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*Enhancing our understanding of Subsidence
RISK induced by groundwater exploitation
towards sustainable urban development*

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DEL 5.2

Report on the current impacts at national, regional and local scales

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Executive summary

This report summarises the results of SubRISK+ Work Package (WP) n.5 (*WP5: Socio-economic impact analysis*), aimed to identify the direct and indirect economic exposure to land subsidence at national, regional and local scales. The analysis has been performed across the 15 metropolitan cities of Italy, the Emilia-Romagna region, and Bologna city.

The input data are the differential displacement hazard maps produced at the national level (in WP2) and for the Emilia-Romagna region (in WP3). To assess the potential socio-economic impacts, Global Human Settlement Layer (GHSL) population grid, the OMI (Osservatorio Mercato Immobiliare — real estate market observatory) data, and different building databases were used.

The final maps provide a classification of the ISTAT census zones that are homogeneous territorial units defined by the Italian National Institute of Statistics (ISTAT). Three levels of socio-economic exposure from low to high are distinguished taking into account the population density and the amount in euro of residential and non-residential elements at risk.

Furthermore, the indirect potential impact of land subsidence is investigated by verifying the hazard level of the UNESCO world heritage sites for the 15 metropolitan cities and for the Bologna area.

The indirect effect of the land subsidence is investigated by a descriptive statistics of the vertical velocity measured using the Copernicus European Ground Motion Service (EGMS) satellite-based Interferometric Synthetic Aperture Radar (InSAR) datasets in the period 2018-2022 within the flood hazard zones mapped by Italian Institute for Environmental Protection and Research (ISPRA).

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1. INTRODUCTION

SubRISK+: *Enhancing our understanding of Subsidence RISK induced by groundwater exploitation towards sustainable urban development* is a collaborative research project funded in 2023-2026 in the framework of the Italian National Recovery and Resilience Plan (NRRP), Mission 4, Component 2 (M4C2) – Investment 1.1: Fund for the National Research Programme (NRP) and Research Projects of Significant National Relevance (PRIN) [Call “PRIN 2022 PNRR”, D.D. no.1409, 14/09/2022], and led by the National Research Council (CNR) of Italy – Institute of Atmospheric Sciences and Climate (ISAC), in collaboration with the University School for Advanced Studies (IUSS) of Pavia – Department of Science, Technology and Society (STS), and the University of Padua (UNIPD) – Department of Civil, Environmental and Architectural Engineering (ICEA).

This report summarises the results of SubRISK+ Work Package (WP) n.5 (*WP5: Socio-economic impact analysis*), aimed to identify the direct and indirect economic exposure to land subsidence for 15 metropolitan cities of Italy, the Emilia Romagna region, and for Bologna.

In particular, section 2 describes the input datasets used (section 2.1) and the developed methodology (section 2.2). The achieved results are then presented in section 3, which provides: the socio-economic impact for the 15 metropolitan cities (section 3.1), for the Emilia Romagna region (section 3.2), and for Bologna city (section 3.3). The conclusions are reported in section 4.

2. DATA & METHODS

2.1. Input datasets

The input datasets used in the analysis include several databases, taking into account the three spatial scales as described in Table 1. The detailed description is included in the following paragraphs.

Table 1. List of input database.

Variable	Name of the dataset	Provider	Source	Spatial scale and resolution
	European Ground Motion Service (EGMS)	Copernicus European Union's Earth observation programme	https://land.copernicus.eu/en/products/european-ground-motion-service	100x100 m
Hazard	Hazard map (10 years)	SubRisk+ project	Deliverable DEL2.2. (Cigna et al. 2024)	National scale
	Hazard map (30 years)	SubRisk+ project	Deliverable DEL3.3. (Bonì et al. 2025)	Emilia-Romagna and Bologna city
Element at risk	ISTAT census zones	Italian National Institute of Statistics	www.istat.it	National scale, Emilia-Romagna and Bologna city
	UNESCO cultural heritage sites	UNESCO's World Heritage Centre	https://whc.unesco.org	Emilia-Romagna and Bologna city
	Emilia-Romagna Building footprint and height database	the Emilia-Romagna region	https://geoportale.regione.emilia-romagna.it	Emilia-Romagna and Bologna city
	Italy Building footprint database	United Nations Office for the Coordination of Humanitarian Affairs (OCHA)	Openstreet map export	National scale

GHS-BUILT-H - R2023A - building height	European Commission's Joint Research Centre (JRC)	https://data.jrc.ec.europa.eu	National scale Spatial resolution of 100 m
Residential and non-residential buildings – GHSL - GHS_BUILT_S_E2018_GLOBE_R2023A	European Commission's Joint Research Centre (JRC)	https://data.jrc.ec.europa.eu	Emilia-Romagna and Bologna city Spatial resolution of 10 m
Residential and non-residential buildings – GHSL - GHS-BUILT-C R2023A	European Commission's Joint Research Centre (JRC)	https://data.jrc.ec.europa.eu	National scale
GHS population grid	European Commission's Joint Research Centre (JRC)	https://data.jrc.ec.europa.eu	National scale, Emilia-Romagna and Bologna city
Real estate market values	OMI (Osservatorio del Mercato Immobiliare)- the Italian Real Estate Market Observatory	https://www.agenziaentrate.gov.it/	National scale, Emilia-Romagna and Bologna city
Indirect impact	Flood hazard zones Italian Institute for Environmental Protection and Research (ISPRA)	https://idrogeo.isprambiente.it	National scale, Emilia-Romagna and Bologna city

2.1.1. Hazard datasets

The hazard levels induced by differential displacement on urban infrastructures can be estimated through the computation of the angular distortion (β) and horizontal strain (ϵ), as derived from the Copernicus European Ground Motion Service (EGMS) satellite-based Interferometric Synthetic Aperture Radar (InSAR) datasets (Cigna et al. 2024). The computation of these two parameters starts by accounting for the vertical (V_U) and east-west (V_E) displacement velocity data provided by the EGMS Ortho layers for the 2018-2022 period.

The hazard level was computed by assuming that the estimated velocities affected the observed areas over a period of 10 years at the national scale (Cigna et al., 2024). For Emilia-Romagna and the city of Bologna, a period of 30 years was considered, taking into account that this region has been historically affected by land subsidence since the 1950s (Bonì et al., 2025). The threshold values adopted for β and ε account for geotechnical practice and are combined to distinguish four hazard levels (Figure 1). Hazard levels are identified according to a scale ranging from low (H1) to very high (H4), indicating an increasing probability of occurrence of fissuring/fracturing and associated damage of the urban infrastructure.

A detailed description of the methods and limits is reported in the two deliverables of the SubRISK+ project DEL2.2 and DEL3.3.

		Total horizontal strain	
		$ \varepsilon < 0.03\%$	$ \varepsilon \geq 0.03\%$
Total angular distortion	$\beta \leq 1/3000$	H1	H2
	$1/3000 < \beta \leq 1/500$	H2	H3
	$1/500 < \beta \leq 1/150$	H3	H4
	$\beta > 1/150$	H4	H4

Figure 1 – Hazard (H) assessment and mapping using SubRISK+ methodology (Source: Cigna et al., 2024; Bonì et al., 2025)

2.1.2. Element at risk datasets

The datasets used to identify the element at risk are:

1. ISTAT census zones. According to the census by the Italian National Institute of Statistics (ISTAT, www.istat.it), Italy's territory is subdivided into census zones. The size of these zones differs based on the surrounding environment, ranging from very small in densely populated urban areas to increasingly larger in suburban, rural, and mountainous regions (Figure 2). In this study, we utilised the 2021 ISTAT census data, provided in the WGS 84 UTM Zone 32N projection, for the 20 Italian regions. The data were then clipped according to the boundaries of the 15 metropolitan cities (see SubRISK+ deliverable DEL2.2, Cigna et al., 2024).

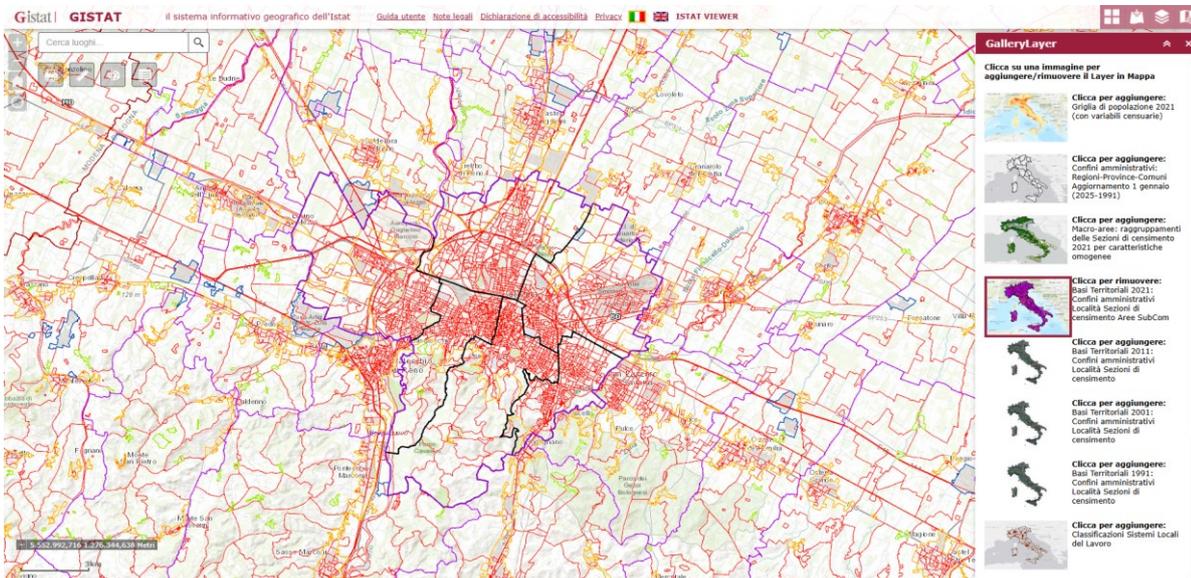


Figure 2 – Overview of the ISTAT geoportal for the city of Bologna. The census zones are detected by violet boundaries (source: www.istat.it).

- UNESCO cultural heritage sites. The GIS data of UNESCO-designated sites (Figure 3) were used to assess the potential direct non-market effect of land subsidence. This is an open-access spatial database that contains detailed geographic and attribute information about all cultural and natural sites recorded in the UNESCO World Heritage List, that is managed and maintained by UNESCO's World Heritage Centre (<https://whc.unesco.org>).

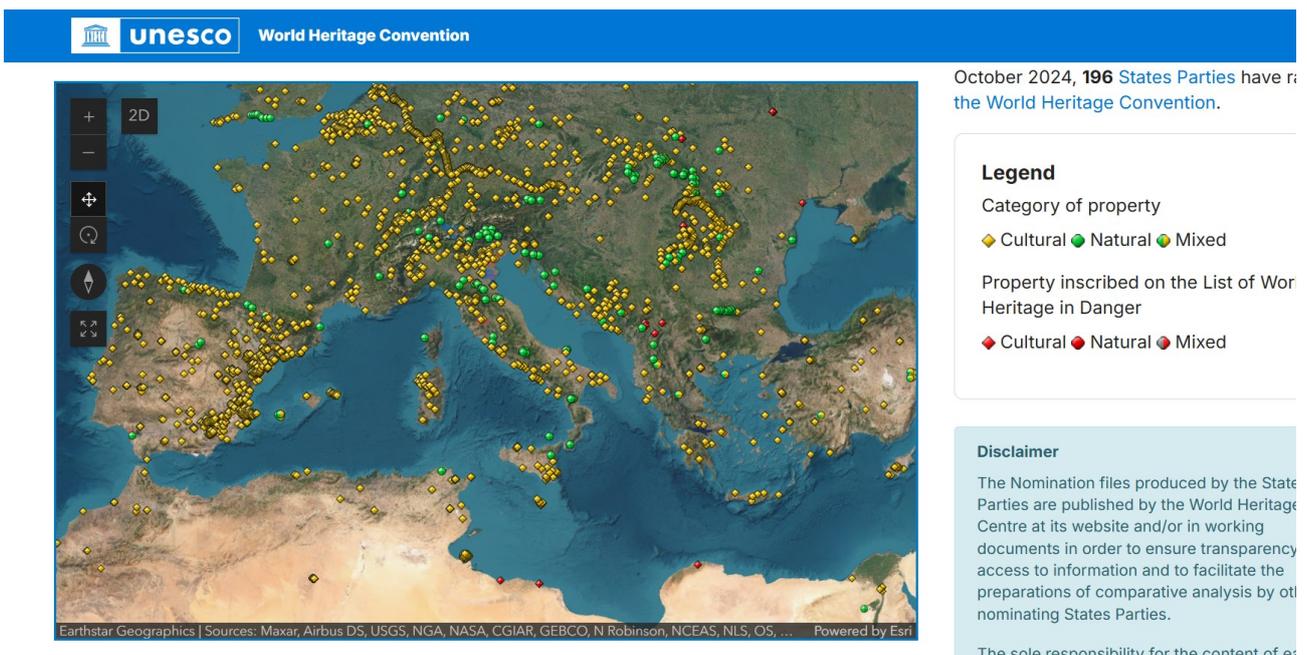


Figure 3 – Overview of the World Heritage Convention website (source: <https://whc.unesco.org/en/list/>).

3. Building datasets. Two datasets were used to obtain information on building footprints. Specifically, for the analysis of the Emilia-Romagna region and the city of Bologna, we used a dataset provided by the Emilia-Romagna regional government, which also includes building height information (source: <https://geoportale.regione.emilia-romagna.it>). For the 15 metropolitan cities, we used a dataset provided by the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) (Herfort et al., 2021). In this case, building height information is not available; therefore, the Global Human Settlement Layer (GHSL) named GHS-BUILT-H R2023A - GHS building height, derived from AW3D30, SRTM30, and Sentinel2 composite was used. This spatial raster dataset provides the distribution of the building heights generalized at the resolution of 100 m, and referred to the year 2018. The estimation of the GHS-BUILT-H error is currently ongoing (Pesaresi et al., 2024).
4. Residential versus non-residential buildings dataset. Two datasets were exploited to distinguish residential and non residential buildings. In particular for the Emilia-Romagna region, we used the GHS-BUILT-S - R2023A. The data report about the total built-up surface and the built-up surface allocated to dominant non-residential (NRES) uses (Pesaresi et al., 2024). Specifically, we used the 2018 dataset at the resolution of 10 m. For the 15 metropolitan cities, we used the GHS-BUILT-C R2023A. These spatial raster datasets delineate the boundaries of the human settlements at 10 m resolution, and describe their characteristics in terms of the morphology of the built settlement and the functional use (Pesaresi et al., 2024).
5. Population datasets. We used the GHS population grid (R2023) in 2020 at the resolution of 100 m for the analysis at the national, regional and local scale. This spatial raster provides information about the human population expressed as the number of inhabitants per cell (Pesaresi et al., 2024).

2.1.3. Real estate market values

To assess the value of the elements at risk, we use information from the Italian OMI (Osservatorio del Mercato Immobiliare) database. It provides comprehensive information on real estate market values across different building types and covers the entire Italian territory (<https://www.agenziaentrate.gov.it>), spanning from 2006 to 2024, and is updated every six months. Specifically, the OMI database offers a classification of municipalities into territorial macro-areas (in Italian “*fasce*”) and micro-areas (OMI zones). The OMI zones are defined considering homogeneous areas where properties have similar economic characteristics and values (Figure 4). Furthermore, each municipality is divided into five “OMI macro-areas” (*fasce*), categorized as follows:

- B – central,
- C – semi-central,
- D – peripheral,
- E – suburban, and
- R – rural.

The data is open access and standardized, offering a consistent overview of real estate values including maximum and minimum real estate market value (€/m²) for different building types.

This study uses data from the second half of 2022.

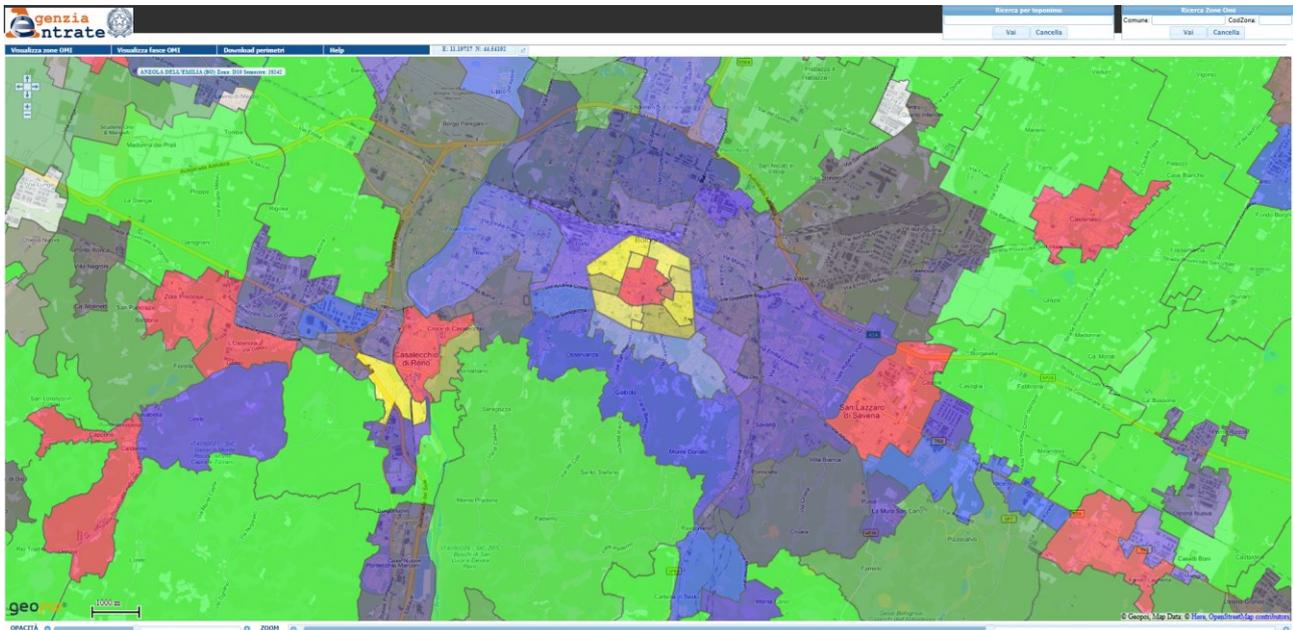


Figure 4 – Overview of the OMI geoportal (source: <https://www.agenziaentrate.gov.it>).

2.1.4. Flood hazard

To take into account of the indirect impact of the land subsidence on the flood prone areas, we used the Italian Institute for Environmental Protection and Research (ISPRA) National mosaic (v 5.0 – 2020) of the flood hazard zones mapped by the River Basin District Authorities according to the 3 scenarios defined by Legislative Decree 49/2010 (implementation of the Flood Directive 2007/60/EC) (Figure 5). Specifically, the ISPRA national mosaic of flood hazard zones is related to the 3 following scenarios: high flood hazard with return period between 20 and 50 years (frequent floods); medium hazard with return period between 100 and 200 years (infrequent floods); low hazard (low probability of floods or extreme event scenarios). The database is open access at the geoportal <https://idrogeo.isprambiente.it/>. We used the high flood hazard areas defined using a return period between 20 and 50 years.

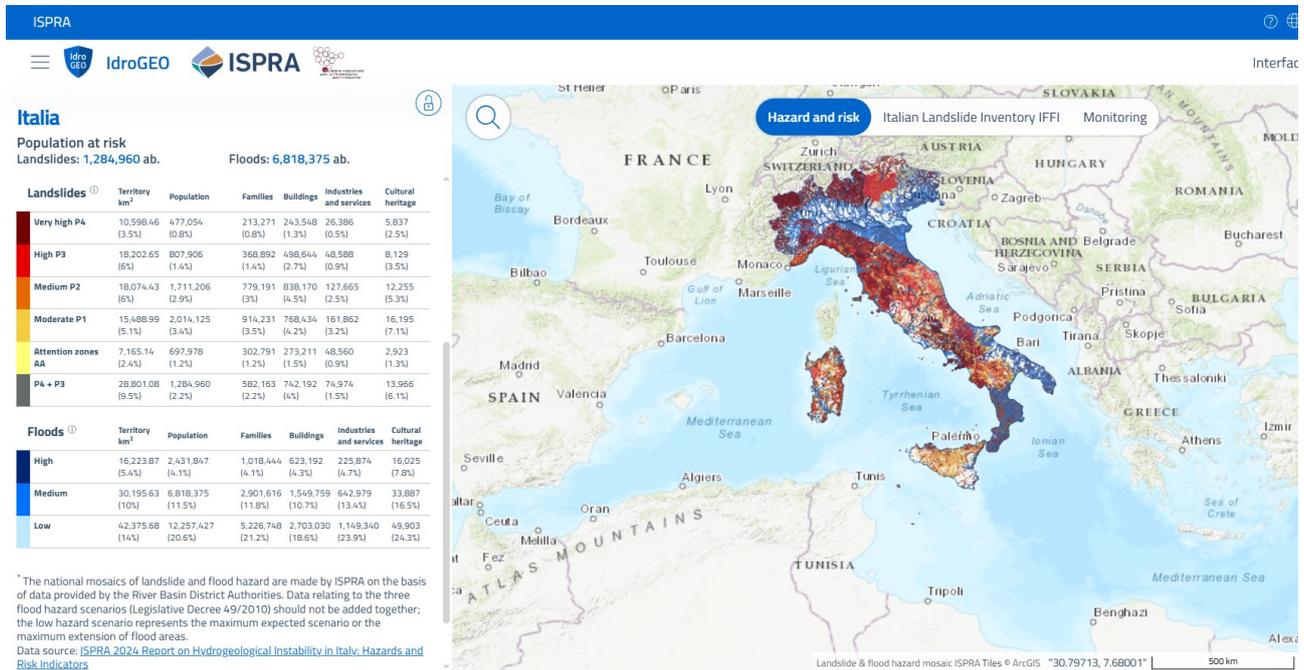


Figure 5 – Overview of IdroGEO geoportale (source: <https://idrogeo.isprambiente.it>).

2.2. Methods

In this work, three technical workflows were developed to assess potential direct and indirect impacts of land subsidence at the three spatial scales: the national scale (i.e. the 15 Italian metropolitan cities), the administrative regional scale (i.e. the Emilia-Romagna region) and the local scale (i.e. the Bologna city). The following paragraphs describe the three approaches characterized by a general similar workflow, but with refinements that take into account the spatial scale specificity.

Additionally, the exposure of the UNESCO cultural heritage maps to differential displacements and the flooding-prone areas exposed to land subsidence are investigated as described in the following paragraphs.

2.2.1. Potential direct impacts of the land subsidence in Italy

The methodology to assess the potential impacts of land subsidence for the national scale is performed taking into account the administrative boundaries of the 15 metropolitan cities of Italy and the four hazard levels results achieved in the DEL2.2. (Cigna et al. 2014). It is worth noting that the hazard level is evaluated by estimating the total angular distortion and horizontal strain for a period of 10 years, and the socio-economic exposure is computed considering the differential ground displacements. First, the total market value of the elements at risk and the population density for each ISTAT census zone are estimated. Then, a matrix is used to combine this information and reclassify the ISTAT census zones into three categories: low, medium, and high socio-economic exposure (Figure 6). No data is assigned for the missing data about the market values.

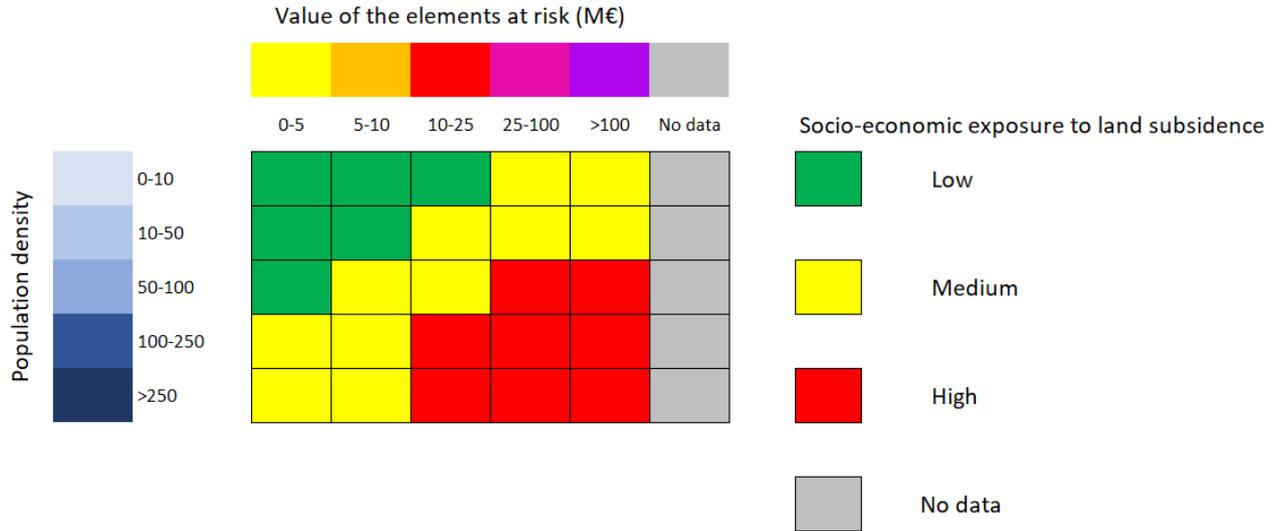


Figure 6 – Matrix of socio-economic exposure to land subsidence (LS) risk.

Specifically, the first step involves filtering the elements at risk by excluding buildings classified as having a low hazard level. Subsequently, the total market value is estimated for each ISTAT census zone (z), distinguishing between residential and non-residential buildings and taking into account the following variables:

- A_i = planimetric area (in m^2) of residential building i within zone z
- A_j = planimetric area (in m^2) of non-residential building j within zone z
- h_i = height (in meters) of residential building i
- h_j = height (in meters) of non-residential building j . In this case, the building height is extracted from the average building height in a cell size of 100 m as provided from GHSL JRC data.
- $n_{i \text{ or } j}$ = number of floors of building i or j , approximated as (1):

$$n_{i \text{ or } j} = h_{i \text{ or } j} / 3 \quad (1)$$

where 3 m is assumed the average floor height as defined by the Italian Ministerial Decree of July 5, 1975.

Therefore, the residential area at risk S_z^{res} for census zone z (in m^2) are estimated using the following equation (2):

$$S_z^{res} = \sum_{i \in res} A_i \times n_i \quad (2)$$

where the summation is over all residential buildings i in zone z .

Non-residential area at risk S_z^{nonres} for census zone z (in m^2) is estimated using the following equation (3):

$$S_z^{nonres} = \sum_{j \in nonres} A_j \times n_j \quad (3)$$

where the summation is over all non-residential buildings j in zone z , with n_j similarly calculated.

Finally, the total market value V_z of the element at risk for census zone z (in €) is estimated using the following equation (4):

$$V_z = (S_z^{res} \times V_z^{res}) + (S_z^{nonres} \times V_z^{nonres}) \quad (4)$$

where V_z^{res} and V_z^{nonres} represents the mean market value per square meter for residential and non-residential buildings in zone z , respectively.

To extract the information about residential and non-residential buildings, the Morphological Settlement Zone delineation and inner classification were used. Specifically, according to the GHS-BUILT-C - R2023A data, the following classes were selected to reclassify the buildings:

- 11 : MSZ, built spaces, residential, building height ≤ 3 m
- 12 : MSZ, built spaces, residential, $3\text{m} < \text{building height} \leq 6$ m
- 13 : MSZ, built spaces, residential, $6\text{m} < \text{building height} \leq 15$ m
- 14 : MSZ, built spaces, residential, $15\text{m} < \text{building height} \leq 30$ m
- 15 : MSZ, built spaces, residential, building height > 30 m
- 21 : MSZ, built spaces, non-residential, building height ≤ 3 m
- 22 : MSZ, built spaces, non-residential, $3\text{m} < \text{building height} \leq 6$ m
- 23 : MSZ, built spaces, non-residential, $6\text{m} < \text{building height} \leq 15$ m
- 24 : MSZ, built spaces, non-residential, $15\text{m} < \text{building height} \leq 30$ m
- 25 : MSZ, built spaces, non-residential, building height > 30 m

Table 2 shows the correspondence developed to extract the mean market value per square meter for residential and non-residential buildings in the ISTAT census zones from the OMI database.

Table 2. Correspondence between the OMI typology description and the residential and non-residential buildings.

OMI typology	Re-classification for this study
Villas and detached houses	Residential buildings
Refined house	
Residential building with good general characteristics	
Local traditional houses	
Residential building with economical characteristics	
Box	
Uncovered parking spaces	
Covered parking spaces	
Industrial shed	
Shed	
Uncovered parking spaces	
Covered parking spaces	
Shopping center	
Building or complex of buildings with shops	
Offices	
Structured offices	
Laboratories	
Warehouses	
Parking	

Figure 7 shows the technical workflow of the methodology to assess the socio-economic exposure at the national scale (i.e., the 15 metropolitan cities).

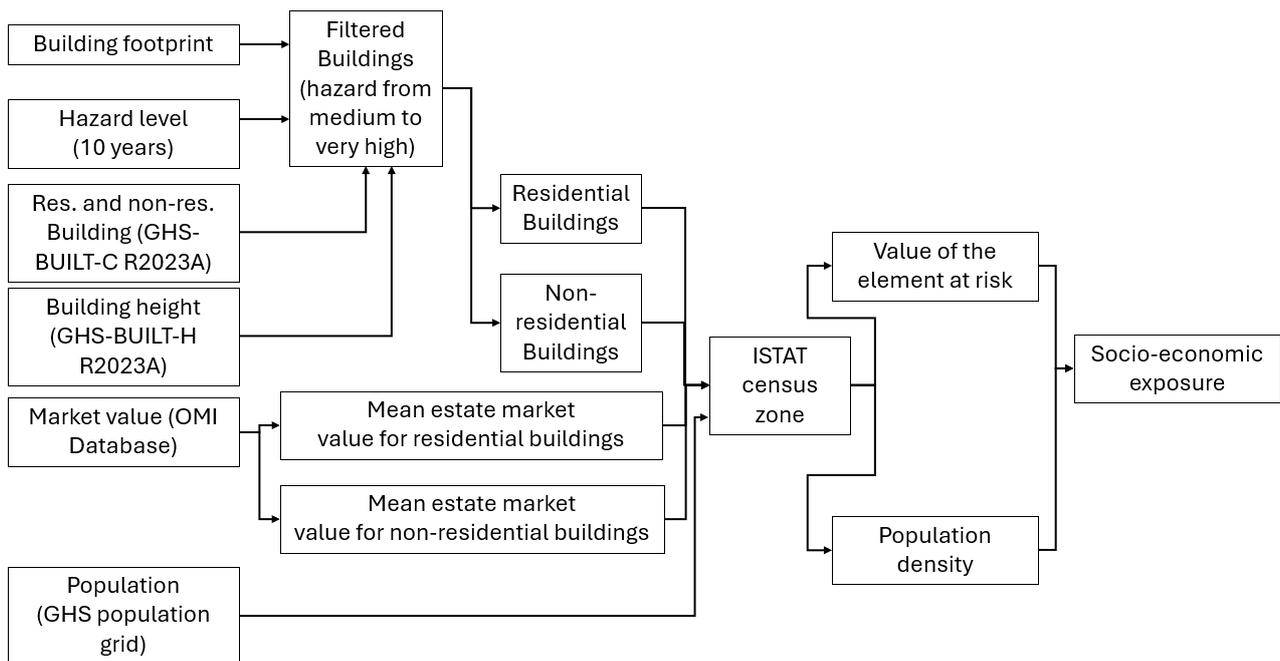


Figure 7 – Methodological workflow to assess land subsidence socio-economic exposure at the national scale.

2.2.2. Potential direct impacts of the land subsidence in Emilia Romagna

For the Emilia-Romagna region, a refinement of the previously described approach is carried out. In particular, the potential impacts of land subsidence are evaluated in the plain areas of the region, excluding the mountainous and hilly zones, where differential displacement may be due to landslides. Furthermore, the 4 hazard levels are evaluated for a period of 30 years as explained in the DEL3.3 (Boni et al., 2025). First, the building database is filtered to include only buildings classified with a hazard level ranging from medium to very high. Then, the total market value of the elements at risk and the population density for each ISTAT census zone are estimated using the same approach described at the national scale. The same matrix shown in Figure 6 is then used to combine this information and reclassify the ISTAT census zones into three categories: low, medium, and high socio-economic exposure. Like in the previous case, no values are assigned where market data are missing. In this case, building height is provided for each structure by the Emilia-Romagna database. To distinguish between residential and non-residential buildings, the GHS-BUILT-S dataset was used.

Figure 8 shows the technical methodological workflow of the methodology to assess the socio-economic exposure at the regional scale (i.e. the Emilia-Romagna region).

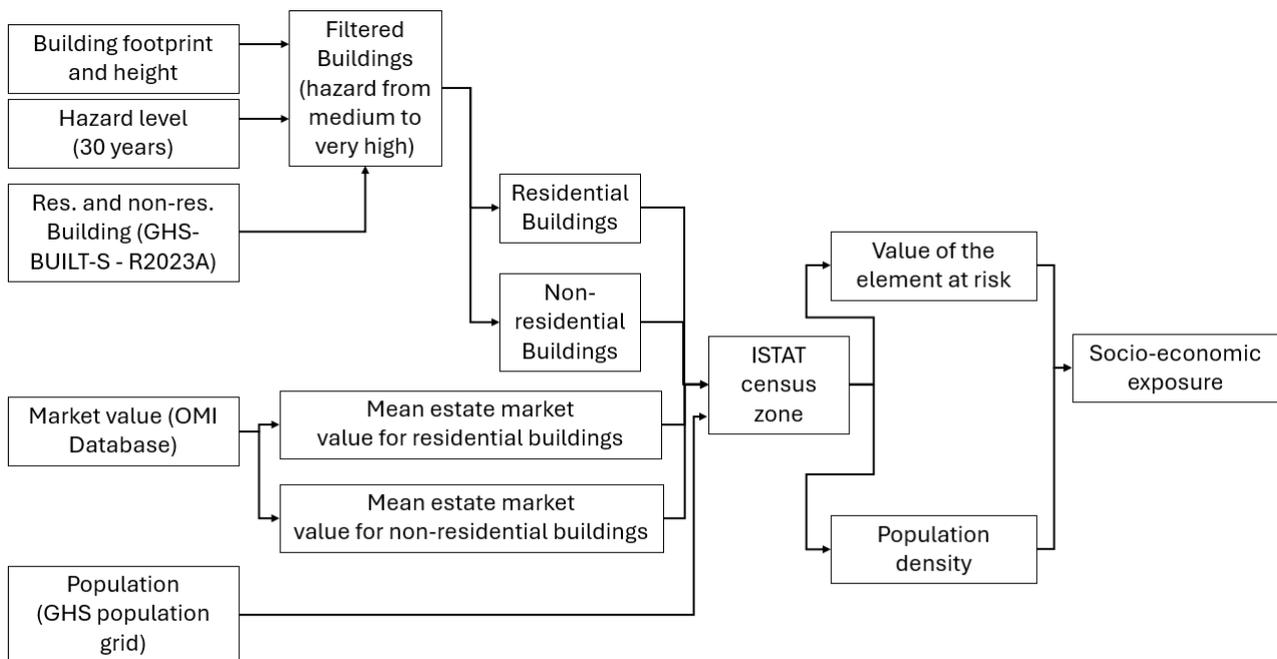


Figure 8 – Methodological workflow to assess land subsidence socio-economic exposure at the regional scale.

2.2.3. Potential direct impacts of the land subsidence in Bologna

A further refinement of the method was implemented at the local scale (such as the city of Bologna). In this case, based on the results from the regional scale, the socio-economic exposure class was downscaled for each building in the Emilia-Romagna database. A bivariate map was then carried out between these exposure classes and the hazard class of each building. The use of bivariate maps is well-documented in the scientific literature (De Cola, 2002; Nelson, 2000), with proven applications

across various fields, including climate science (Teuling et al., 2011) and hydrology (Speich et al., 2015).

In this study, we apply the conceptual framework of bivariate mapping to visually represent the relationship between the exposure classes and the hazard classes assigned to each building within the study area. By applying a 2×2 colour matrix, resulting in four classes in total. The reclassification method employed to stratify the continuous outputs into classes depends on the exposure classes (i.e., medium, high) and the hazard classes (i.e., medium, high). In particular, the bivariate maps are constructed using two separate single-hue colour gradients, where each gradient intensifies in both saturation and brightness to represent one of the two variables. When these gradients are combined, they form a unified bivariate colour scheme that visually encodes the relationship between both variables. Each colour represents a unique combination of exposure and hazard levels, allowing for rapid identification of areas where highly exposed buildings are located in zones of elevated hazard. Figure 9 shows the technical methodological workflow of the methodology to assess the socio-economic exposure at the local scale (i.e. the Bologna city).

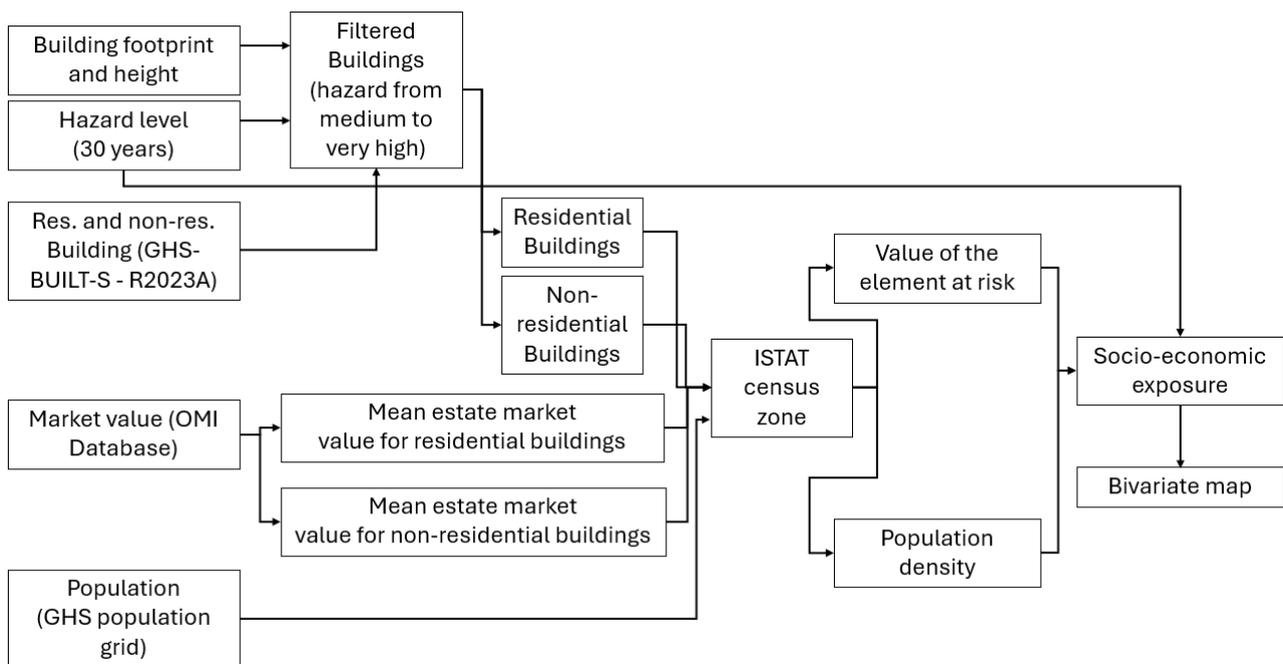


Figure 9 – Methodological workflow to assess land subsidence socio-economic exposure at the local scale.

2.2.4. Exposure of the UNESCO cultural heritage maps to differential displacements

In particular, to assess the potential impact of land subsidence on cultural heritage, a spatial analysis was conducted by performing a geographic overlay (spatial join) between the land subsidence hazard maps available for the 15 metropolitan cities and Emilia-Romagna region, and the mapped locations of UNESCO cultural heritage sites. By intersecting the two datasets, it was possible to attribute a hazard value to each cultural site based on its geographic position relative to the available land subsidence hazard zones mapped in the framework of the SubRISK+ project (Cigna et al. 2024, Boni et al., 2025).

2.2.5. Flooding-prone areas exposed to land subsidence

A descriptive statistical analysis was carried out to characterize EGMS-based vertical velocity within flood-prone areas across the 15 metropolitan cities. The method focused on extracting key statistical indicators, including the median, first quartile (Q1), third quartile (Q3), and mean values of vertical velocity derived from EGMS InSAR data. These statistics were used to generate boxplots for each metropolitan city, enabling the identification of areas with prevalent subsidence or uplift trends within zones already exposed to flood risk.

3. RESULTS

3.1. Potential impacts of the land subsidence in Italy

The value of the elements at risk for the 15 metropolitan cities indicates lowest class (0-5 M€) across more than 87% of the of the mapped areas (Figure 10a). The greatest proportion of the value from 5 to 100 M€ are found in Roma (0.2%), Bologna (0.3%) and Napoli (0.8%). In terms of absolute extent, Roma (~17 km²), Bologna (~13.7 km²), Napoli (~11.1 km²) provide the greatest extent, however, there is no extent of 5-100 M€ value in Reggio Calabria, Palermo, Messina, Catania, Sassari, and Cagliari. Moreover, the greatest market values (>100 M€) are generally limited to Roma, Napoli and Bologna with absolute extents of 5.84, 2.76, 0.4 km² respectively.

Lowest class of population density (0-10 inhabitants/km²) generally covers a larger proportion of the mapped areas, ranging from 20% in Napoli to 87% in Cagliari (Figure 10b). The second highest proportion corresponds to the class of 10-50 inhab./km², with a peak at Bologna (40%) while it is only 8% in Cagliari and Sassari. Moreover, a total of 3773 km² of 50-100 inhab./km² density range and 2187 km² of 100-250 inhab./km² are found overall across the 15 metropolitan cities. On the other hand, 4910 km² of mapped areas of metropolitan cities host the highest class (>250 inhab./km²) of population density. More significant extent are found in Roma (~1000 km²), Torino (~570 km²), Napoli (~569 km²) and Milano (~498 km²).

The socio-economic exposure obtained through integration of the market value of the elements at risk and population density, depicts a low level of exposure covering 36-93% of mapped areas with peaks at Palermo (~93.5%), Messina (~92.6%), and Reggio Calabria (~92.4%) (Figure 10). Medium exposure areas extend (~3-62%), with peaks at Napoli (~61.8%) and Milano (~39.8%). Besides, a total of 19.53 km² high exposure areas are found overall across the 15 metropolitan cities which is mostly limited to Napoli, Roma and Bologna (Figure 11).

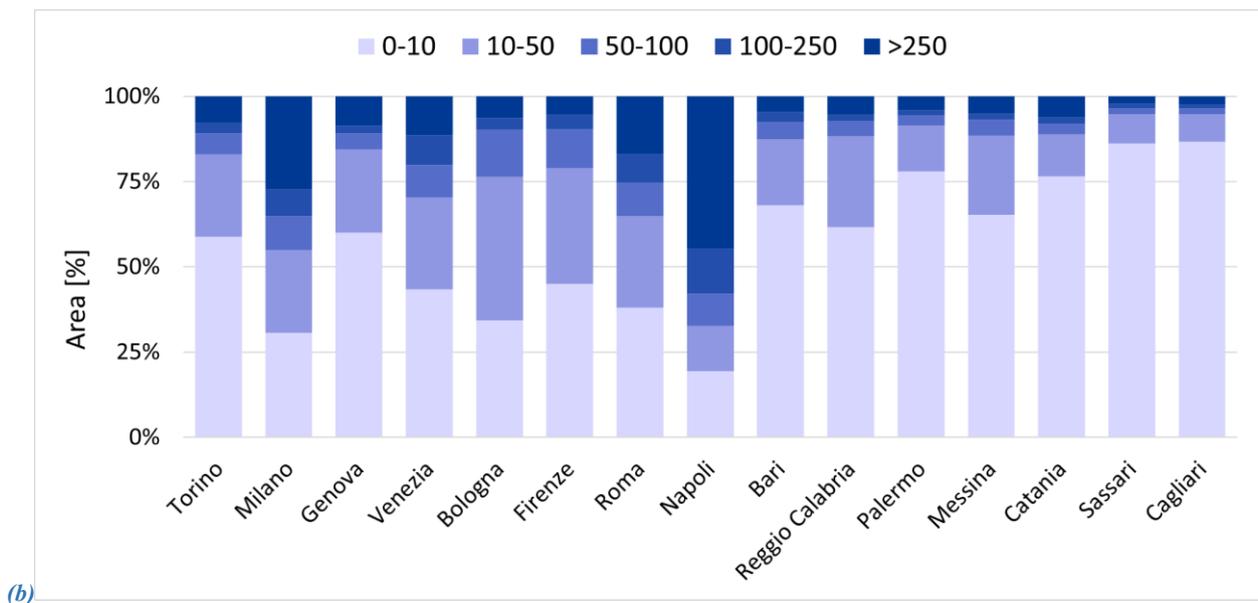
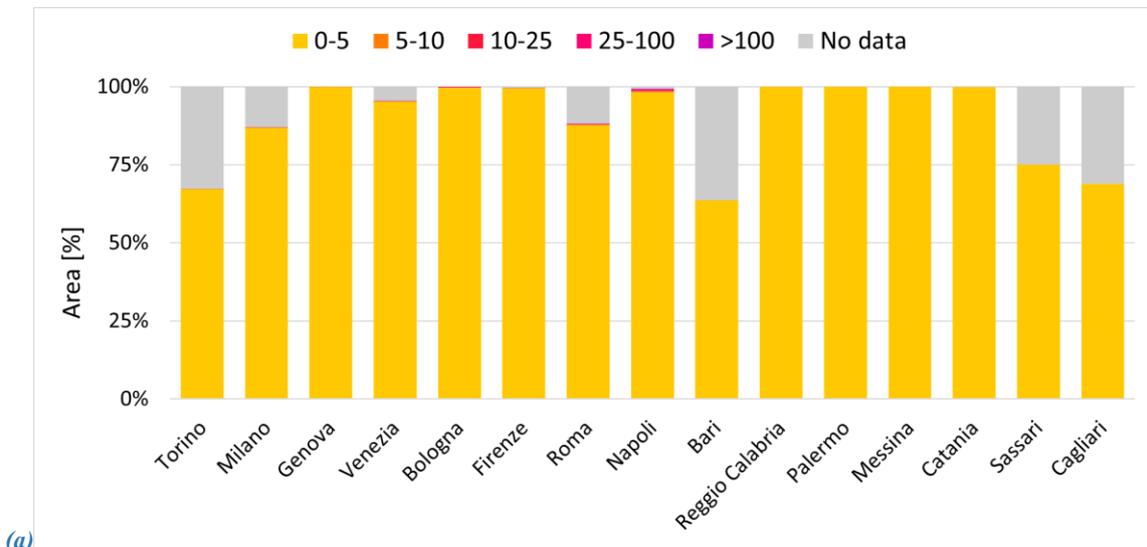


Figure 10– (a) Extent of the Value of the elements at risk (M€) within the 15 metropolitan cities of Italy, displayed using a percentage scale (100% refers to the total extent of the exposure data within each city), (b) Extent of the population density (inhabitants/km²) classes within the 15 metropolitan cities of Italy, displayed using a percentage scale (100% refers to the total extent of the exposure data within each city).

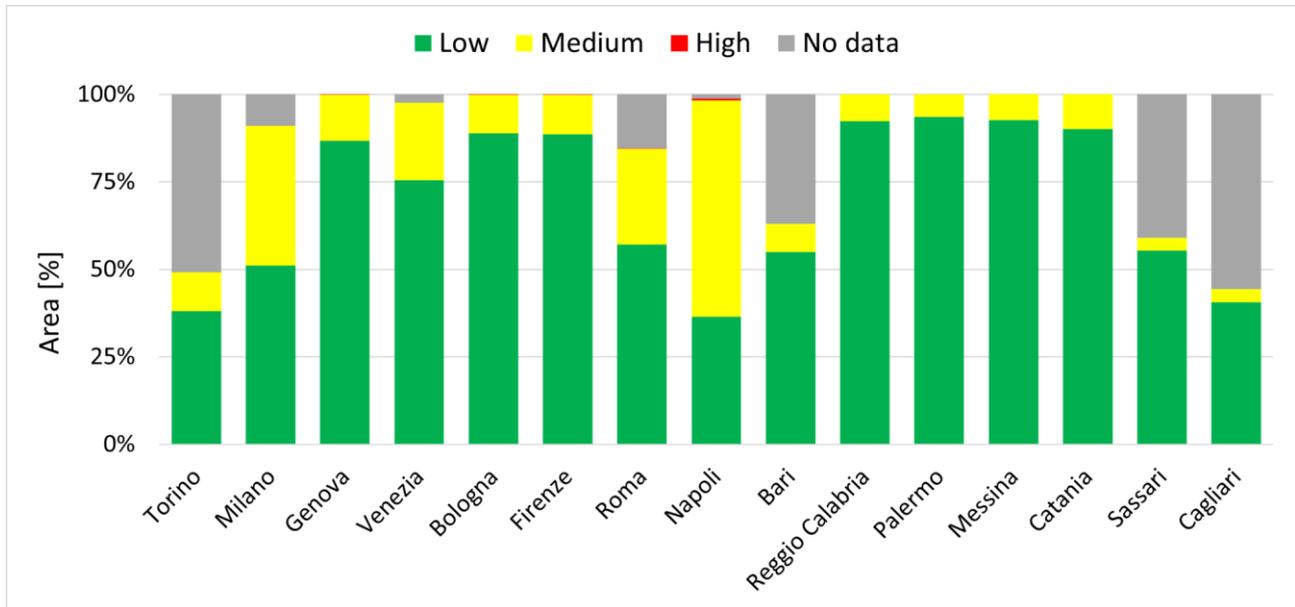
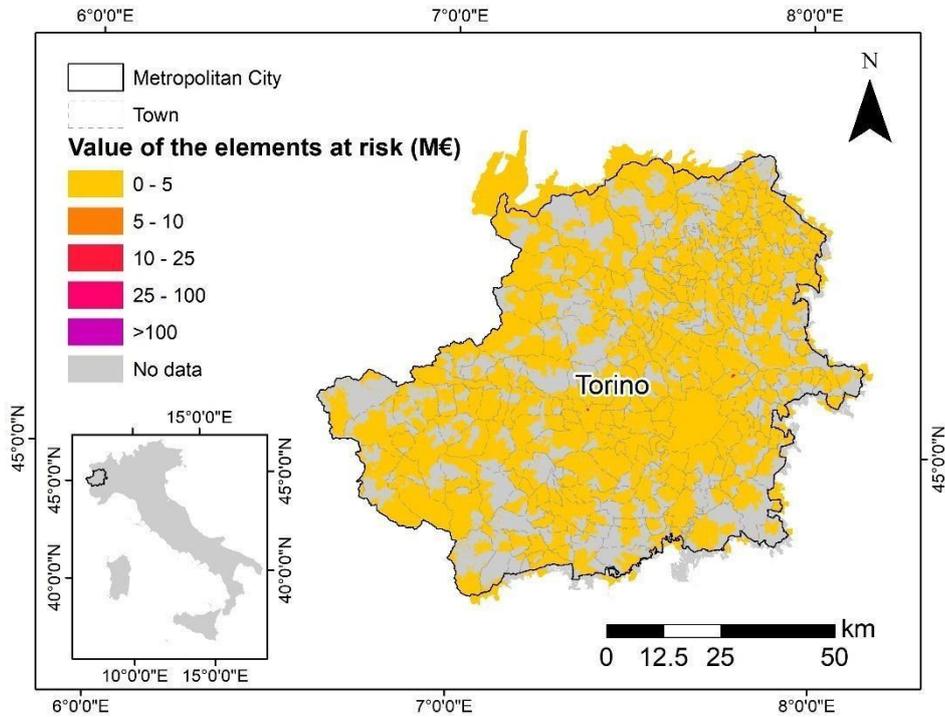


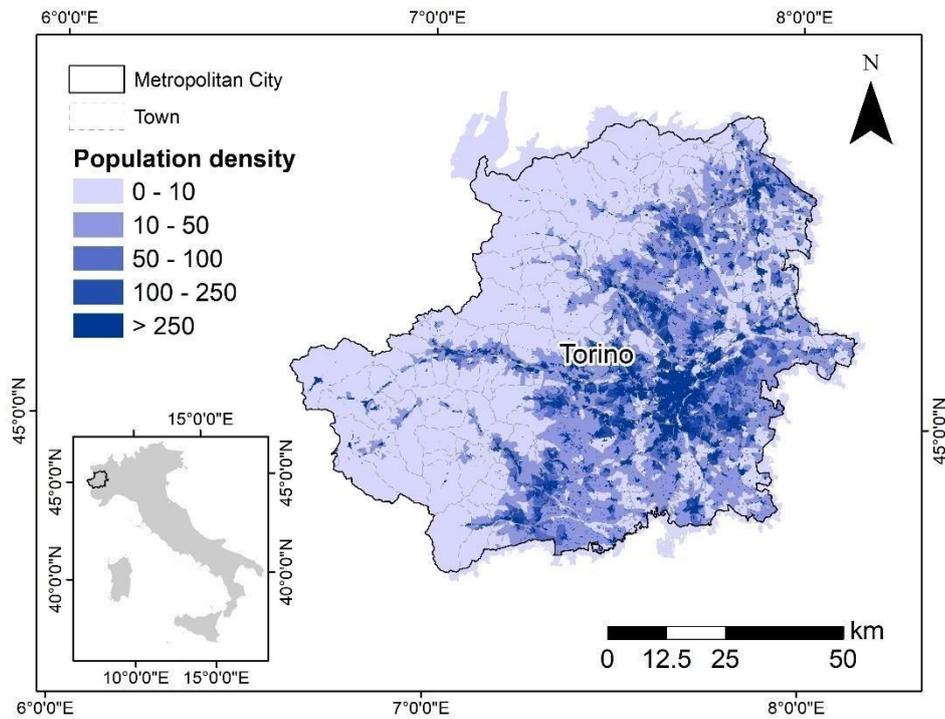
Figure 11 – Extent of the Socio-economic exposure classes to land subsidence within the 15 metropolitan cities of Italy, displayed using a percentage scale (100% refers to the total extent of the exposure data within each city).

The following sub-sections provide the full set of maps of the value of the elements at risk, the population density and the resulting socio-economic exposure maps generated for each of the 15 metropolitan cities of Italy.

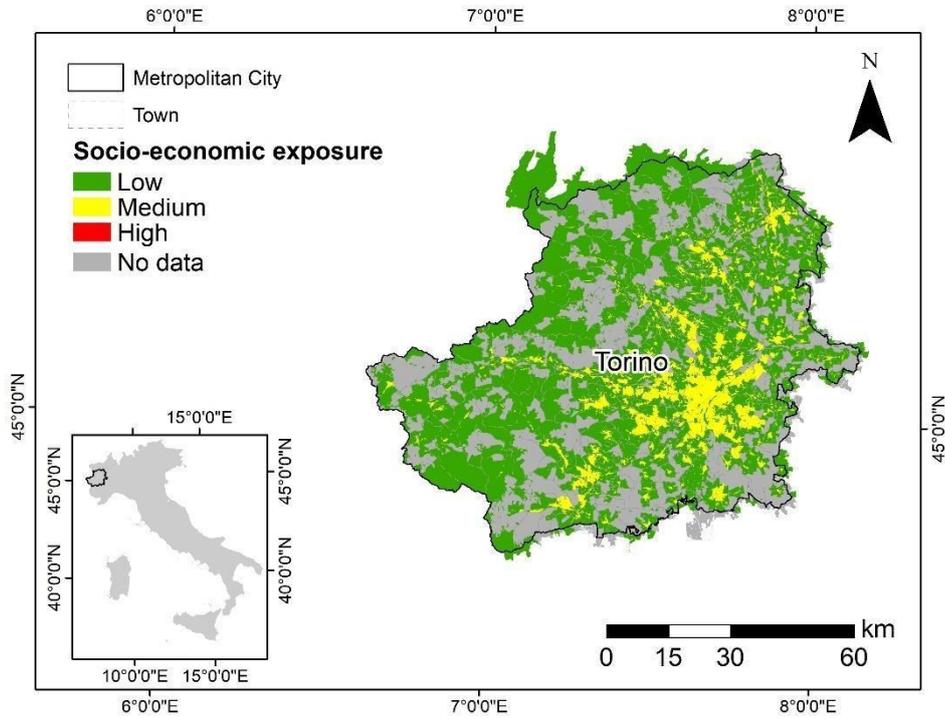
31.1. Torino



(a)



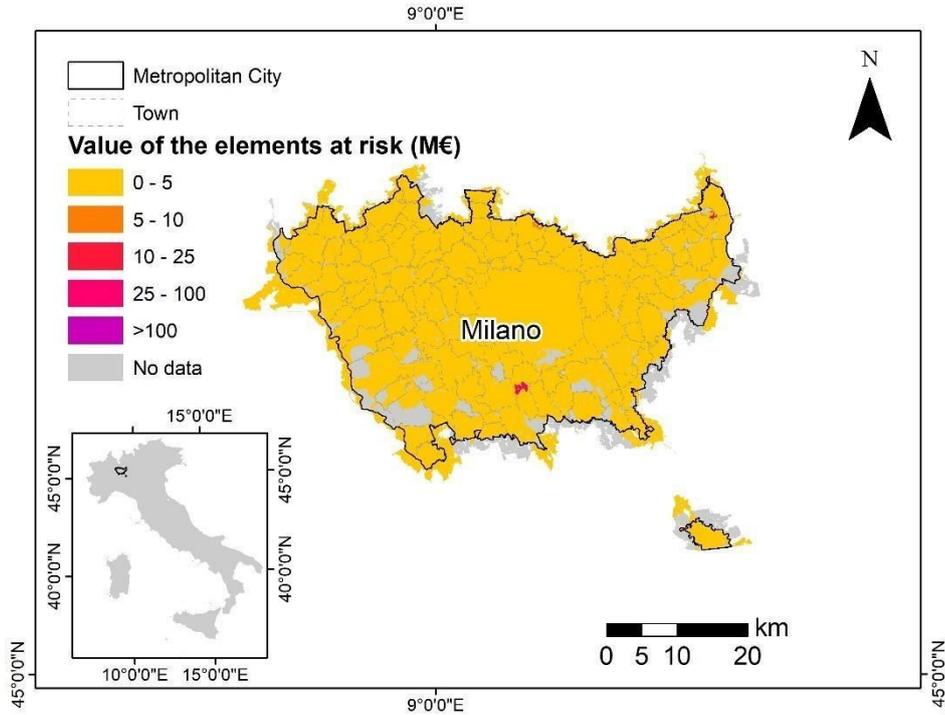
(b)



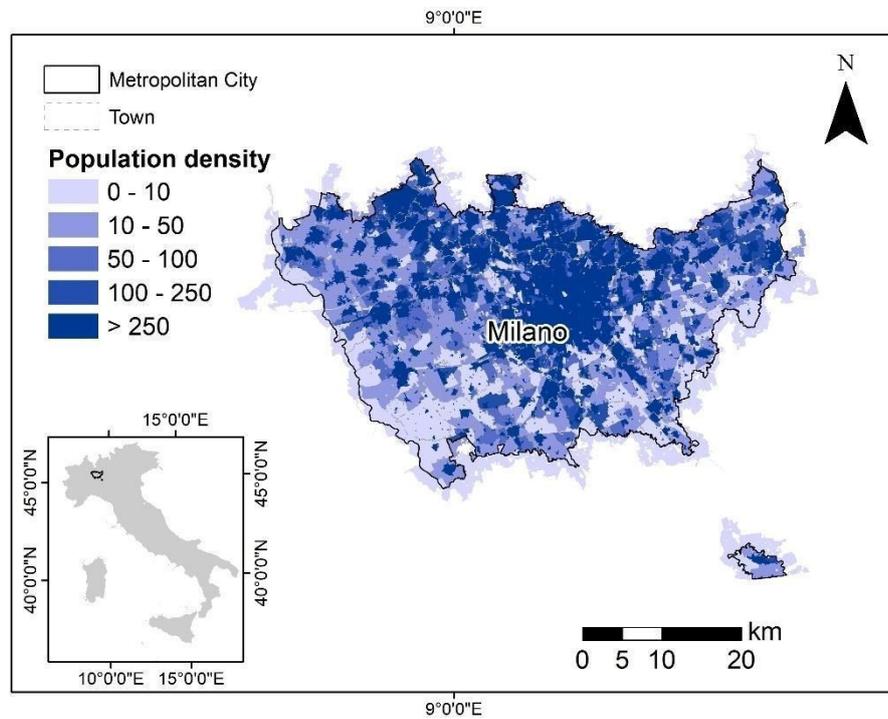
(c)

Figure 12– Socio-economic exposure to land subsidence in the metropolitan city of Torino: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

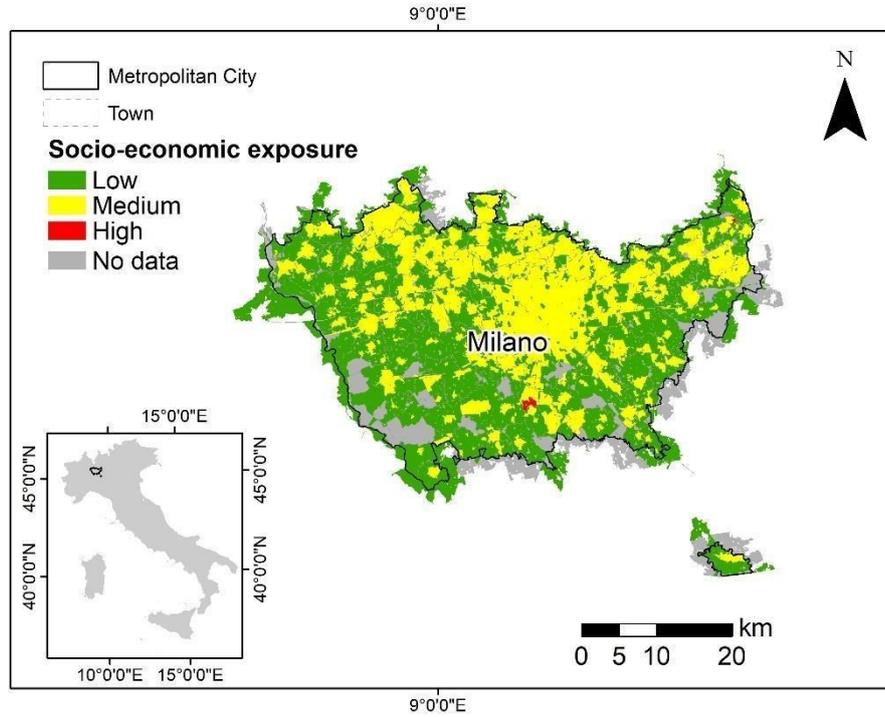
31.2. Milano



(a)



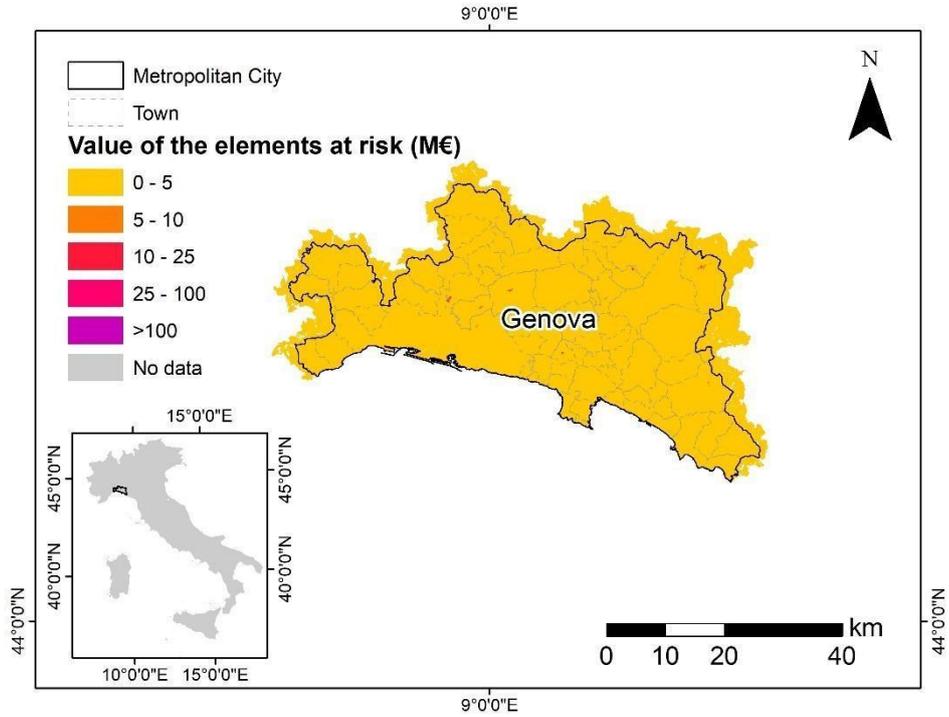
(b)



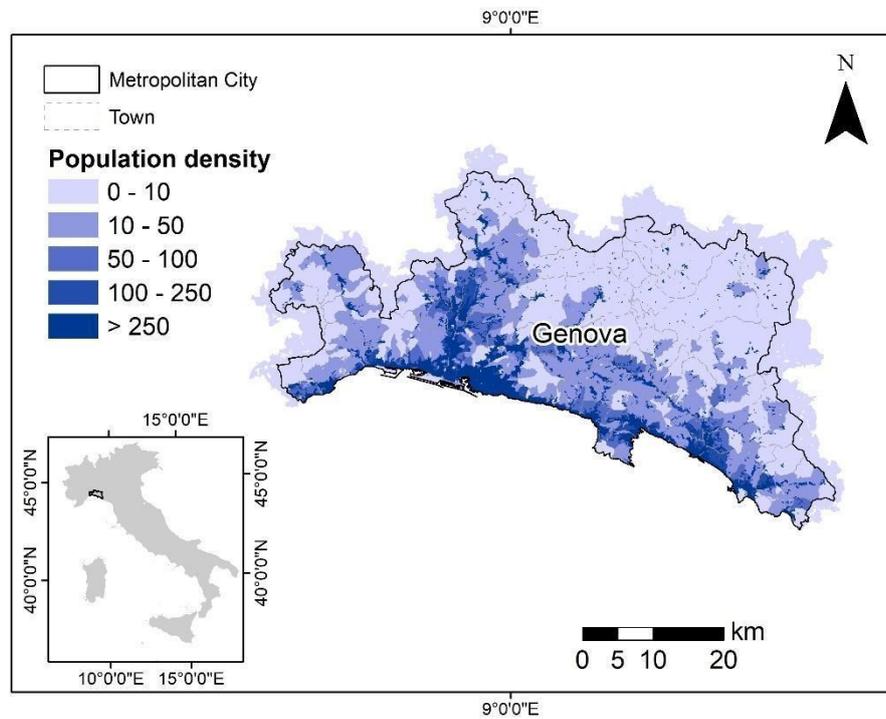
(c)

Figure 13– Socio-economic exposure to land subsidence in the metropolitan city of Milano: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

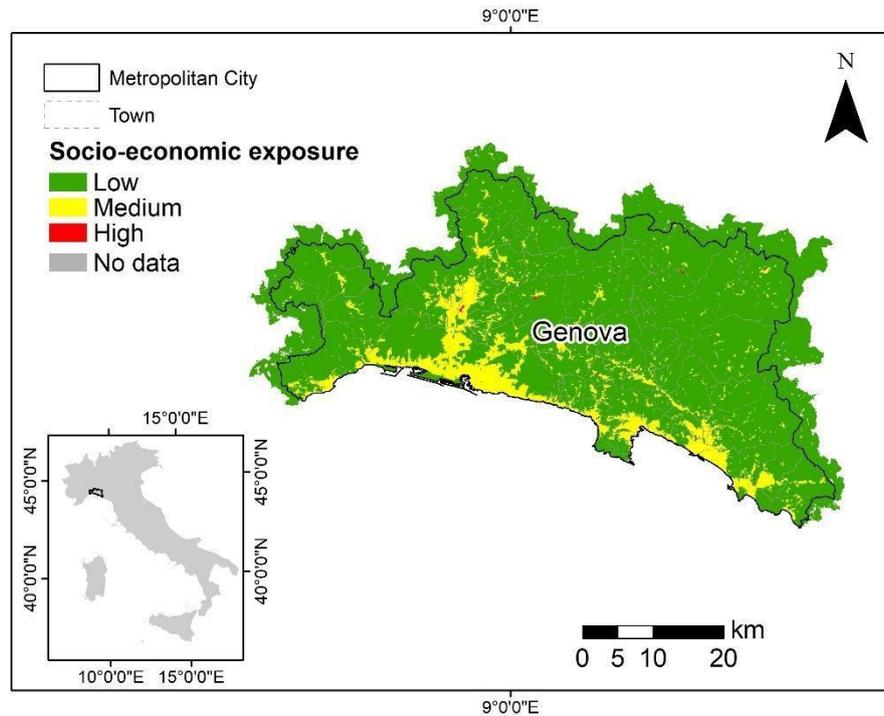
31.3. Genova



(a)



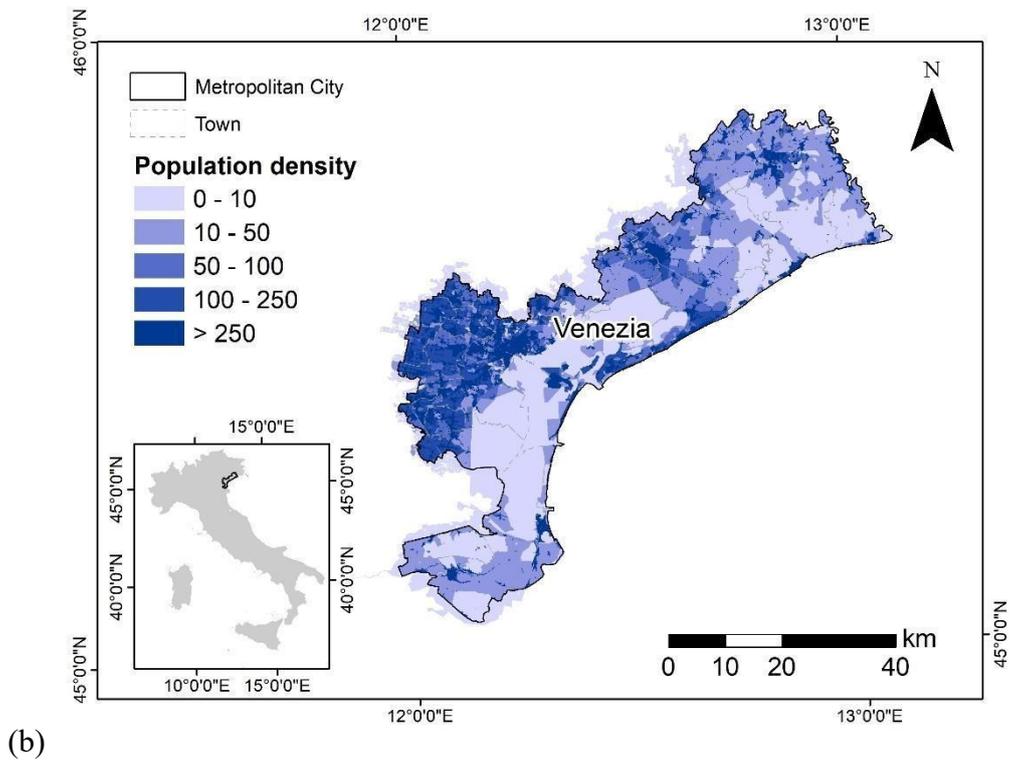
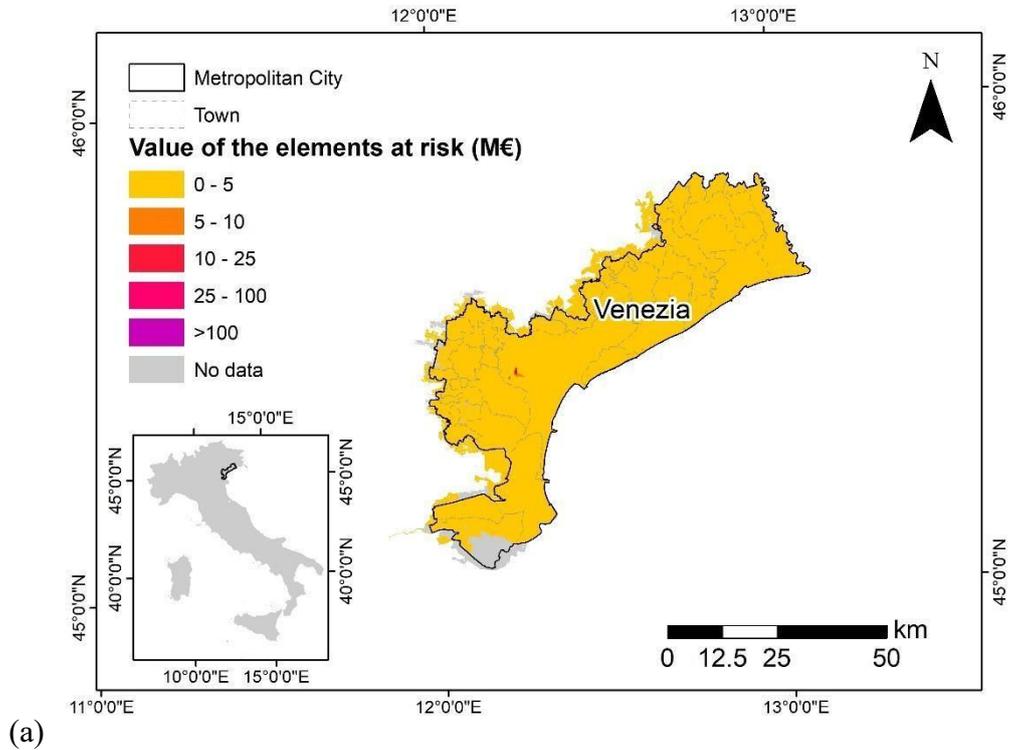
(b)

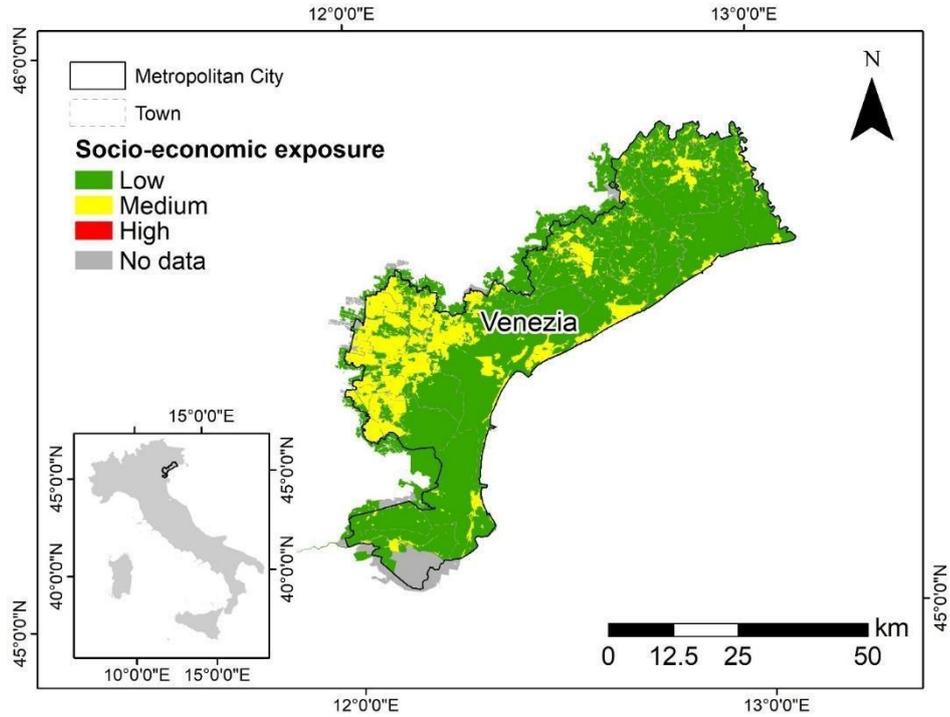


(c)

Figure 14– Socio-economic exposure to land subsidence in the metropolitan city of Genova: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

31.4. Venezia

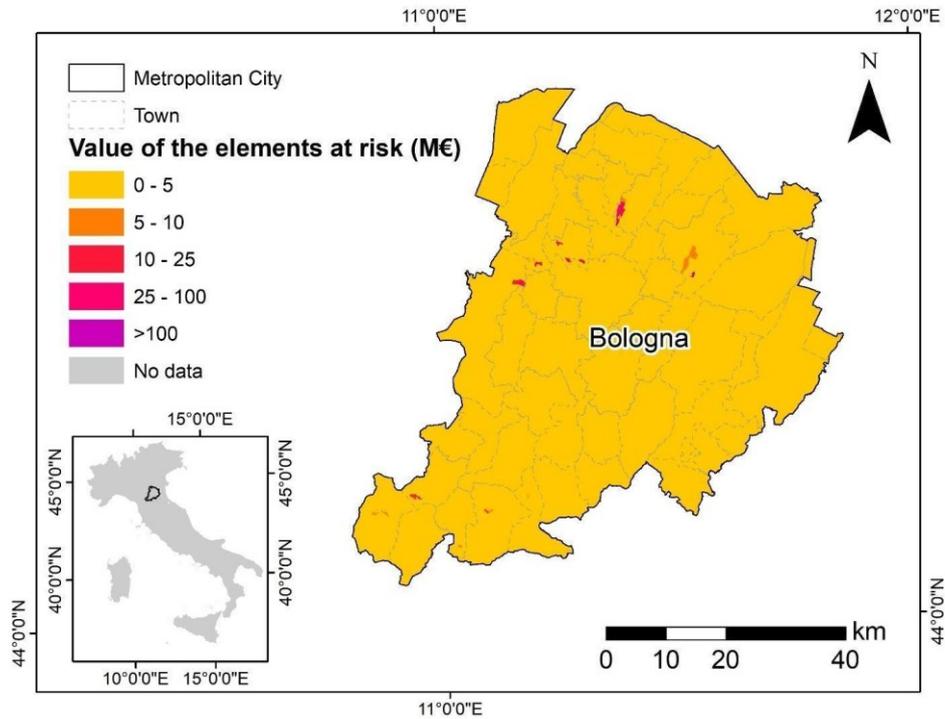




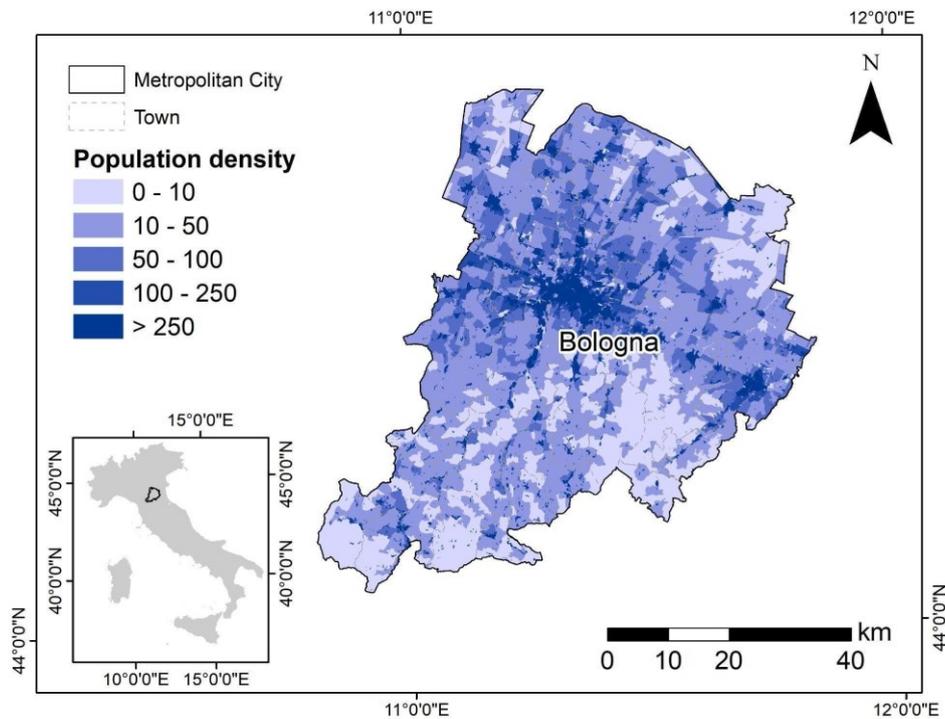
(c)

Figure 15– Socio-economic exposure to land subsidence in the metropolitan city of Venezia: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

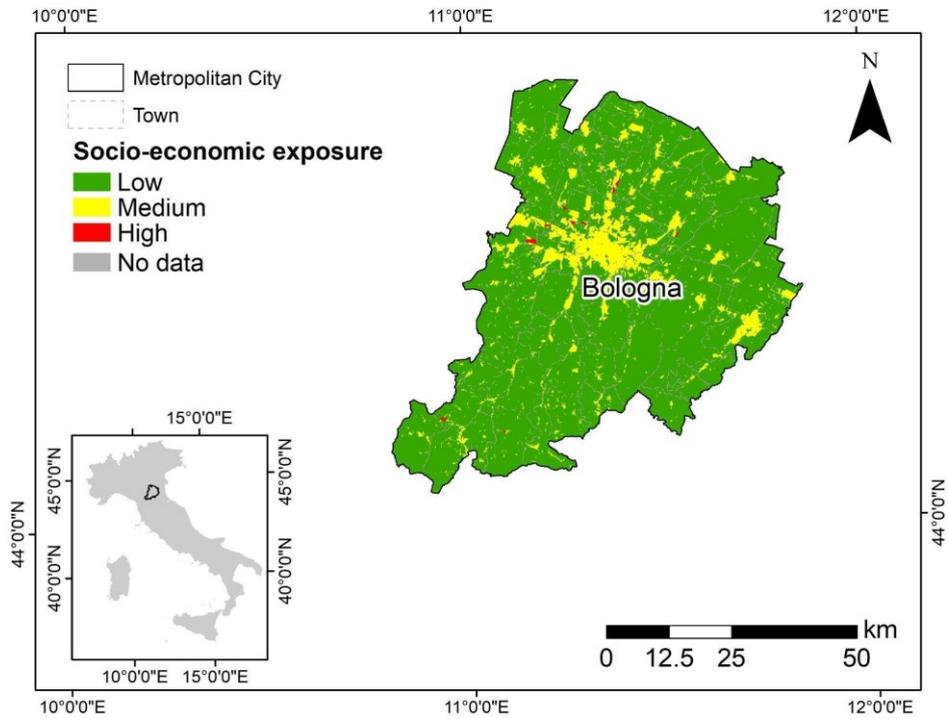
31.5. Bologna



(a)



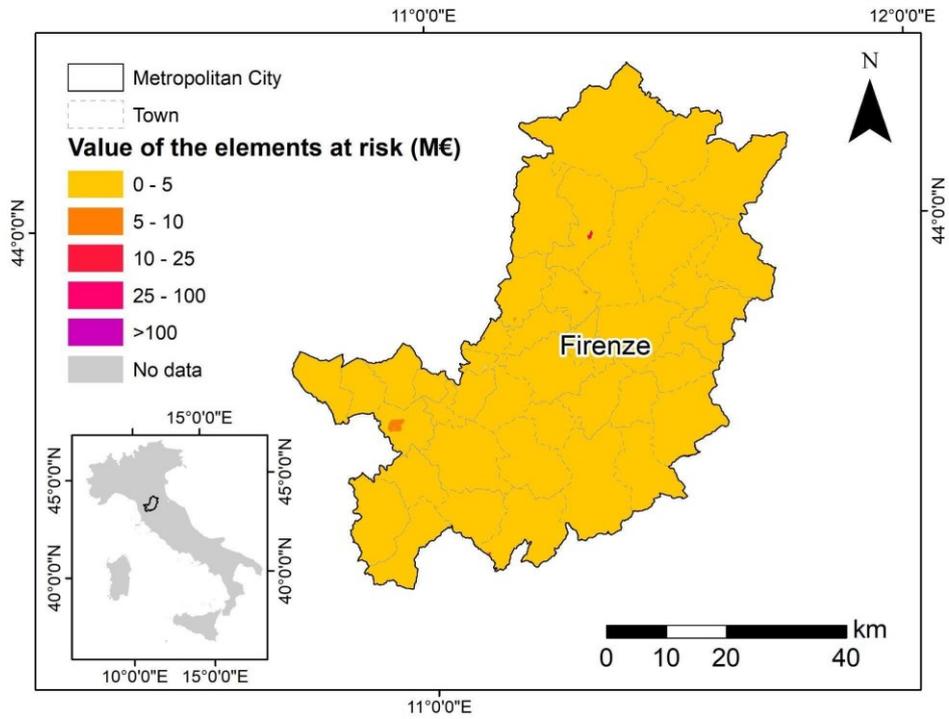
(b)



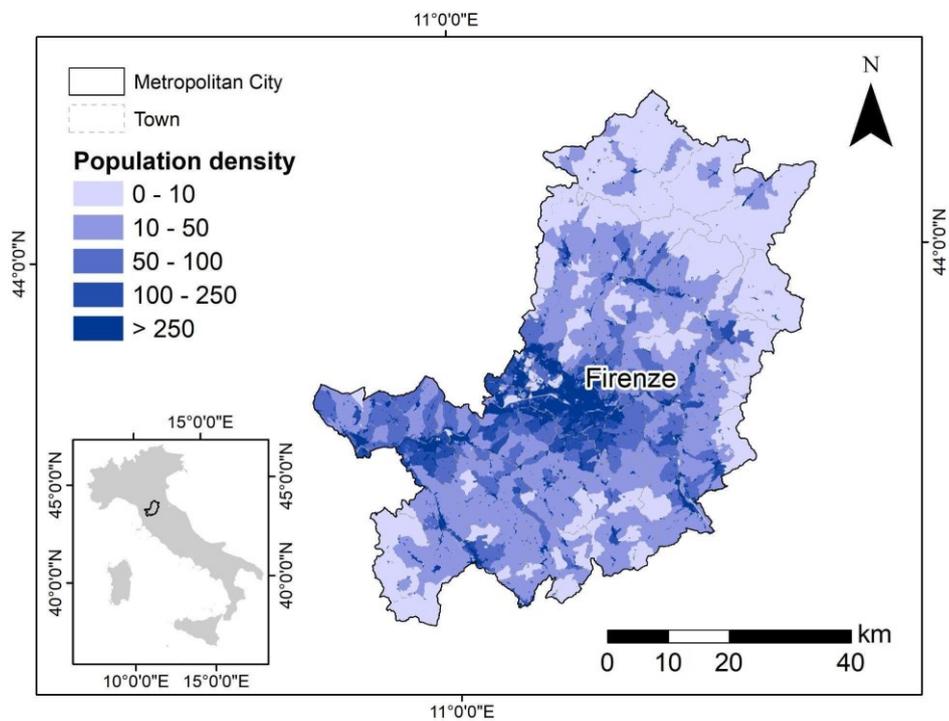
(c)

Figure 16– Socio-economic exposure to land subsidence in the metropolitan city of Bologna: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

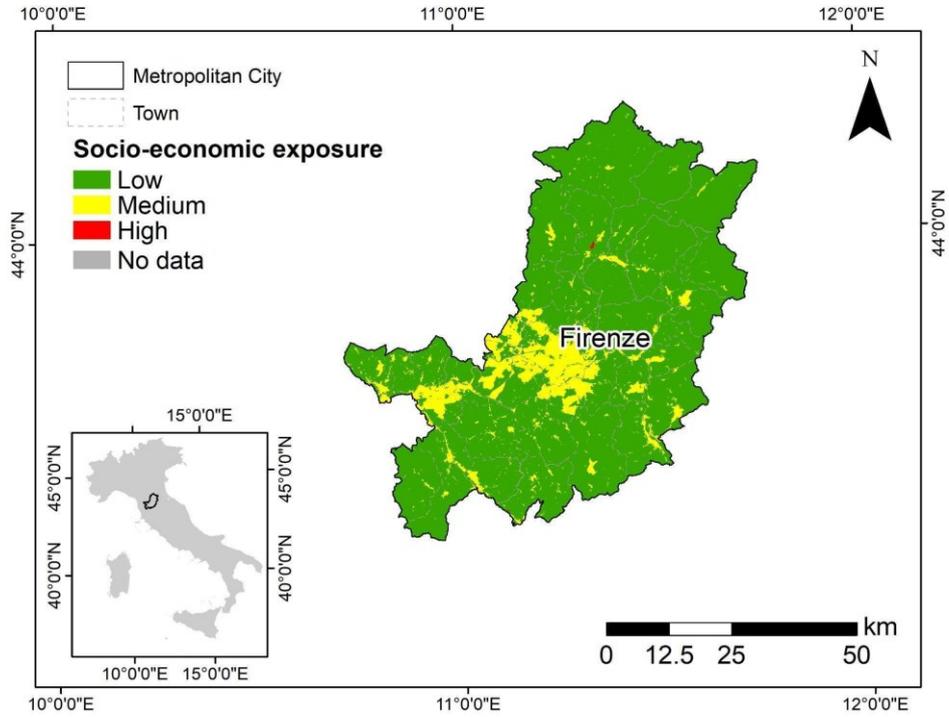
31.6. Firenze



(a)



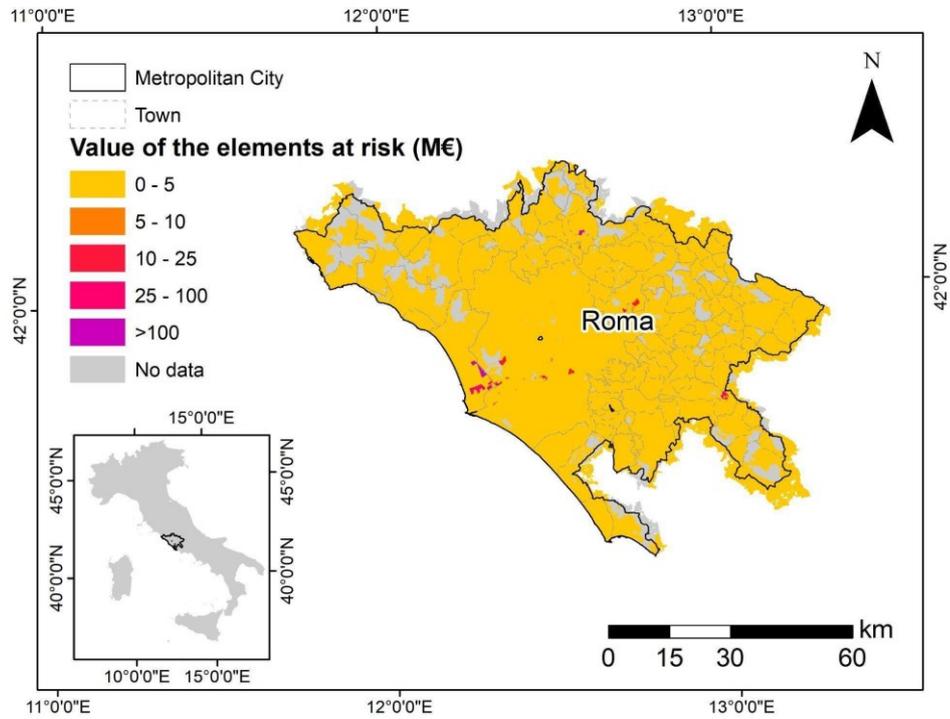
(b)



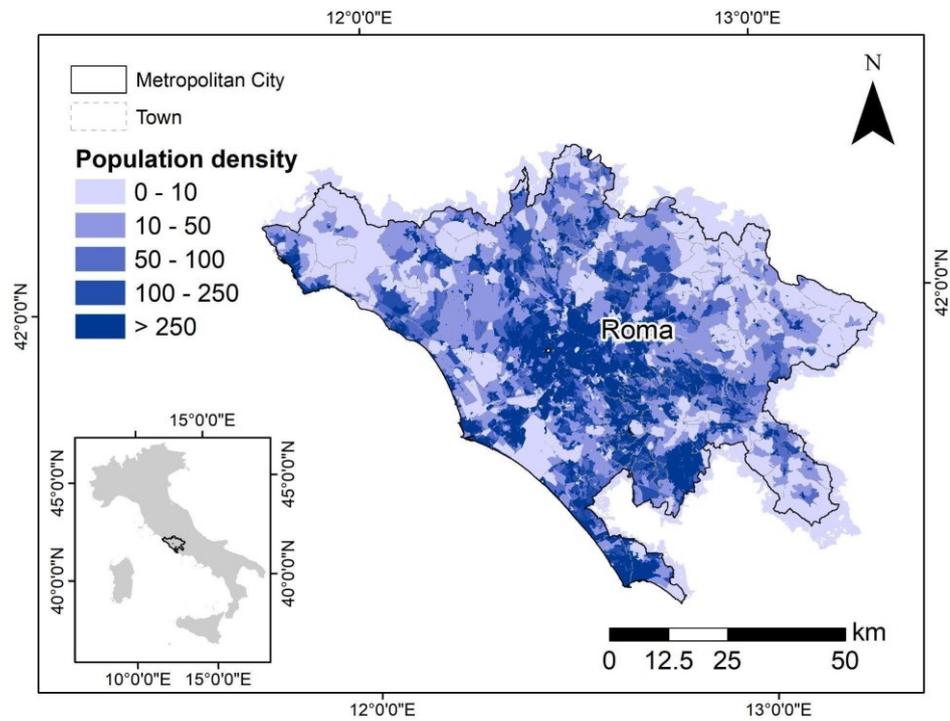
(c)

Figure 17– Socio-economic exposure to land subsidence in the metropolitan city of Firenze: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

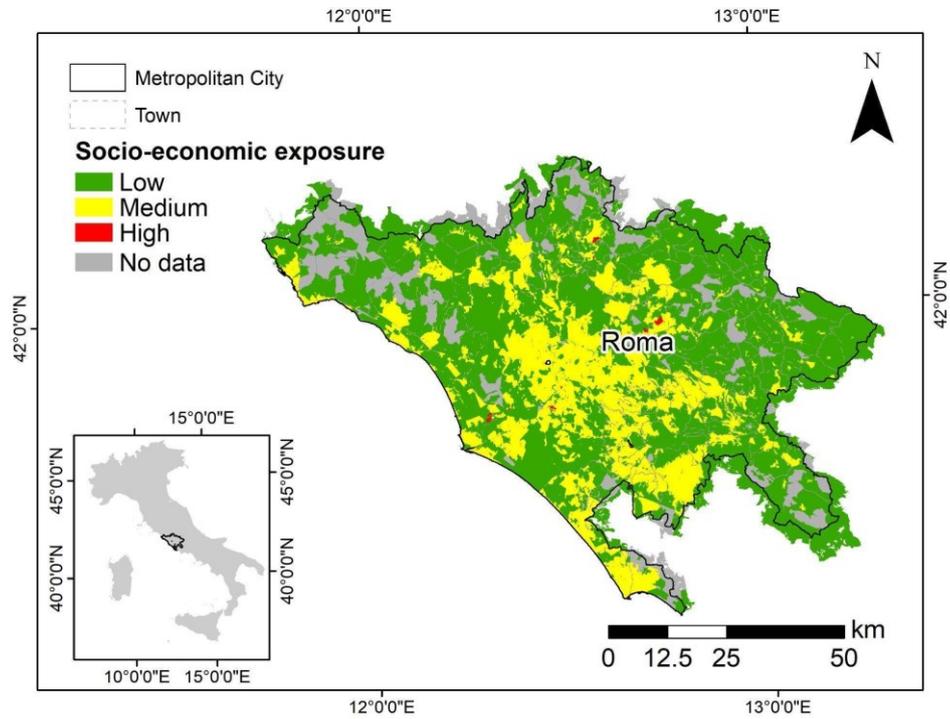
31.7. Roma



(a)



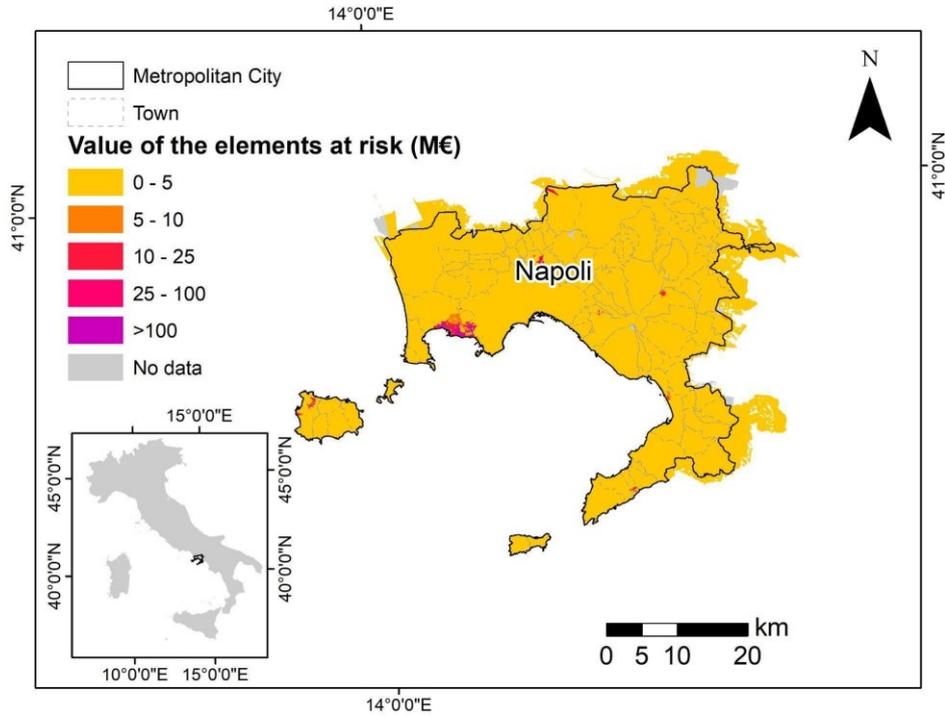
(b)



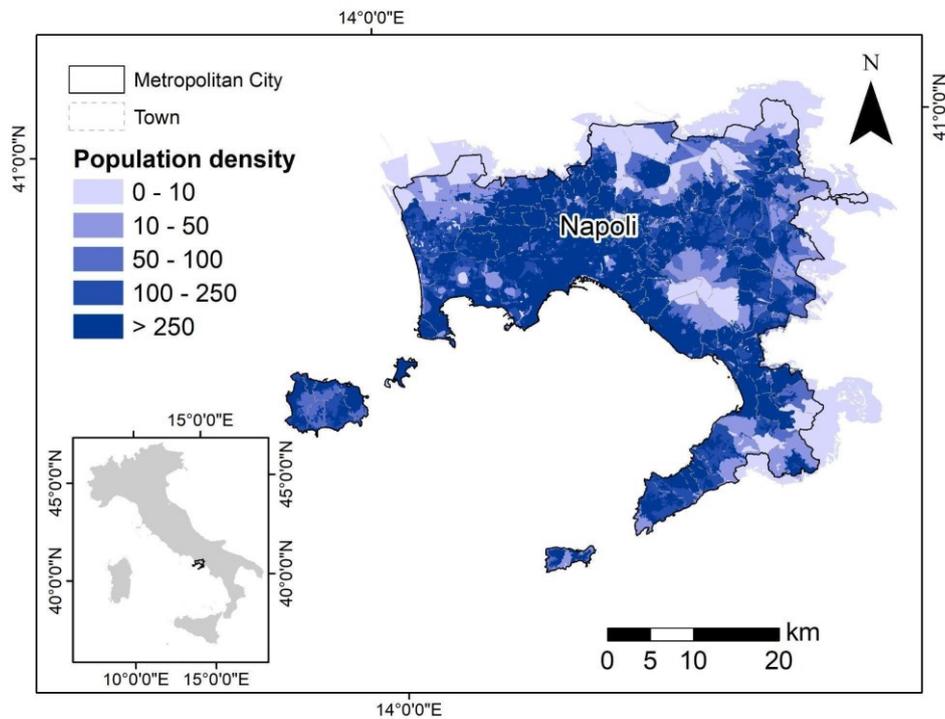
(c)

Figure 18– Socio-economic exposure to land subsidence in the metropolitan city of Roma: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

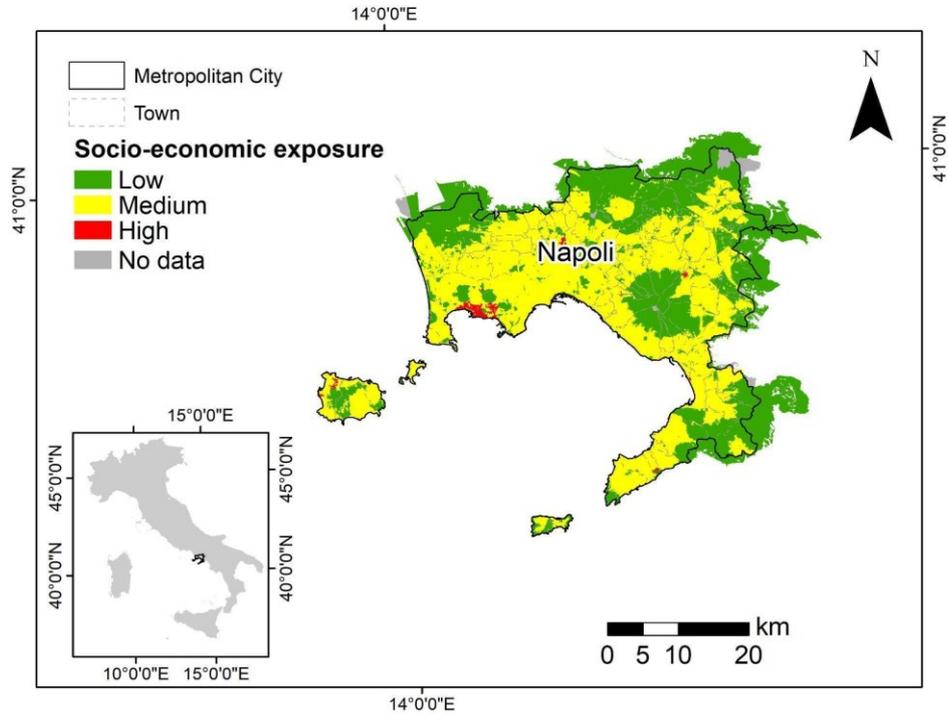
31.8. Napoli



(a)



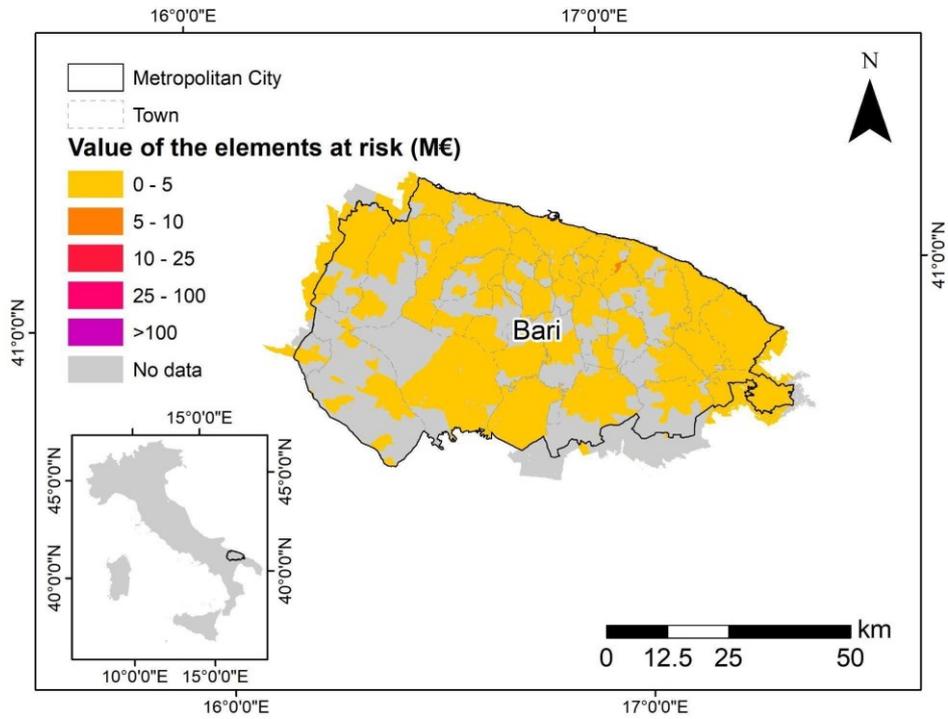
(b)



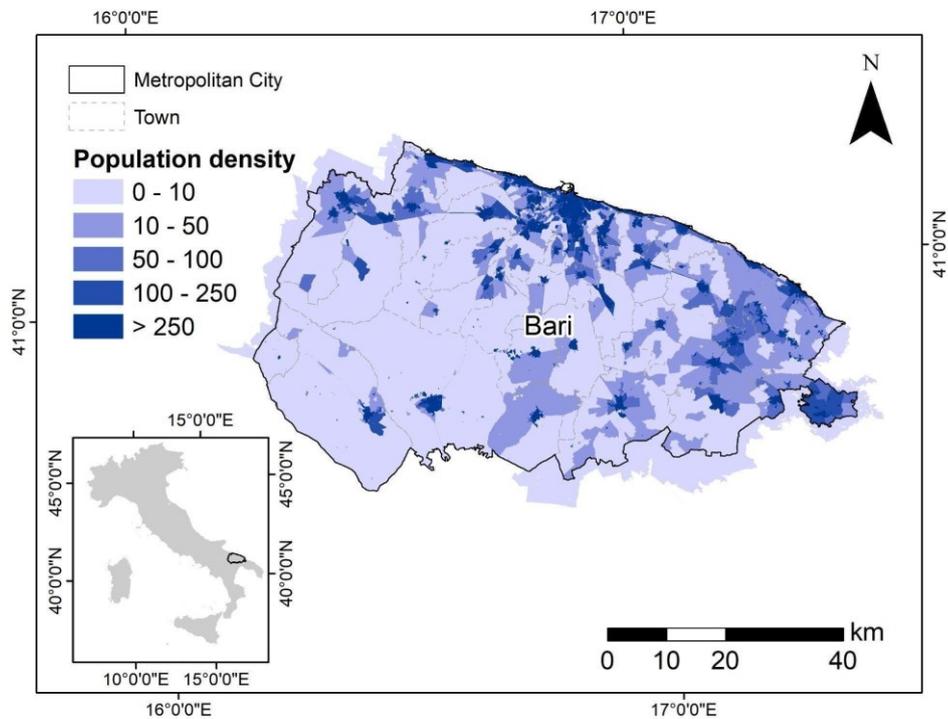
(c)

Figure 19– Socio-economic exposure to land subsidence in the metropolitan city of Napoli: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

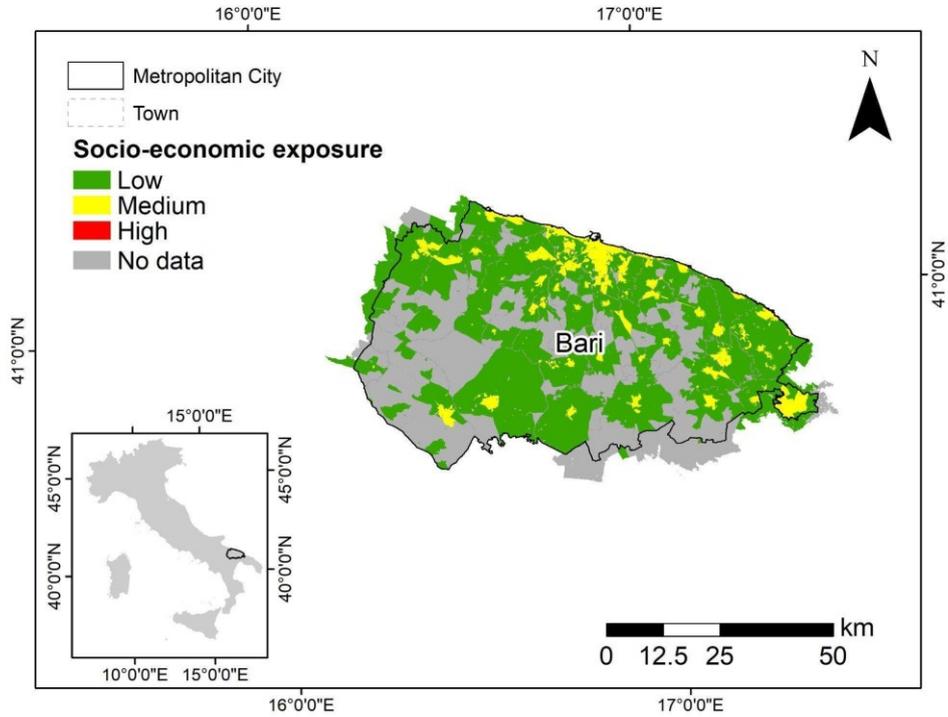
31.9. Bari



(a)



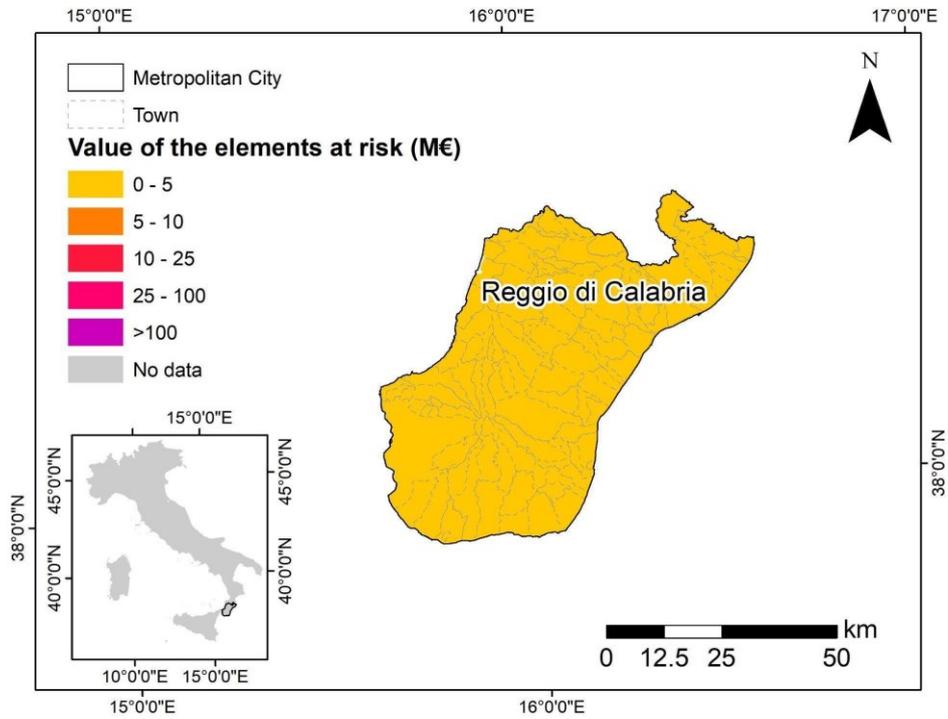
(b)



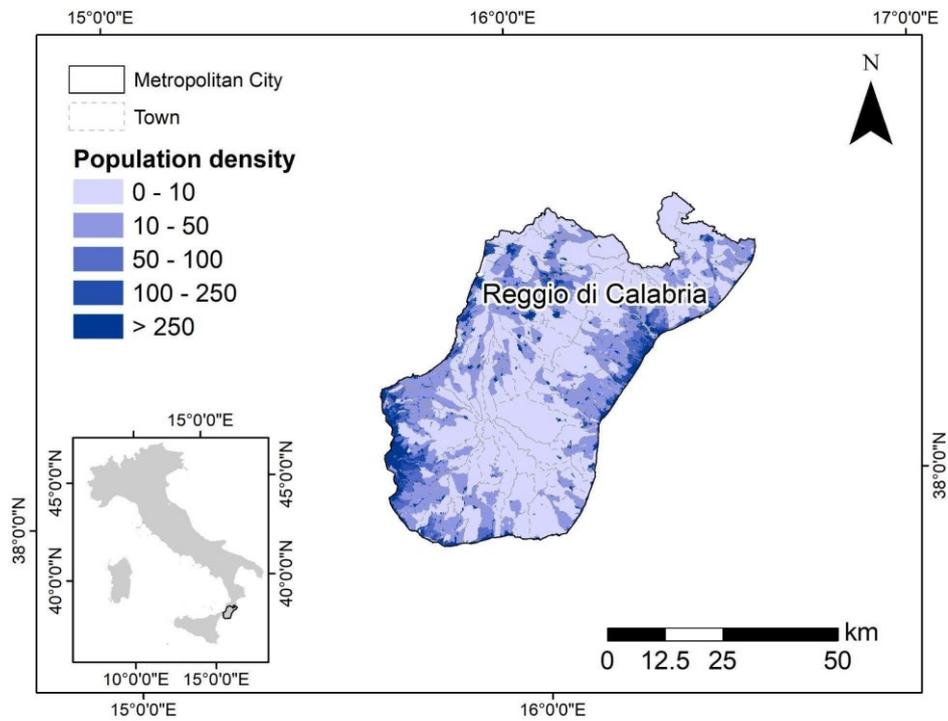
(c)

Figure 20 – Socio-economic exposure to land subsidence in the metropolitan city of Bari: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

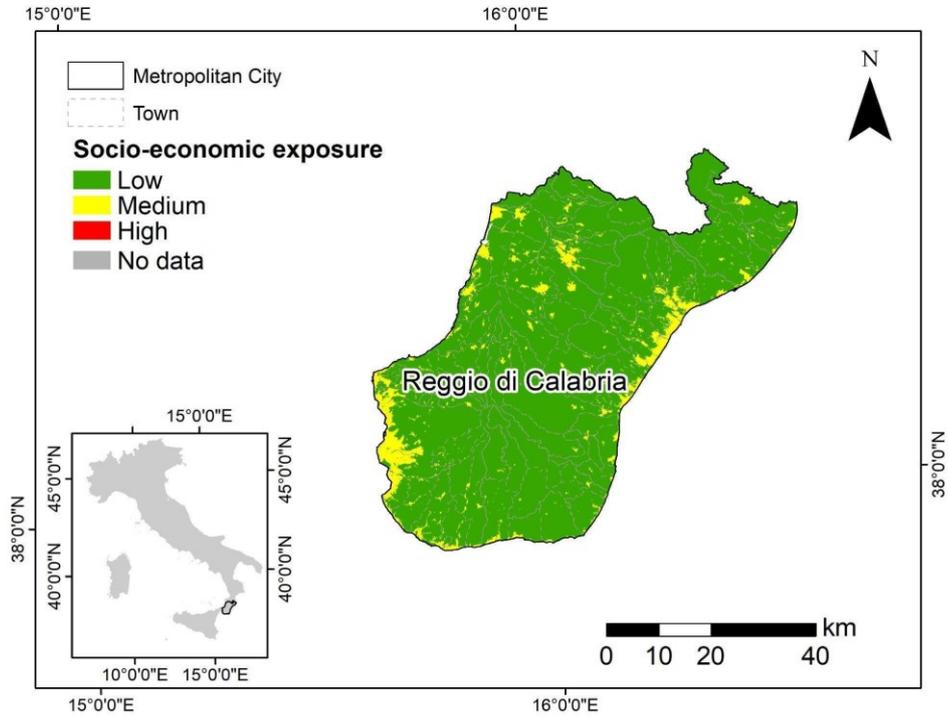
31.10. Reggio di Calabria



(a)



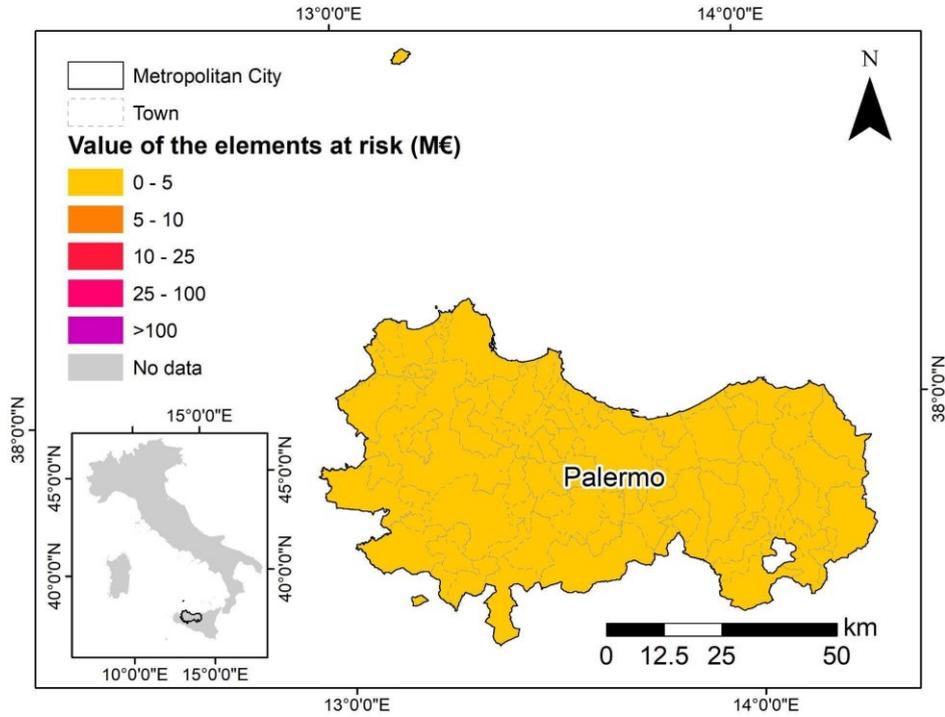
(b)



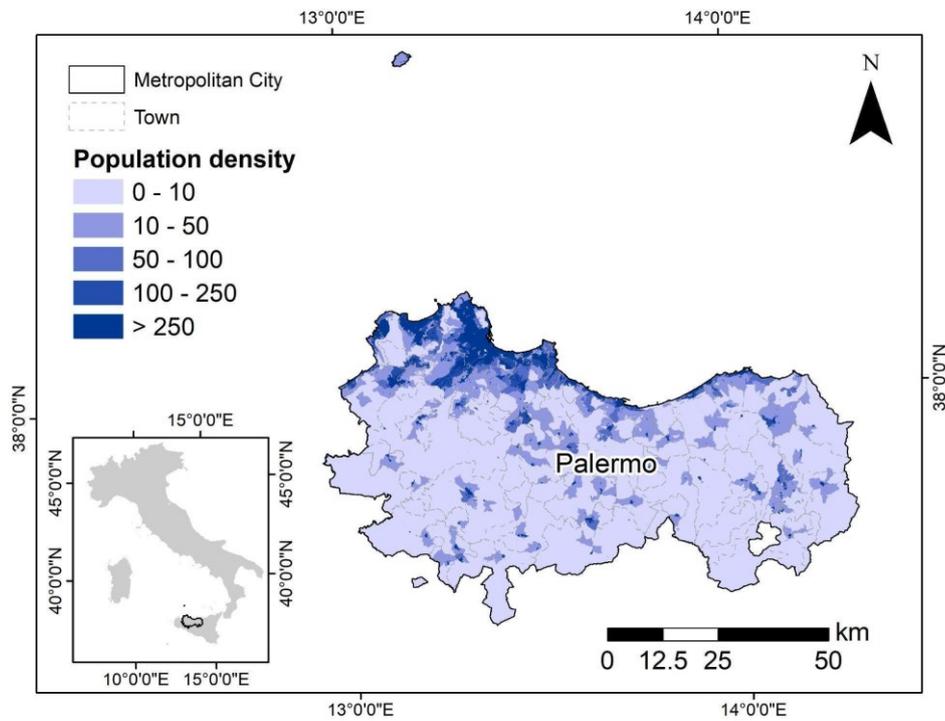
(c)

Figure 21 – Socio-economic exposure to land subsidence in the metropolitan city of Reggio Calabria: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

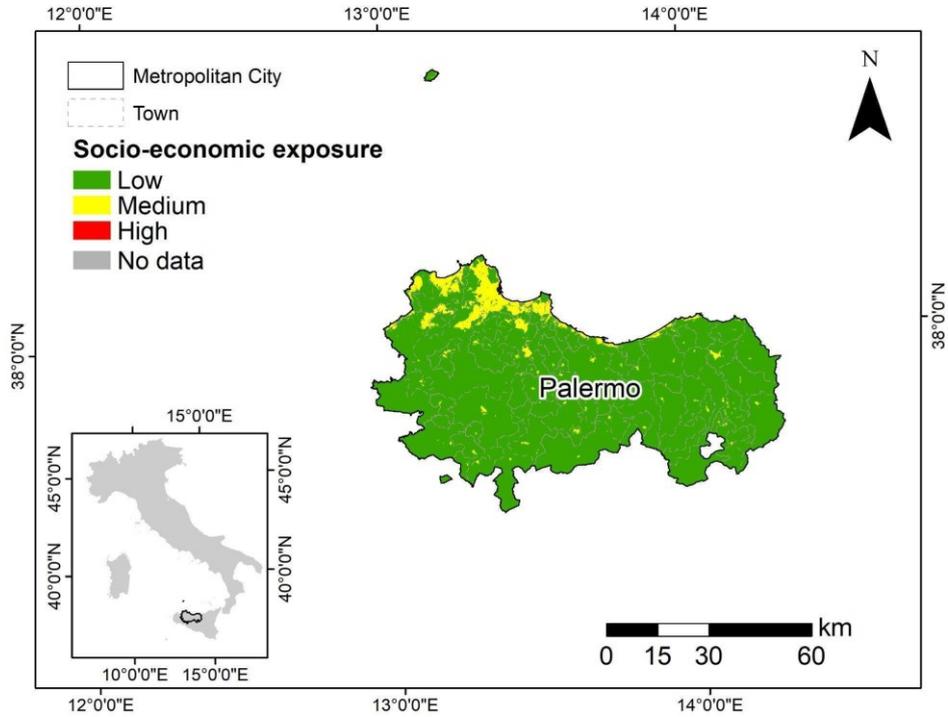
31.11. Palermo



(a)



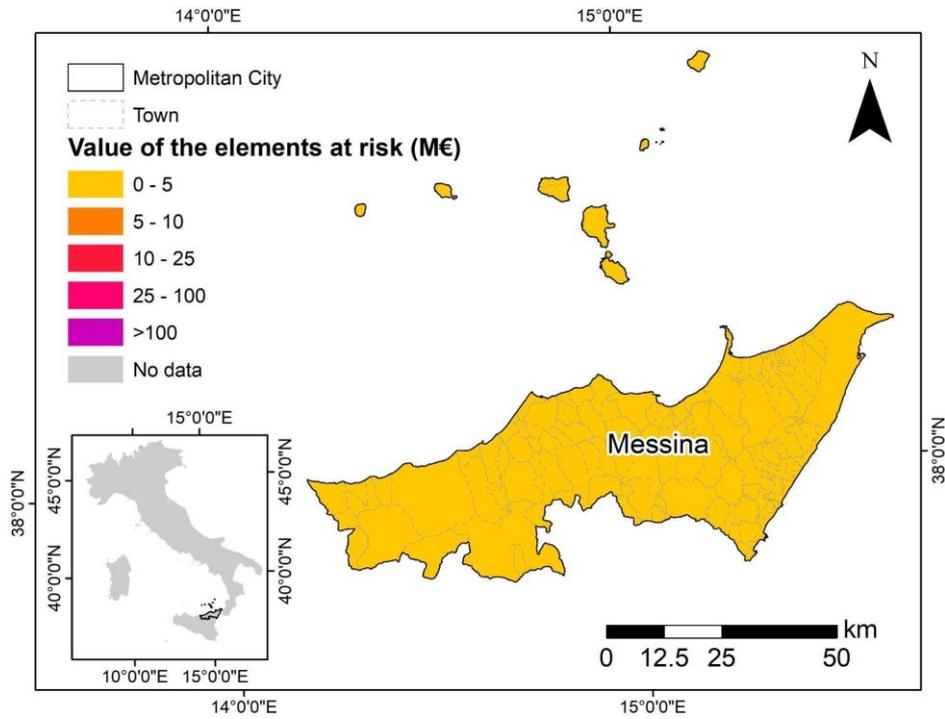
(b)



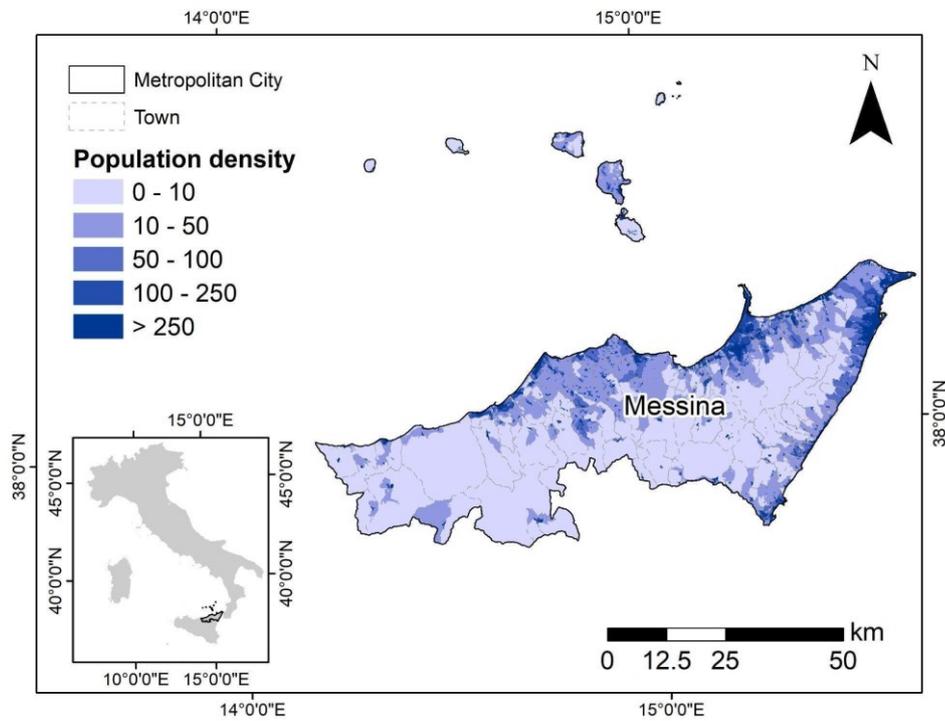
(c)

Figure 22 – Socio-economic exposure to land subsidence in the metropolitan city of Palermo: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

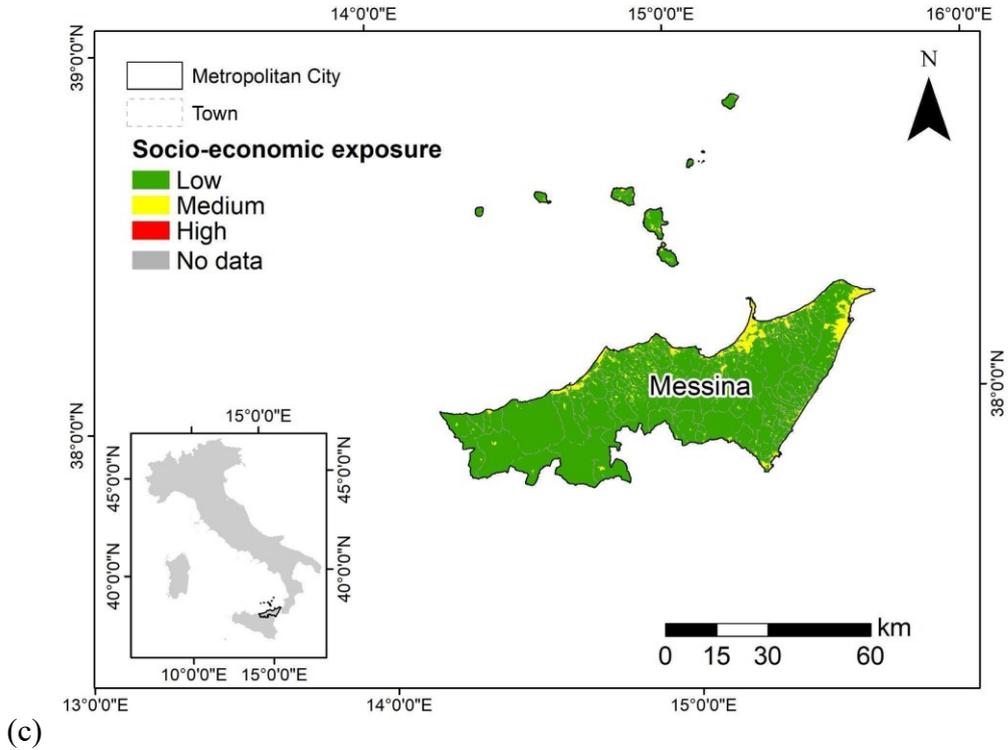
31.12. Messina



(a)

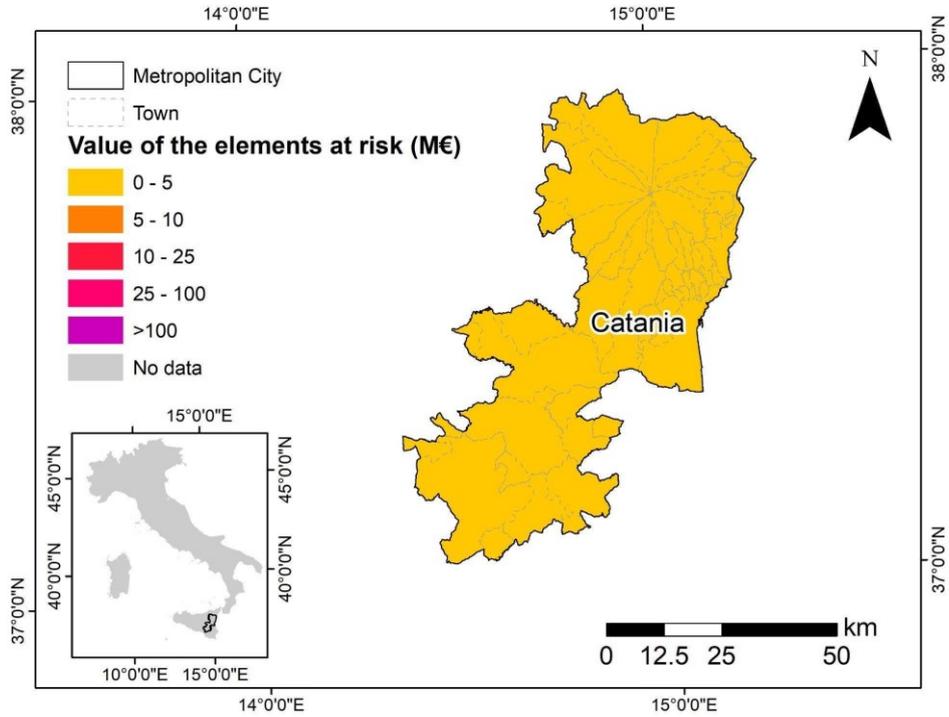


(b)

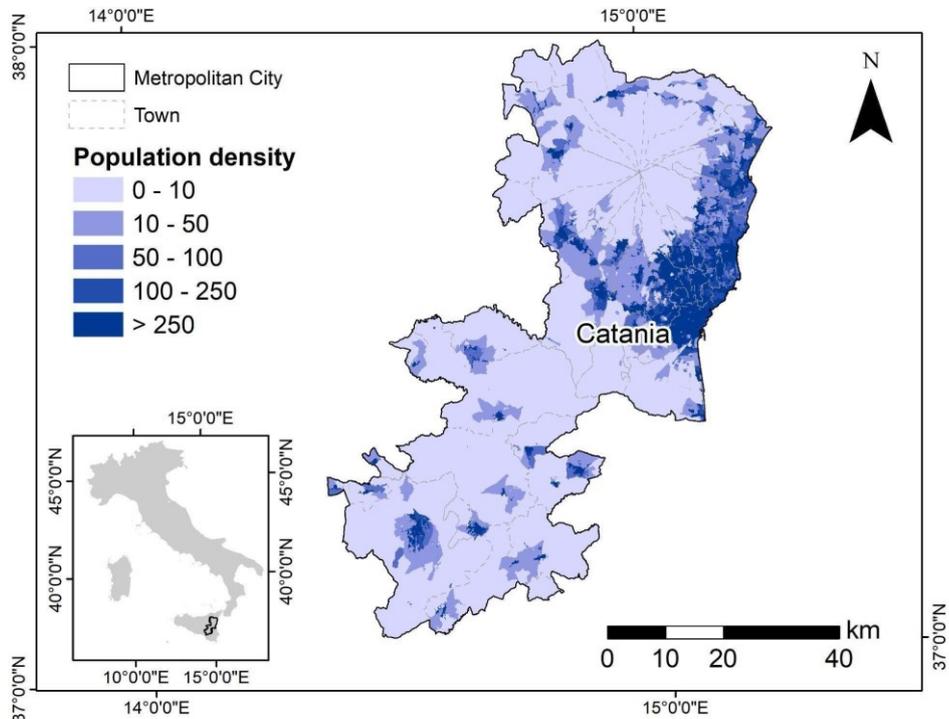


(c) *Figure 23 – Socio-economic exposure to land subsidence in the metropolitan city of Messina: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.*

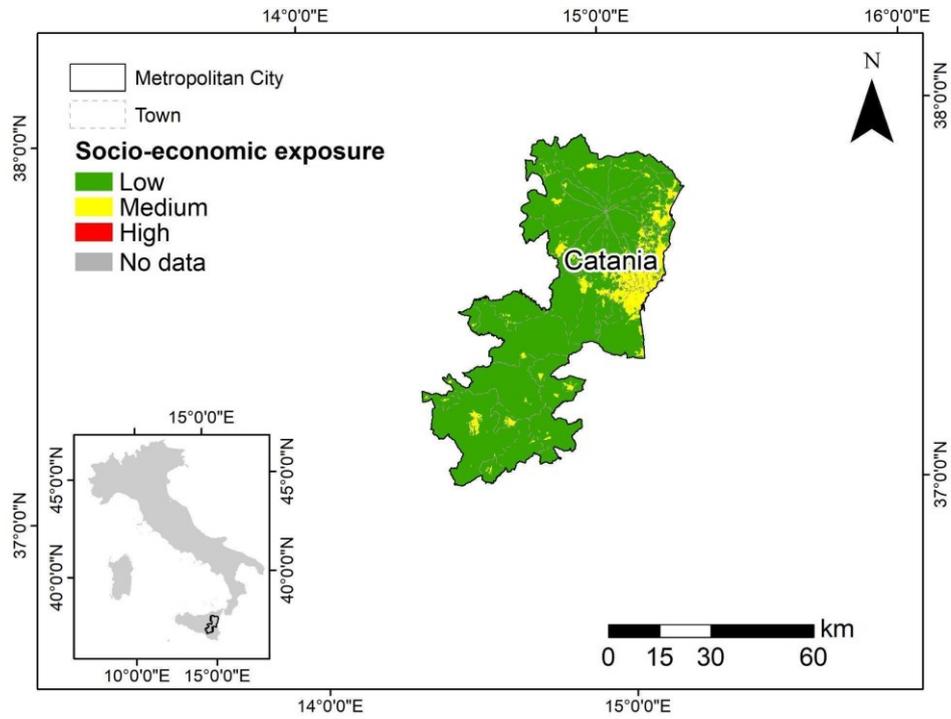
31.13. Catania



(a)



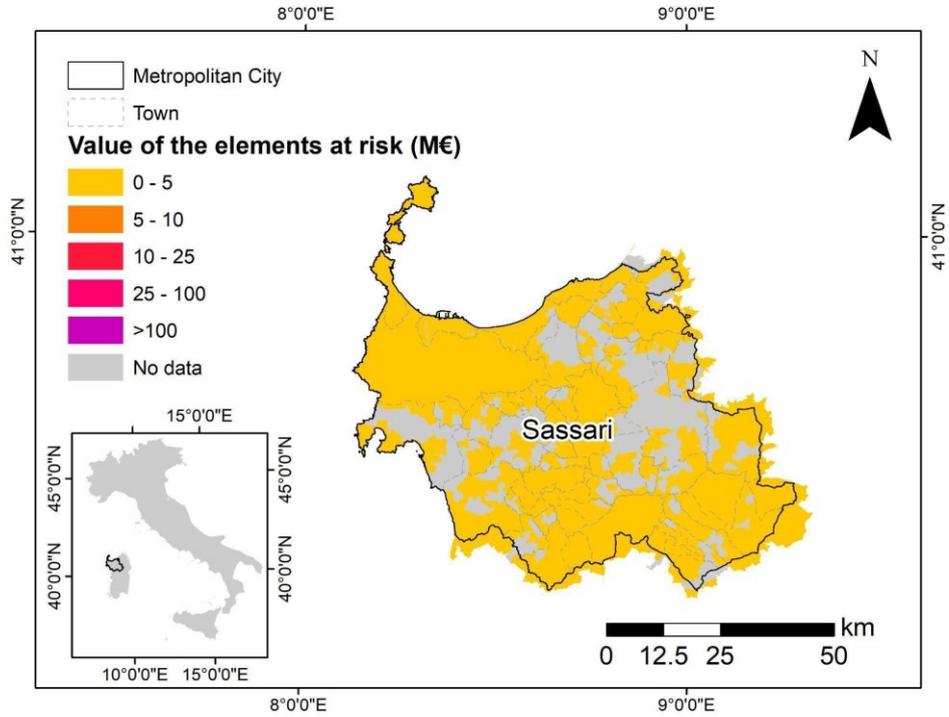
(b)



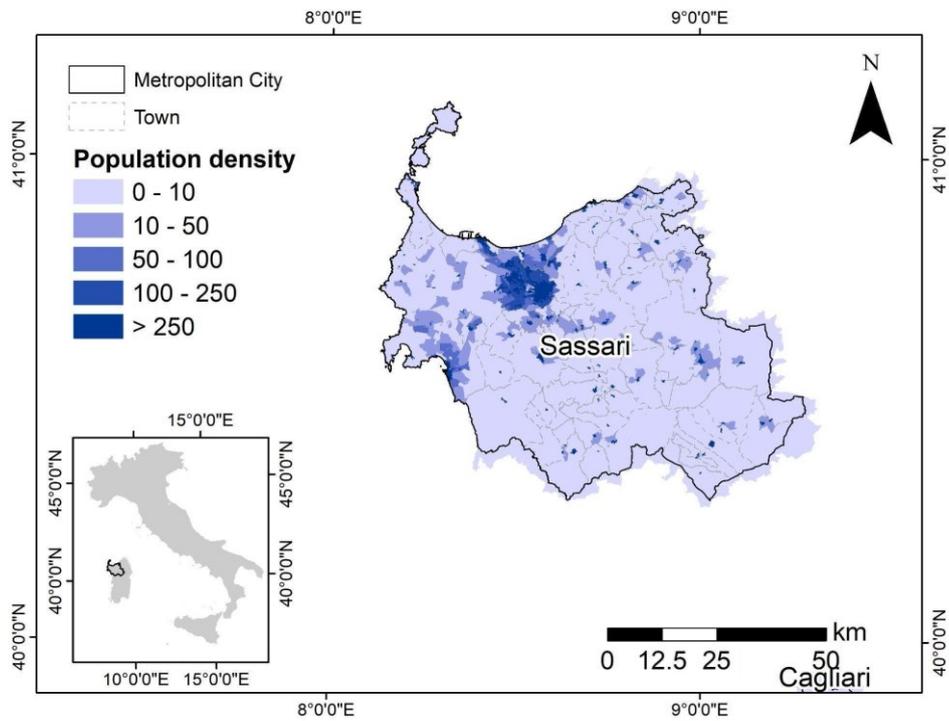
(c)

Figure 24 – Socio-economic exposure to land subsidence in the metropolitan city of Catania: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

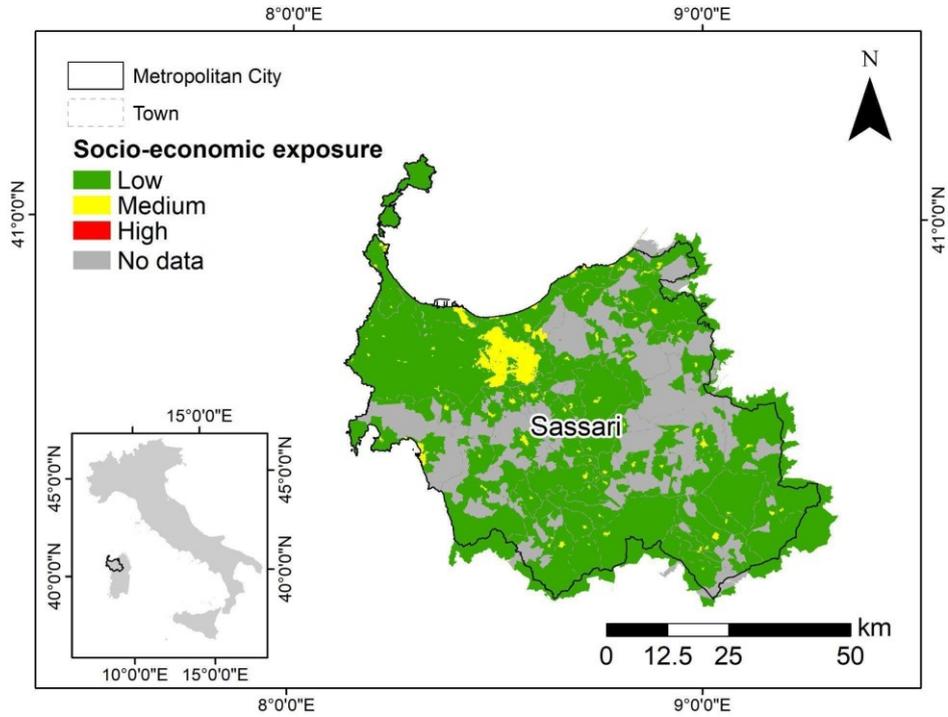
31.14. Sassari



(a)



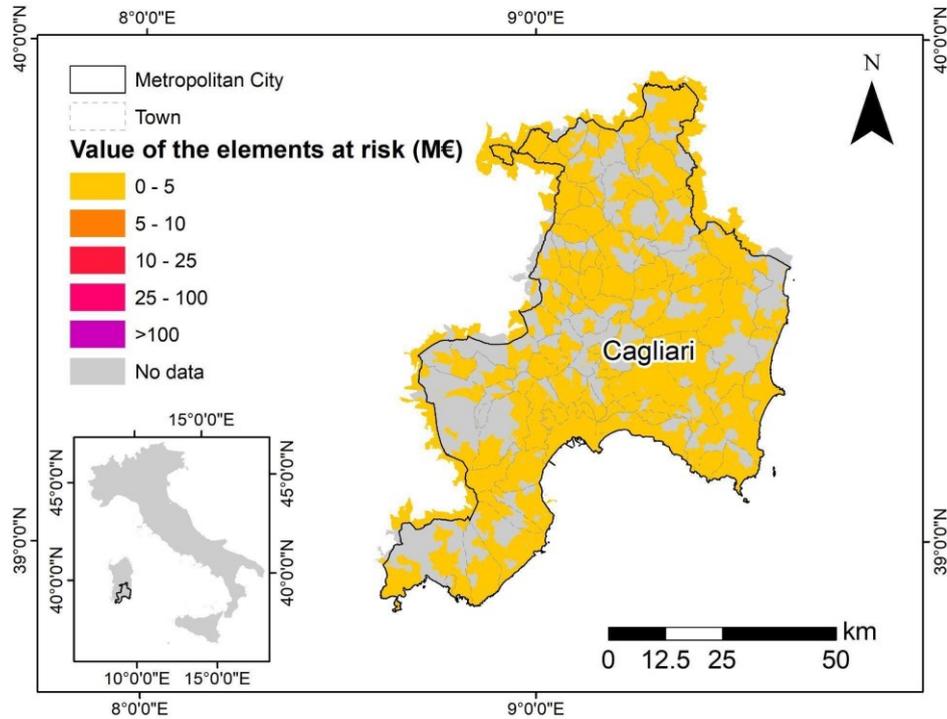
(b)



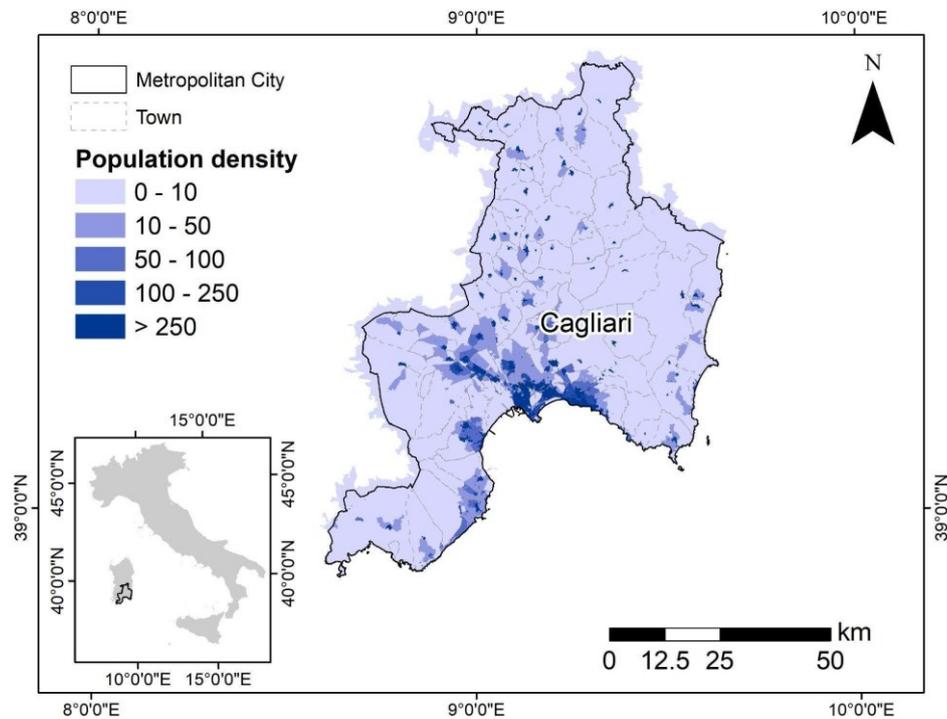
(c)

Figure 25 – Socio-economic exposure to land subsidence in the metropolitan city of Sassari: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

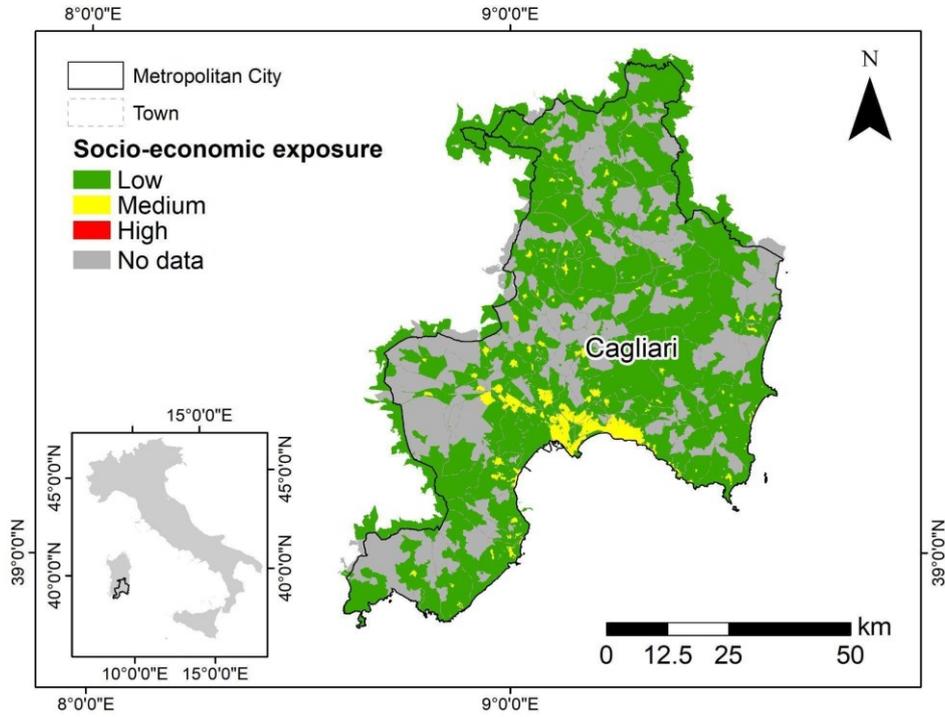
31.15. Cagliari



(a)



(b)

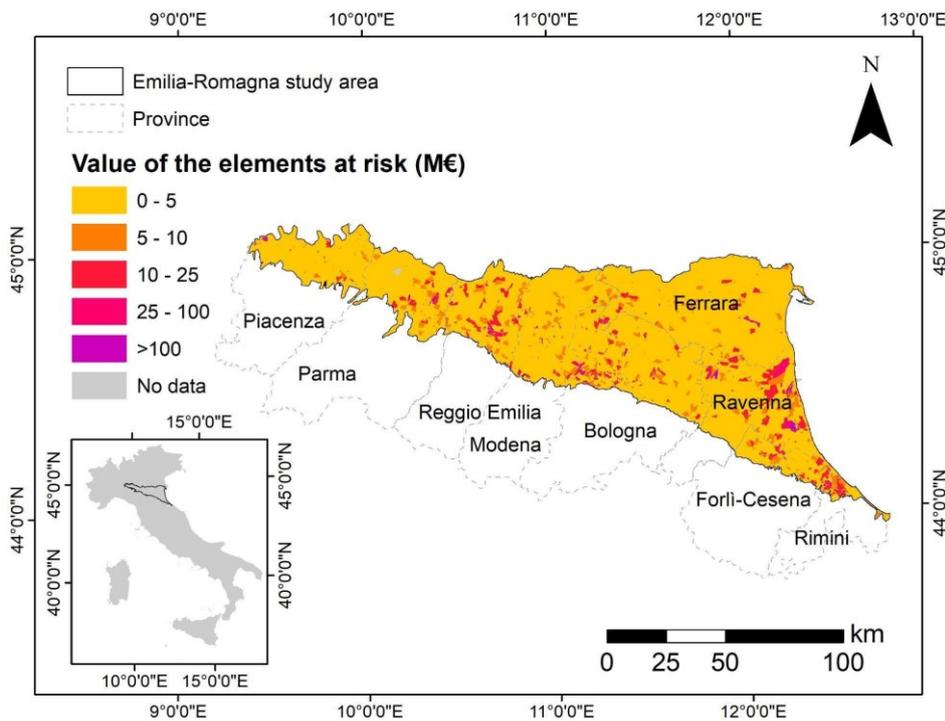


(c)

Figure 26 – Socio-economic exposure to land subsidence in the metropolitan city of Cagliari: (a) Value of the elements at risk (M€) for each ISTAT census zone, (b) population density (in inhabitants for ISTAT census zone per square kilometer), (c) socio-economic exposure map.

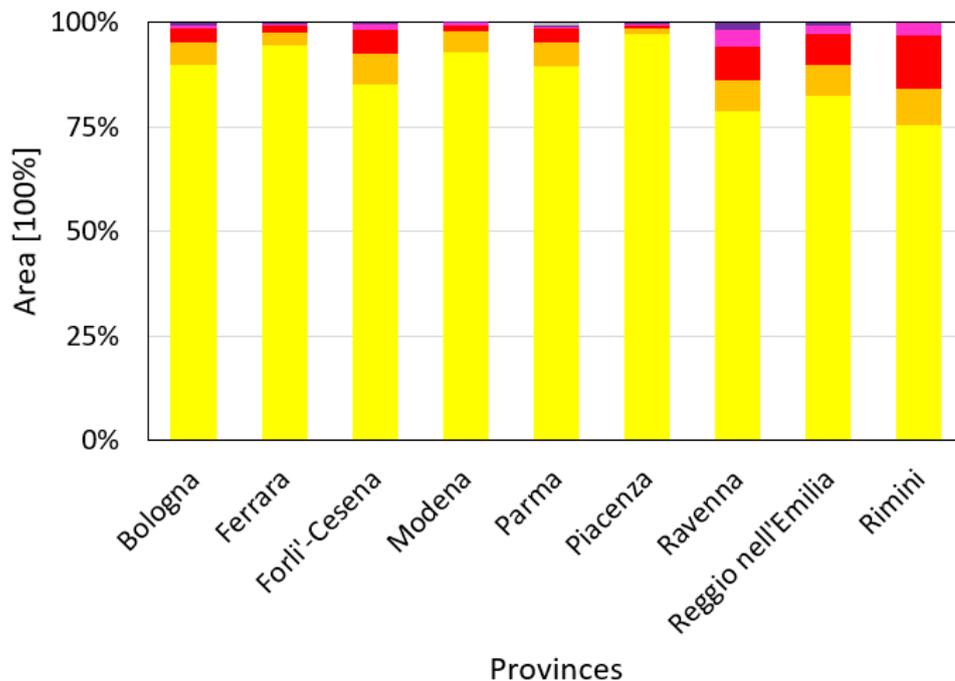
3.2. Potential impacts of the land subsidence in Emilia Romagna

The analysis of the value of elements at risk to land subsidence across the provinces of Emilia-Romagna reveals significant variation in the distribution of economic exposure. Most provinces, including Ferrara (94.72%), Modena (92.81%), and Bologna (89.89%), have the vast majority of their at-risk value concentrated in the lowest class (€0–5M), indicating a prevalence of lower-value assets. Piacenza stands out with the highest proportion in this class (97.27%), while Ravenna shows the most diverse distribution, with only 78.86% in the €0–5M range and a significantly higher proportion in higher value classes: 8.01% in the €10–25M range and 4.09% in the €25–100M range. Forli-Cesena also displays a relatively broader spread, with 7.14% in €5–10M and 5.69% in €10–25M. Parma is the only province with a measurable share (0.64%) in the "No data" category. These results suggest that while most provinces have predominantly low-value risk exposure, a few exhibit a higher value of the elements at risk (Figure 27).



(a)

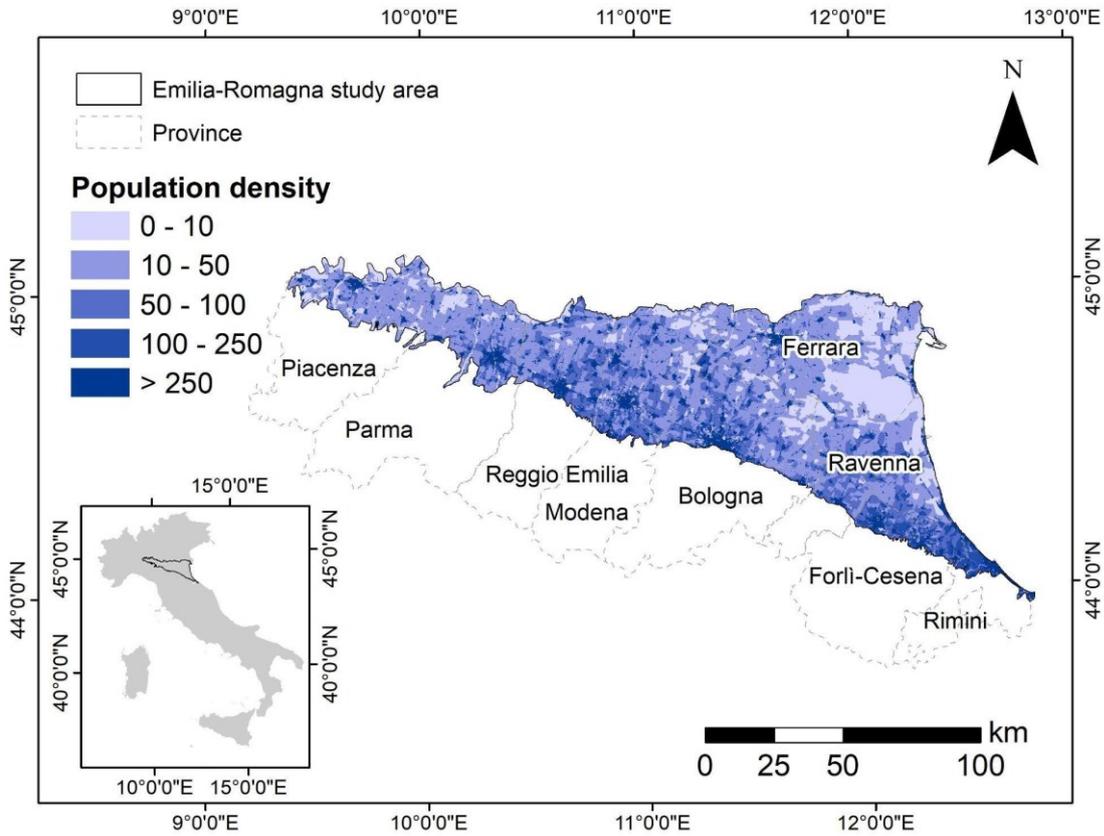
Value of the elements at risk (M€) 0-5 5-10 10-25 25-100 >100 No data



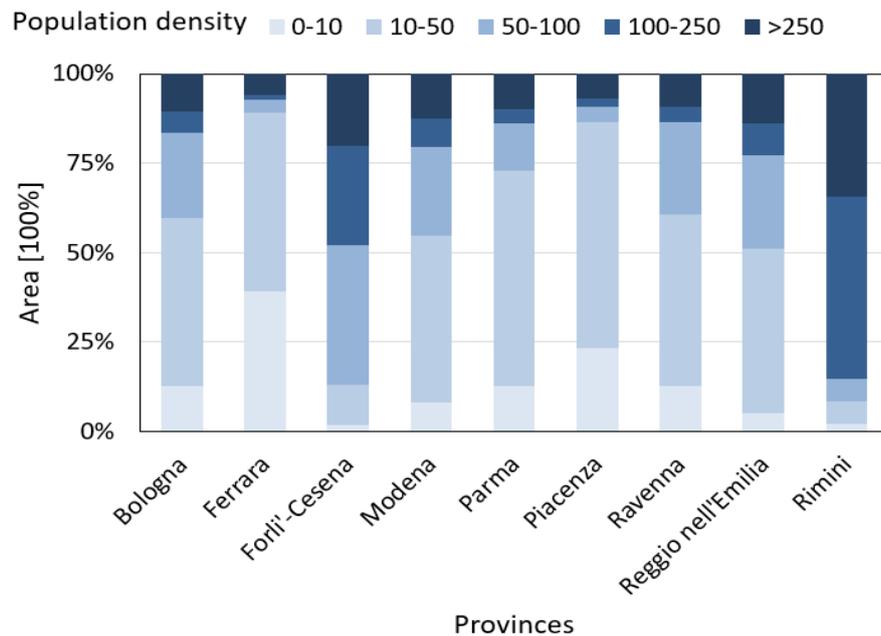
(b)

Figure 27 – (a) Value of the elements at risk (M€) for each ISTAT census zone. (b) Extent of the Value of the elements at risk (M€) within the provinces of Emilia-Romagna region, displayed using a percentage scale (100% refers to the total extent of the exposure data within each province).

The results highlight clear differences in population distribution patterns across the provinces. Ferrara and Piacenza show the highest concentration of low-density areas, with 88.96% and 86.57% of their territory respectively falling within the 0–50 inhabitants/km² of the ISTAT census zones, reflecting a predominantly rural or dispersed settlement pattern. Similarly, Parma and Bologna have 72.93% and 59.83% of their area in these lower density classes. In contrast, Rimini stands out with a strong urban profile: 85.38% of its territory falls within the higher density classes (100–250 and >250 inhabitants/km² of the ISTAT census zones), the highest among all provinces, indicating intense urban development, particularly along the coast. Forlì-Cesena also shows a relatively high level of urbanization, with 47.9% of its area above 100 inhabitants/km² of the ISTAT census zones. Modena, Reggio nell’Emilia, and Ravenna display a more balanced distribution, with around 20–25% of their territory in the higher density ranges and a significant share in the mid-density classes (50–100 inhabitants/km² of the ISTAT census zones). These results underline the contrast between inland provinces, where lower density is dominant, and coastal or more urbanized provinces, where population concentration is much higher (Figure 28).



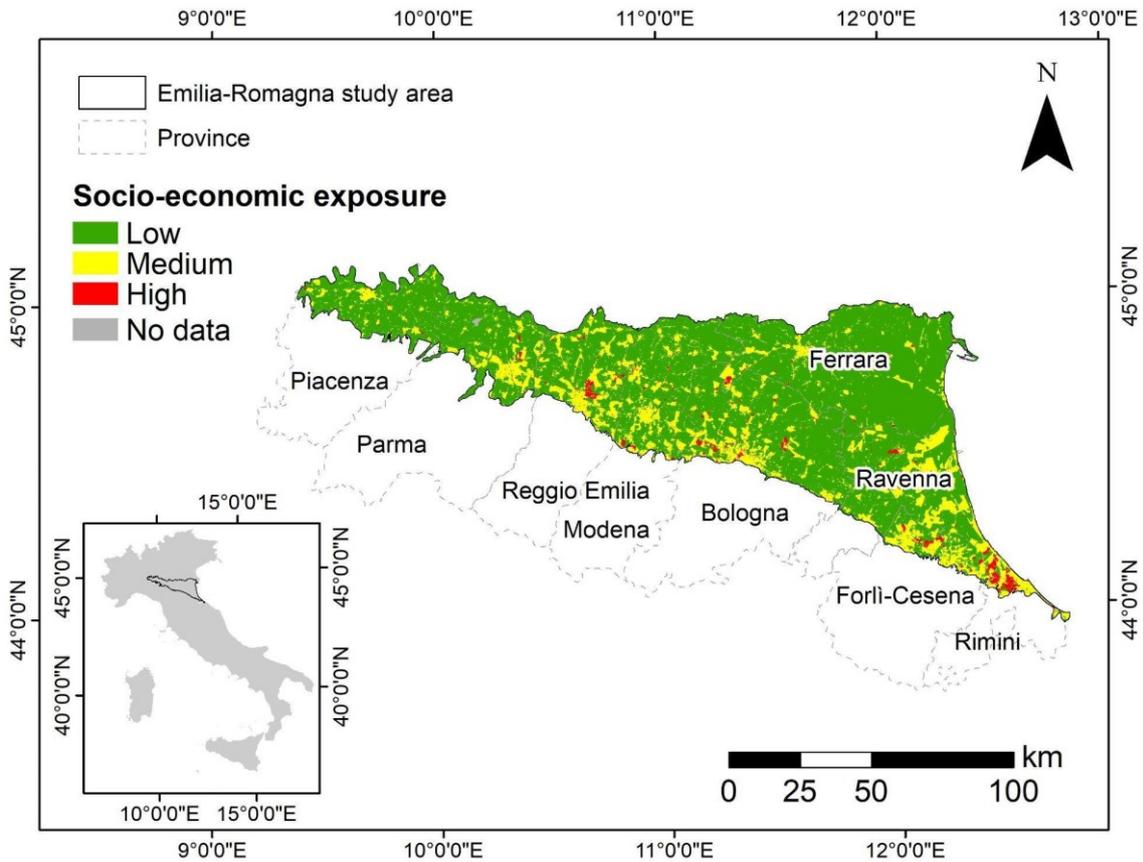
(a)



(b)

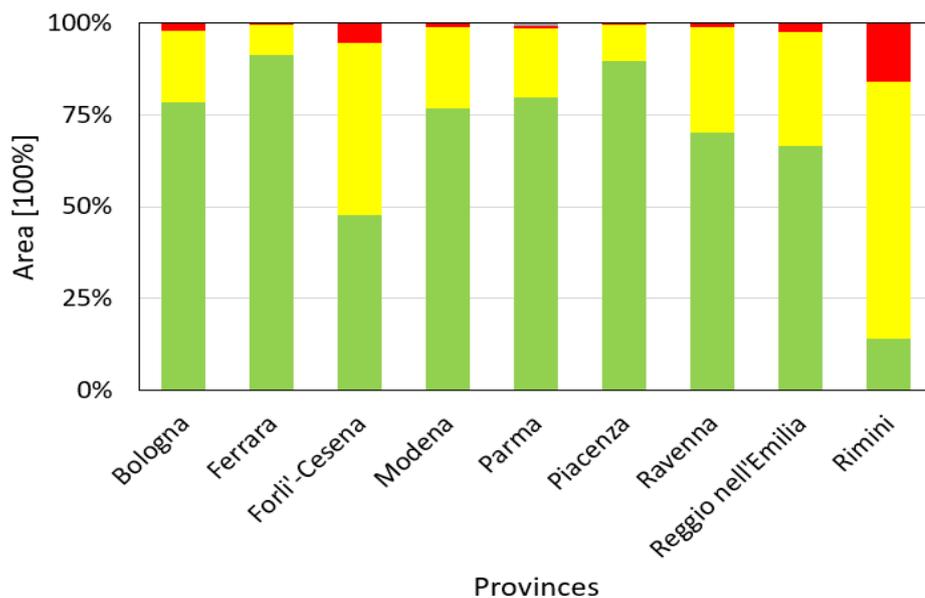
Figure 28 – (a) Population density (in inhabitants for ISTAT census zone per square kilometer). (b) Extent of the population density classes within the provinces of Emilia-Romagna region, displayed using a percentage scale (100% refers to the total extent of the exposure data within each province).

In most provinces, the majority of the area falls within the low socio-economic exposure to land subsidence, with Ferrara (91.25%), Piacenza (89.79%), Parma (79.72%), and Bologna (78.44%) showing the highest values, suggesting relatively lower economic concentration and population density in those areas. Modena and Ravenna also follow this trend, with over 70% of their areas classified as low exposure. In contrast, Rimini stands out with only 14.07% in the low exposure class and a predominant area in the medium (70.01%) and high (15.92%) socio-economic exposure classes, indicating a higher concentration of socio-economic assets and potentially increased vulnerability. Forlì-Cesena also shows a more balanced distribution, with nearly equal percentage of the area in the low (47.88%) and medium (46.9%) classes, and a relatively higher high exposure proportion (5.22%) compared to most provinces. Reggio nell'Emilia reflects a similar intermediate profile, with 66.5% low, 31.06% medium, and 2.44% high socio-economic exposure to land subsidence. Overall, the results highlight a pattern where inland provinces tend to have lower socio-economic exposure, while more urbanized or coastal areas, particularly Rimini, demonstrate a higher concentration of socio-economic assets (Figure 29).



(a)

Socio-economic exposure to land subsidence ■ Low ■ Medium ■ High ■ No data



(b)

Figure 29 – (a) Socio-economic exposure map to land subsidence in Emilia-Romagna region. (b) Extent of the Socio-economic exposure classes to land subsidence within the provinces of Emilia-Romagna region, displayed using a percentage scale (100% refers to the total extent of the exposure data within each province).

3.3. Potential impacts of the land subsidence in Bologna

The bivariate analysis combining land subsidence hazard levels with socio-economic exposure in Bologna city reveals that the majority of exposed buildings (69%) are located in areas characterized by high hazard and medium socio-economic exposure, accounting for 22,287 structures. This is followed by 22% of buildings situated in medium hazard zones with medium socio-economic exposure. A smaller proportion (2%) of the building stock falls within medium hazard areas but is associated with high socio-economic exposure, while only 1% of buildings are located in high hazard–high exposure zones, representing the most critical risk category. Additionally, data are unavailable for approximately 6% of the building footprint database (Figure 30).

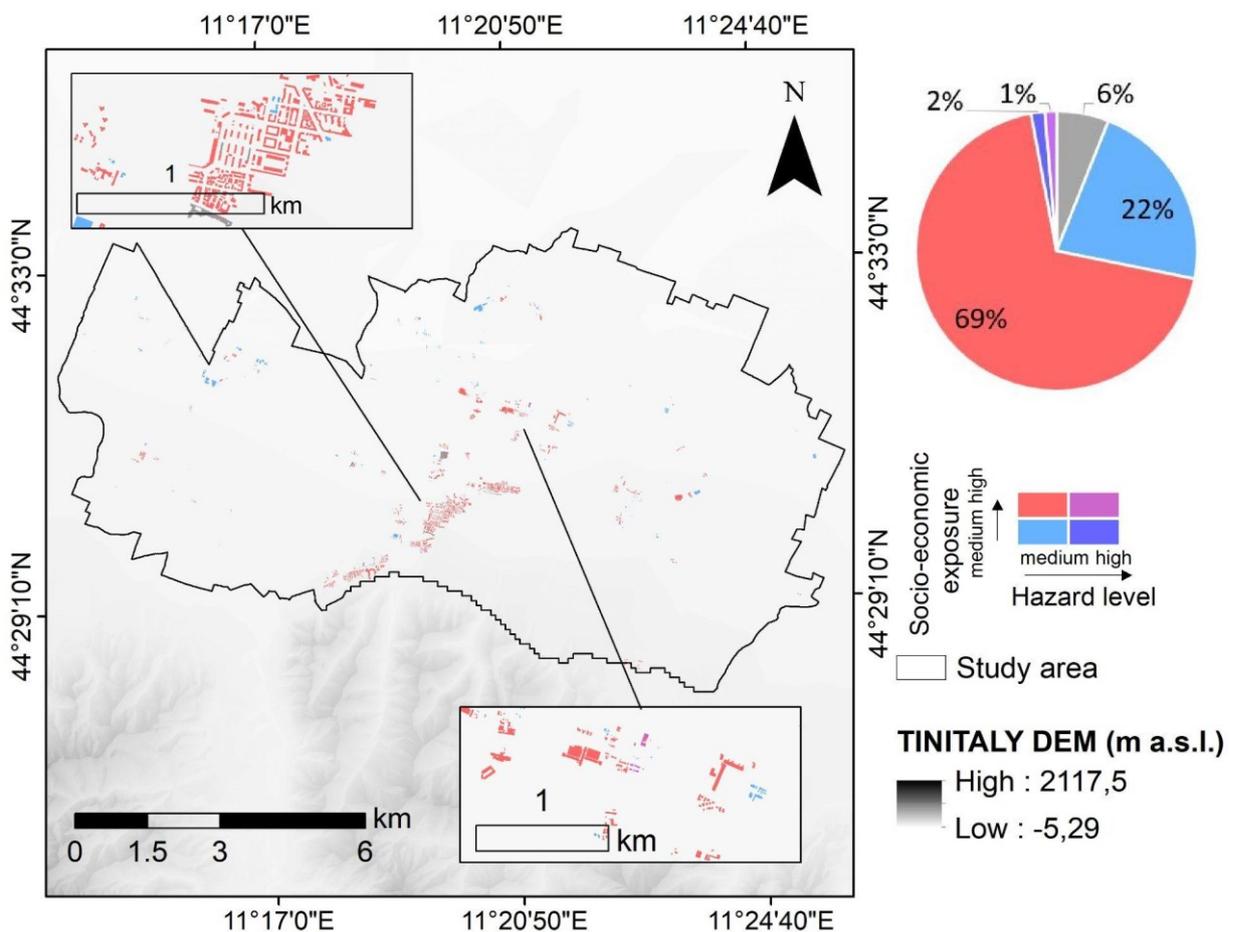


Figure 30 – Bivariate analysis of the socio-economic exposure and hazard level in the plain area of Bologna city.

3.4. Potential impacts of land subsidence on UNESCO cultural heritage sites

At the national scale, the impact of land subsidence across metropolitan cities suggests that all cultural heritage elements are predominantly exposed to a low level of hazard.

Since Bologna has historically been affected by land subsidence, the hazard levels are based on the estimated total angular distortion and strain over a 30-year period, whereas in other metropolitan cities, 10-year intervals were used. The analysis of the impact of land subsidence on UNESCO cultural heritage sites at the local scale in Bologna reveals that only one site, named "Certosa" is subject to a medium level of subsidence hazard (Figure 31).

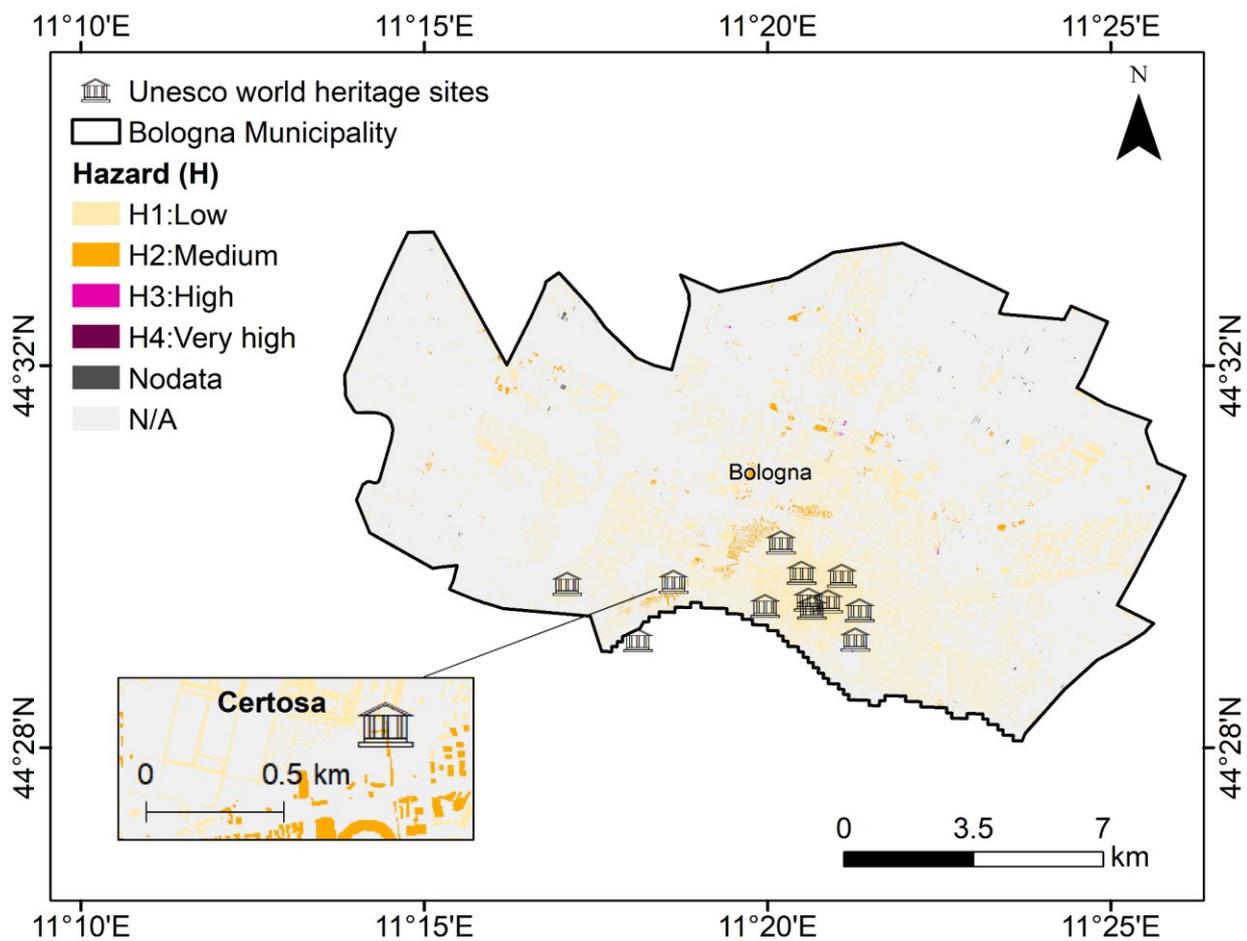


Figure 31 – Overview of land subsidence hazard on cultural heritage sites in the plain area of the Bologna city.

3.5. Flooding-prone areas exposed to land subsidence

A descriptive statistical analysis was carried out on vertical ground velocity parameters within flood-prone areas across 15 metropolitan cities in Italy. The results highlight a wide range of land subsidence and uplift behaviours, with minimum velocities ranging from -28.5 mm/year in Bologna to -5.4 mm/year in Palermo, indicating significant localized land subsidence in several urban areas. The first quartile (Q1) values show that a substantial portion of the monitored areas experience negative vertical movement, particularly in cities such as Bologna (-13.01 mm/year) and Reggio Calabria (-1.98 mm/year). The median values also reveal predominantly negative trends, with Bologna (-8.35 mm/year), Venezia (-2.99 mm/year), and Roma (-2.02 mm/year) showing notable subsidence. Conversely, some cities, such as Napoli and Catania, display median uplift values, which can be attributed to ongoing volcanic activity, such as the bradyseism phenomena in the Campi Flegrei caldera, and magmatic dynamics of Mount Etna (Figure 32).

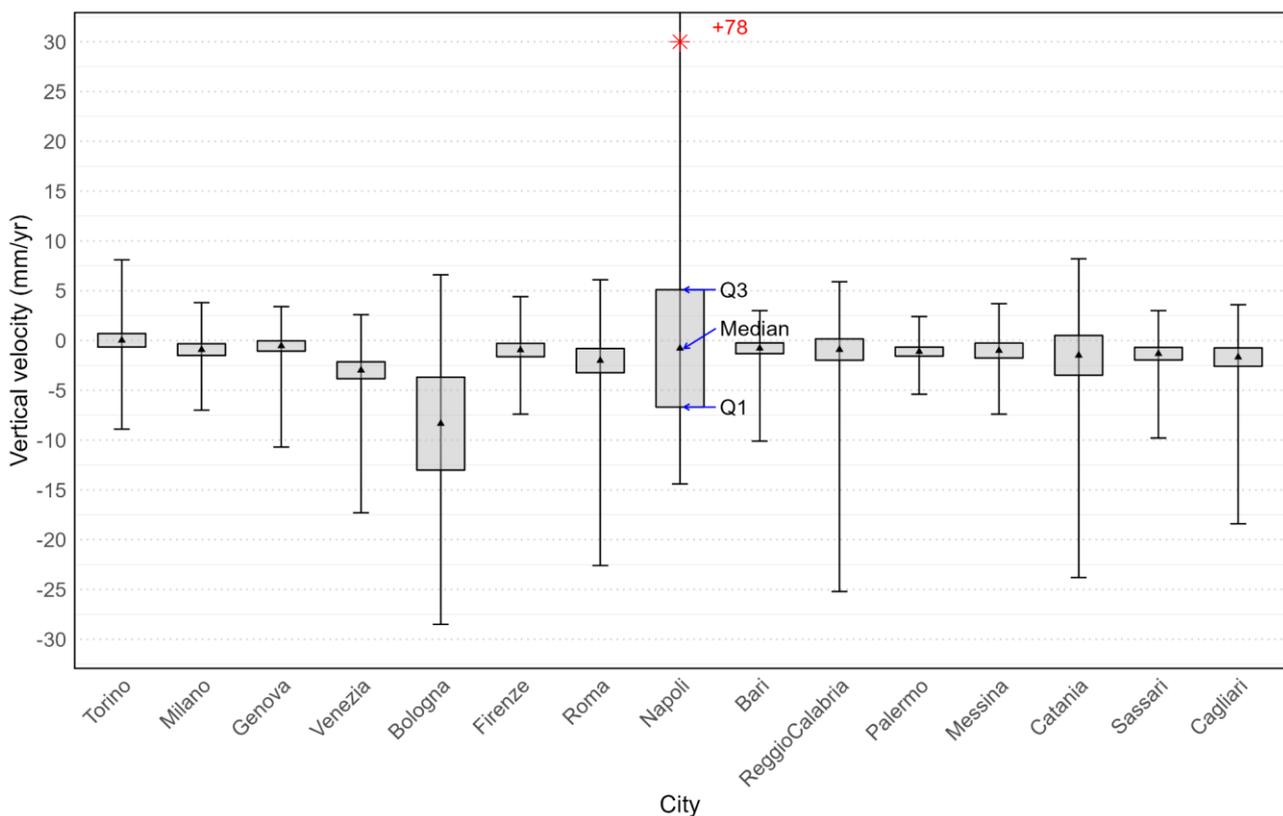


Figure 32 – Boxplot of vertical velocity in the flood-prone areas of the 15 metropolitan cities.

4. CONCLUSIONS

This report presents a comprehensive assessment of the direct and indirect socio-economic exposure to land subsidence across the 15 metropolitan cities in Italy, the Emilia-Romagna region, and the city of Bologna. Through the integration of hazard maps, economic asset values, population density data, and EGMS vertical ground displacements, the study provides a multi-scalar understanding of potential direct and indirect impacts of land subsidence.

The analysis of the economic value of elements at risk reveals that in more than 87% of the mapped areas across the metropolitan cities, exposure falls within the lowest value class (0–5 M€), with higher-value concentrations (5–100 M€ and >100 M€) mainly limited to large urban centers such as Roma, Bologna, and Napoli. These same cities also account for the largest extents of high socio-economic exposure zones, over relatively limited areas.

The socio-economic exposure, derived from the integration of market value and population density, shows that the majority of the area across most metropolitan cities and provinces falls within the low exposure class, especially in more inland or less urbanized areas (e.g., Ferrara, Piacenza, Parma). Conversely, urban and coastal locations such as Rimini and Napoli exhibit a higher proportion of medium to high exposure, indicating a greater concentration of economic and demographic assets in zones potentially affected by land subsidence.

When using information provided in this report, it is worth accounting for the following:

- The input EGMS Ortho layers do not provide information on N-S displacement that may occur, hence horizontal strain along the N-S direction is not accounted for; in such cases, other geodetic data (e.g., GPS/GNSS) might provide complementary data to enhance the detection of the ground displacement and the hazard assessment. Moreover, a PS-based processing of the interferometric acquisitions would provide a more accurate quantification of the angular distortion and horizontal strain, as already mentioned in DEL2.2
- The hazard mapping is influenced by the time period considered for calculating the cumulated angular distortion and strain. Therefore, further verification should be carried out at the local scale, particularly in the case of UNESCO cultural heritage sites.
- The classification of value classes or categories, and the level of spatial detail (e.g., use of OMI zones versus building-level data), can affect both the resolution and the reliability of the output.
- The overall accuracy and reliability of the outputs depend on the quality and resolution of the geospatial input layers.

5. References

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