purple block). This interface may give the opportunity to range from a regional view of the hazard level to a local focus on a city level, exploiting the different datasets available. This visualisation must include the possibility to change time coordinates and show past heat waves effect and forecasts of future ones with their computed hazard level. In addition, it can be useful if there will be the possibility to explore both the spatial and temporal extent of past, present and future heat waves along with their hazard levels.

10. Conclusions

By adopting a pragmatic yet modular approach based on risk storylines and related impact chains, this Deliverable showcases the development of a template structure and smart data model for risk assessment suitable for the needs of RETURN and specifically to address risk assessment within urban and metropolitan settlements. In practice, this Deliverable complements and finalizes the introductory steps taken in previous WP5.2 Deliverables (DV 5.2.1, 5.2.2 and 5.2.3), preliminary to the development of the data platform in WP5.5 and the development of risk models in WP5.3.

Substantially, after the description of the indicators and example algorithms for risk calculation for a subset of selected risk components and risk storylines, and based on the data recommendations and constraints provided in DV 5.2.3, here we first select the indicators (thus, the variables) which will be used for risk assessment; based on the selection of the indicators, we then present and describe relevant data sources available for risk calculation, considering, when available, the options of describing both past and future events; after that, relevant data characteristics in terms of format, resolution (spatial and temporal), variables considered, availability, are presented; finally, smart data models are presented for the quantification and assessment of some specific risks. As noted in the Deliverable text, the list of data sources provided in this Deliverable does not claim to be fully exhaustive and comprehensive. However, the depiction given in this Deliverable provides a roundup of the diverse possible data sources available to calculate risk and of their different characteristics. Indeed, even from this preliminary and partial view we can observe that data can derive from well different data sources, including for instance station data at a single station, gridded data with a certain spatial resolution, or census or municipality data (most often for the description of the vulnerability and exposure components). Such data sources are inherently characterized by well different formatting, which has to be taken into account into the data processing and in the development of the smart data model. The final choice of the datasets used is then fully determined by the precise scope of the analysis, and specifically by the required resolution and uncertainty, as well as by the application type (e.g., analysis of past events or forecast of future ones).

As such and integrating the results of DV 5.2.3, the Deliverable demonstrates the capabilities and advantages of the adoption of a standardized, yet flexible and modular approach based on risk storylines and impact chains for the integration and processing of heterogenous data sources in RETURN. Considering the multiple parallel and transdisciplinary development of project activities across Vertical, Transversal and Diagonal Spokes and WPs, the flexibility of the approach adopted seems crucial to enable future integrations and modifications of the processed data sources or algorithms utilized, yet maintaining scientific rigorousness and high quality.

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Appendix A. Focus on buildings exposure to hazards

Buildings are exposed to continuous, low-intensity natural stress factors, such as weather events and air pollution (so-called extensive risks), as well as intermittent, high-intensity events, such as extreme weather conditions, volcanic activity, or seismic events (so-called intensive risks). The building envelope is both the most exposed and the most vulnerable element during such events, and its damage leads to loss of building functionality, decreased urban safety, and economic losses.

However, the focus here is exclusively on hazards with low intensity, as considering high intensity hazards for the architectural elements of the envelope would have been superfluous. Indeed, while medium or high-risk factors could cause significant damage to the building's structural system, significant damage can occur with lesser stresses. Table A1 lists the envelope elements exposed to the set of hazards of interest.

Table A1. Exposure matrix for envelope elements.

		Cornice	Balcony	Infills	Household drain system	Roof	Openings / Windows
Geophysical Hazards	***Earthquake***	✓	✓	✓	✓	✓	✓
	Landslide			✓	✓		
Hydrology	***Avalanche***				✓	✓	✓
	Flood				✓	✓	✓
Meteorological Hazards	***Coastal risk***	✓	✓	✓	✓	✓	✓
	Extreme weather	✓	✓	✓	✓	✓	✓
	Heatwave	✓	✓	✓	✓	✓	✓
	Windstorm	✓	✓	✓	✓	✓	✓

To determine the behavior of elements subject to hazardous events, two possible approaches were identified: one predominantly qualitative and the other quantitative. As illustrated in Fig. A1, the approach used in this study involves a literature review to understand the effects of hazards on the elements of interest, with the aim of defining a standardized action-reactivity phenomenon. In this way, a preliminary assessment of vulnerability to various hazards was performed, providing a solid foundation for future studies.

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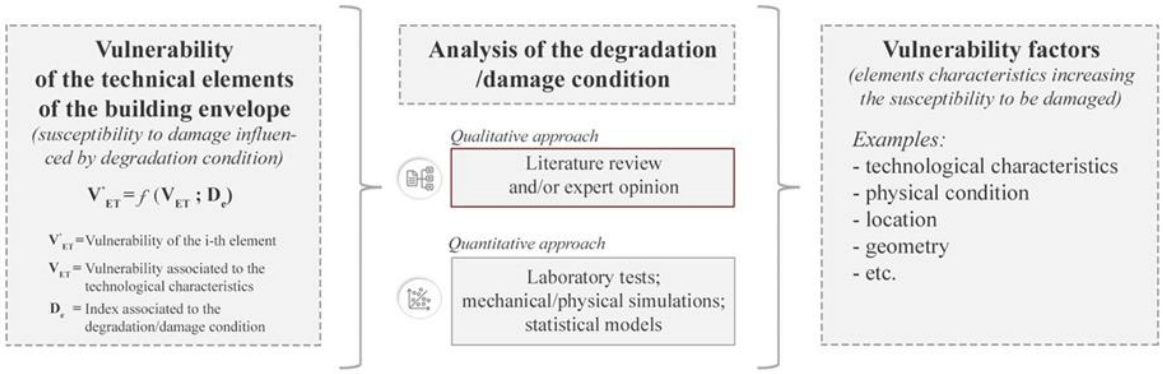

Figure A1. Approach utilized in the study for the analysis of vulnerability of the building envelope to specific hazards.

The natural hazards of greatest interest are those typical of the Italian context and those affecting the building envelope as a whole, including earthquakes, rainfall, heatwaves, and windstorms. The hazards of greatest interest were identified by analyzing the exposure matrix represented in Table A1. The Sections below analyze damage mechanisms and vulnerability factors, as well as vulnerability reduction interventions, irrespective of the magnitude of the hazardous event under analysis.

Earthquakes

There are numerous documents on how earthquakes damage architectural elements, revealing that, in general, the behavior of these elements is similar regardless of the material composition, except for specific cases[1]. The identified vulnerability factors for this technical element include material fragility, element rigidity, span, and mass, as greater mass results in greater effects[2-3].
For example, in the case of hollow brick infills, a performance intervention could involve increasing the tensile strength of the mortar[4]. In the case of local edge crushing, an intervention might be improving the joints between the load-bearing structure and the infill, making them more elastic[5]. Regarding drainage system elements, considering that damage is related to the structure to which they are anchored, reducing the distance between support systems near direction changes can help reduce the likelihood of pipe breakage[6-7]. For balconies, it has been reported that certain construction solutions, such as metal brackets and marble slate, are particularly vulnerable to earthquakes due to their fragility. At the same time, the shape factor of balconies influences their deformation and, consequently, their vulnerability.

Rain

During precipitation, one of the main issues is damage related to water infiltration. A key vulnerability factor is the permeability of various materials to both water and vapor. A study was conducted on the difference between water and vapor permeability to define the behaviors of various elements[8]. The analysis revealed that the primary damage caused by precipitation concerns moisture. Moisture infiltration causes water to transfer from regions of higher concentration to less humid areas, resulting in capillarity phenomena with consequent microcracking, followed by plaster detachment and subsequent damage with final detachment of the finish. Proper moisture management in buildings requires that water does not accumulate within the structures and that water vapor can be adequately ventilated to prevent moisture and mold problems[9]. For example, plaster detachment is caused by water deposits containing salts (or dissolving those present in the masonry), which, once they reach the surface and the water evaporates, crystallize, increasing their volume and causing the breakage of plaster and coatings. The high hygroscopicity of salts can lead to further moisture even after eliminating the causes of capillary rise[10]. These phenomena can generate both internal and external condensation in the walls and cause a decrease in thermal insulation. Factors that increase the vulnerability of elements affected by water can be attributed to both the intrinsic characteristics of the materials and their chemical composition[11]. Vulnerability factors include high water permeability; use of materials vulnerable to corrosion; unsealed fixings and anchors; and absence of overhanging elements (allowing direct impact of rain and water splashes).

Freezing

Freezing undermines building elements primarily by affecting the water and vapor present within various materials. In general, freezing can have damaging effects on building elements, both directly through the freezing of water or water vapor, and indirectly through the expansion and contraction of materials[12]. It is important to adopt preventive measures such as adequate thermal insulation and regular maintenance to protect building elements from frost damage. If water vapor within building elements condenses due to cold and subsequently freezes, it can cause mechanical deterioration. For example, the freezing of water vapor within porous materials like wood can lead to the formation of cracks or material expansion, resulting in long-term structural damage. Many of these phenomena, in addition to those mentioned above, can be caused by freeze-thaw cycles, where water within various elements solidifies, increases in volume, and then melts, reducing in volume and causing severe damage. Among the factors that increase vulnerability, the extreme permeability to water and vapor of the materials stands out[13].

Extreme Heat

During extreme heat, many materials used in facade construction, such as metal and PVC, can undergo deformation and expansion due to high temperatures[14]. This phenomenon can lead to distortions, cracks, or separations in joints. Materials such as wood, paint, or plastic can experience rapid deterioration due to prolonged exposure to high temperatures and solar radiation[15]. Surface finishes may fade, crack, or peel off, compromising the aesthetic appearance of the facade and urban safety. The main factors that increase vulnerability to these elements are the coefficient of thermal expansion and the coefficient of thermal conductivity.

Windstorms

Wind can cause damage to non-structural elements due to the high pressure and suction forces that compromise joints and fragile components. Vulnerability factors include low compressive strength, low suction resistance, large surface area (which increases wind force), and poorly designed connections. Additionally, wind can strike cladding and roofing materials with debris, requiring a certain level of surface resistance[16]. Wind can cause the detachment of roofing, especially when tiles are not well anchored to the support or when metal panels are subjected to high suction forces (e.g., when the element area is large and the element mass is low). When roof materials are damaged, rainwater can infiltrate, causing further damage to the building envelope. Factors that increase vulnerability include roof slopes between 0 and 29 degrees, excessive lightness of the element, and very lightweight elements. The integrity of windows can also be compromised[17]. According to UNI 11673-1 standard, mechanical resistance provides guidelines on the management of point mechanical fastening, evaluation of the window/wind pressure ratio, and consistency with any anti-burglary values of the window. This implies that a stiffer and smaller window better withstands wind gusts. Furthermore, strong winds can cause glass breakage, with the risk of fragments falling both inside and outside. Factors that increase vulnerability include lack of sealing, flexibility of the window frame, and extremely fragile glass[18].

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