# Subsidenza differenziale e rischio indotto sulle infrastrutture delle metropoli italiane: situazione attuale e scenari futuri

***F. Cigna*** [1], *R. Paranunzio* [1], *R. Bonì* [2], *P. Teatini* [3]

SubRISK+

***Enhancing our understanding of Subsidence RISK induced by groundwater exploitation towards sustainable urban development*** [2023-2026]

Italian Ministry of University and Research (MUR)'s "**PRIN 2022 PNRR" Call** to fund Research Projects of Significant National Interest (PRIN) in the framework of the National Recovery and Resilience Plan (PNRR)

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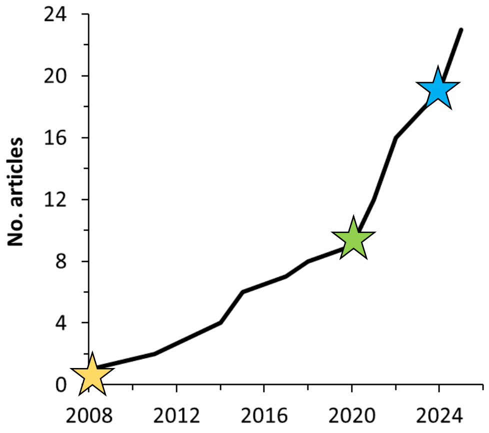
# Scientific goals

Trending topic in the InSAR literature

**** transforming satellite observations into information layers on exposure, hazard and risk for urban infrastructure ****




- Differential settlements and structural stress affecting buildings, to gather insights into surface faulting hazard
- InSAR-based risk assessment workflows based on risk matrices
- Exposure of communities and urban infrastructure to land subsidence and differential settlement

Adaptability to a variety of geographical contexts in the US, Latin America, Europe, Africa and Asia

**OUR GOALS**

→ **Innovating the risk assessment workflow** to enable exposure-vulnerability rating, hazard quantification and risk assessment by integrating InSAR-derived ground displacement, land cover and urban settlement characteristics

→ Estimating present-day **land subsidence-induced risk in Italy**, one of the world countries most affected by ground deformation processes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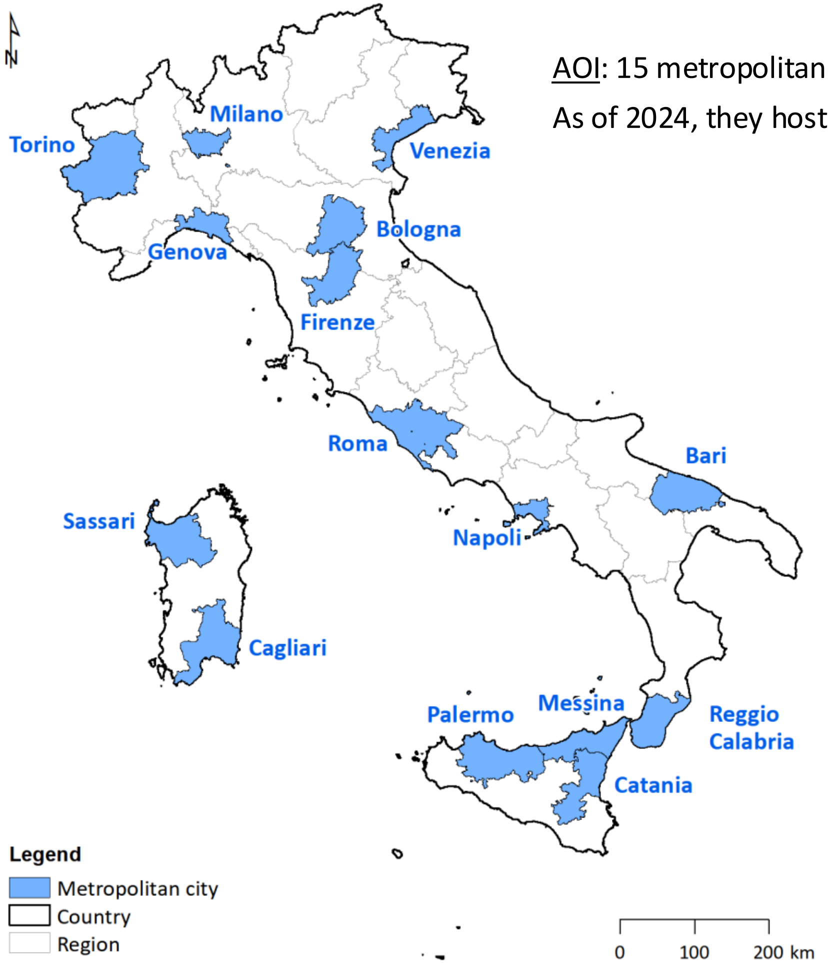
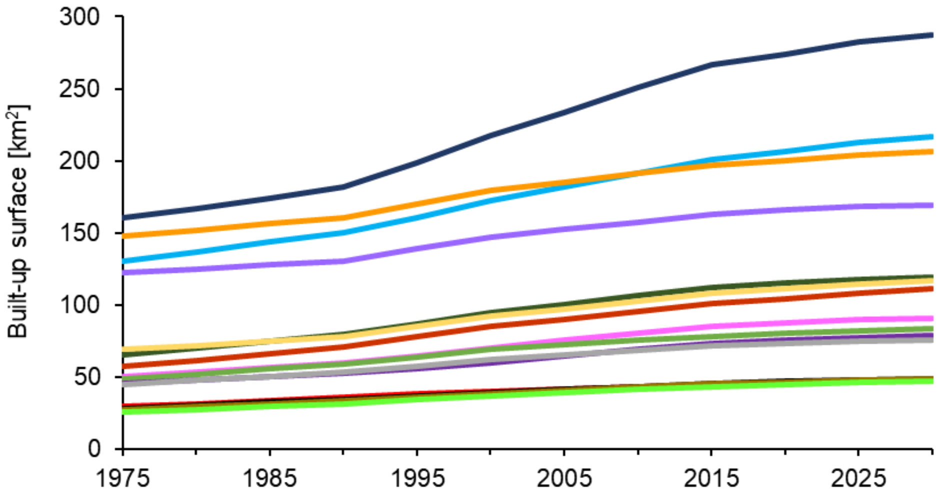
# National scale risk assessment in Italy




AOI: 15 metropolitan cities

As of 2024, they host > 21.7 M inhabitants across 54,380 km² (out of 59 M censed in the whole country)

~1700 km$^2$ built-up surface as of 2025




| | *AUER* [%] | *UEII* [%] | *UGR* [%] |
|---|---|---|---|
| Rome | 1.53 | 0.046 | 1.14 |
| Turin | 1.25 | 0.024 | 0.98 |
| Milan | 0.76 | 0.071 | 0.65 |
| Naples | 0.75 | 0.078 | 0.64 |
| Bari | 1.61 | 0.027 | 1.19 |
| Venice | 1.33 | 0.037 | 1.02 |
| Bologna | 1.80 | 0.028 | 1.29 |
| Catania | 1.56 | 0.022 | 1.16 |
| Florence | 1.38 | 0.019 | 1.06 |
| Palermo | 1.39 | 0.013 | 1.06 |
| Cagliari | 1.33 | 0.013 | 1.02 |
| Genoa | 1.22 | 0.019 | 0.96 |
| Messina | 1.40 | 0.012 | 1.07 |
| Reggio Calabria | 1.53 | 0.013 | 1.14 |
| Sassari | 1.62 | 0.010 | 1.19 |

CIGNA *et al.* 2025, doi:10.1038/s41598-025-18941-8

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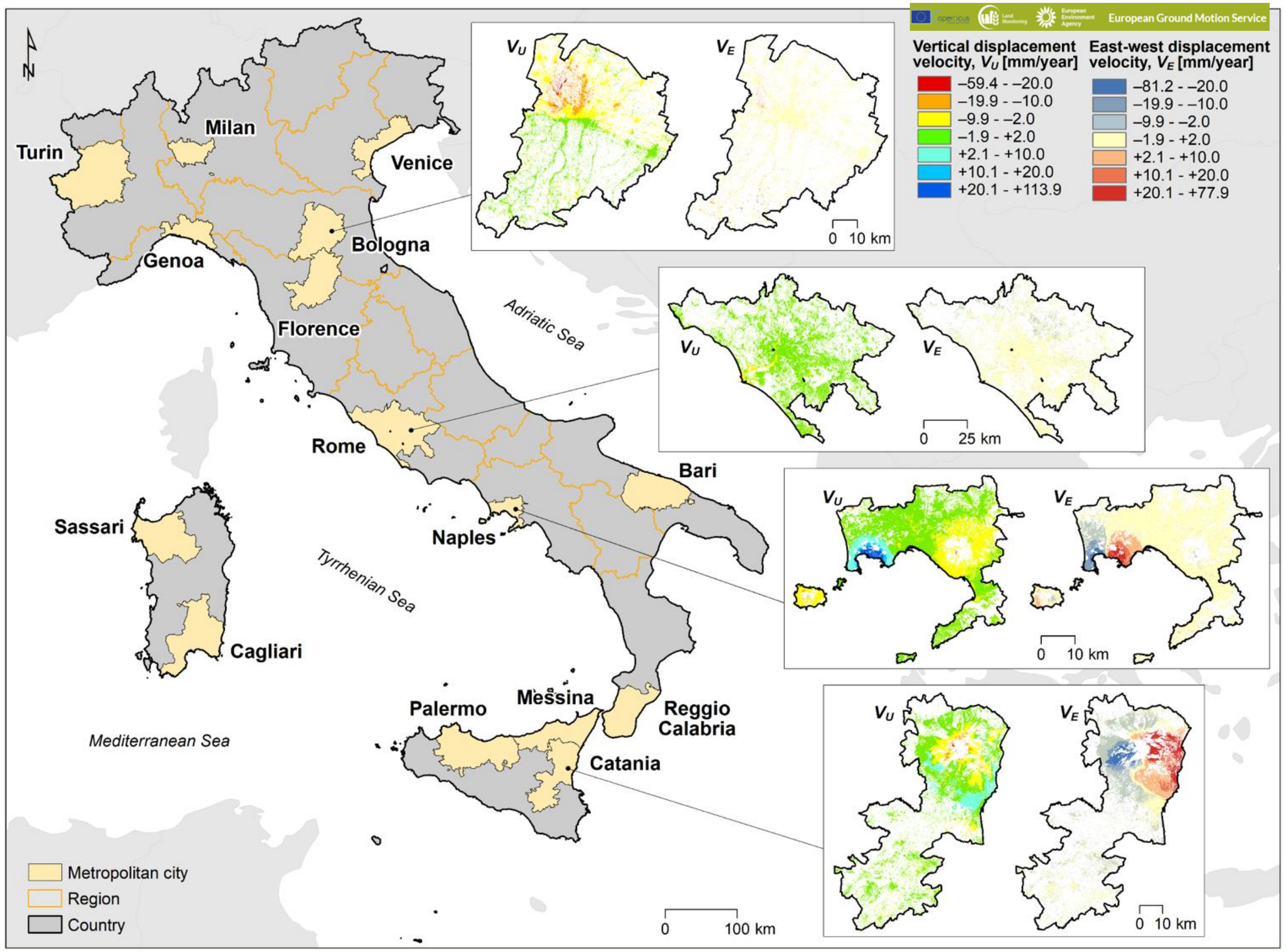
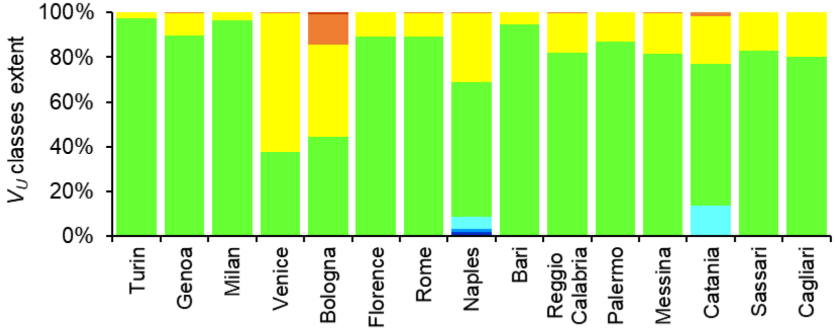
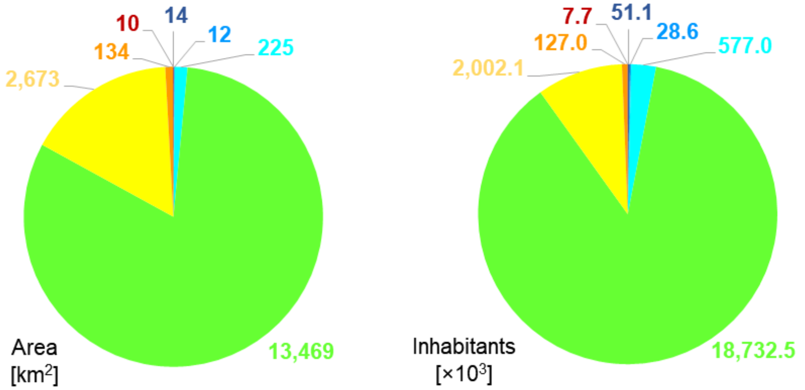
# Urban land and population exposed




Built-up lands exposed to $V_U$ **> ± 2.0 mm/year** (subsidence/uplift) span ~**3070 km²** across the 15 cities (~19% of the InSAR data coverage), involving **2.8 million inhabitants** (~13%)

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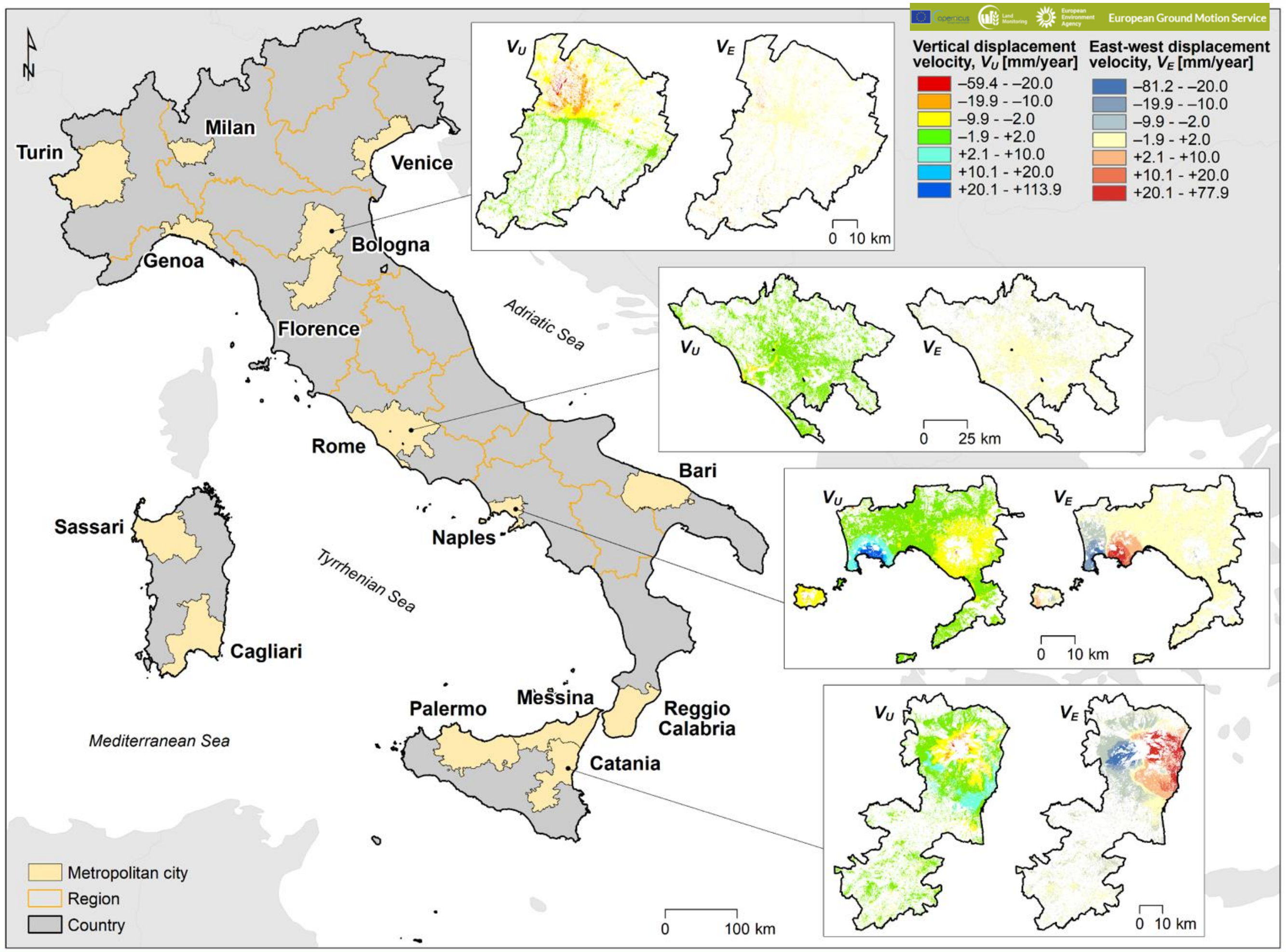
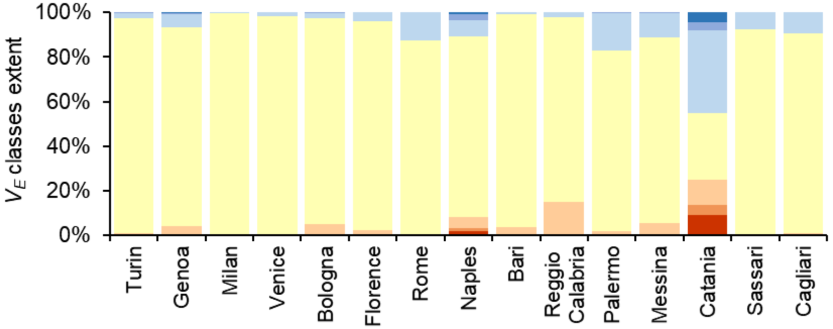
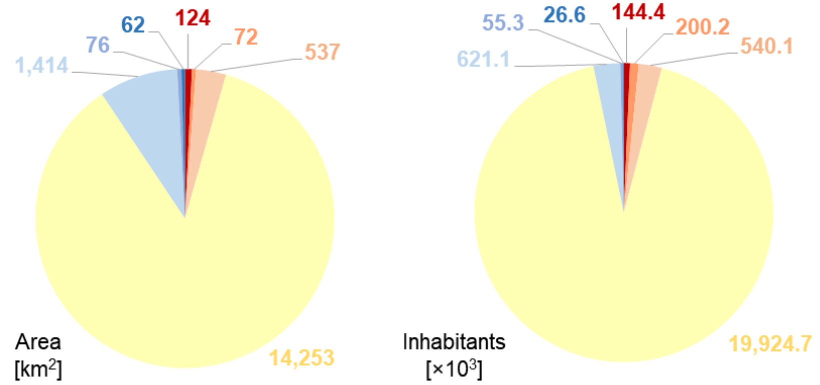
# Urban land and population exposed




Built-up lands exposed to $V_E$ **> ± 2.0 mm/year** (eastward/westward) cover **~2285 km²** across the 15 cities (~14% of the InSAR data coverage), involving **1.6 million inhabitants** (~7%)

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# Ground displacement-induced risk

***R**isk = **H**azard x **E**xposure x **V**ulnerability*

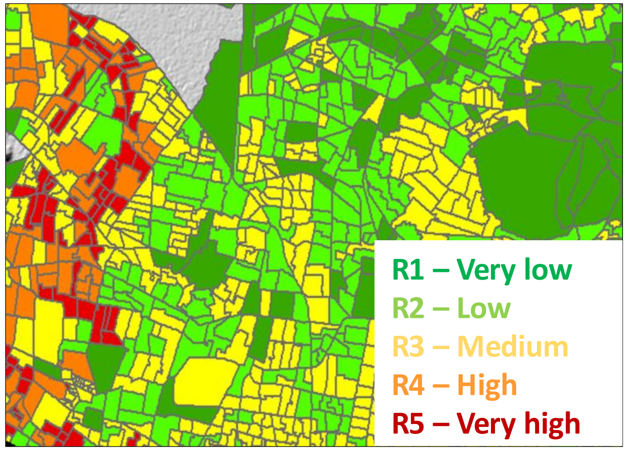
*expected loss from a given natural hazard*

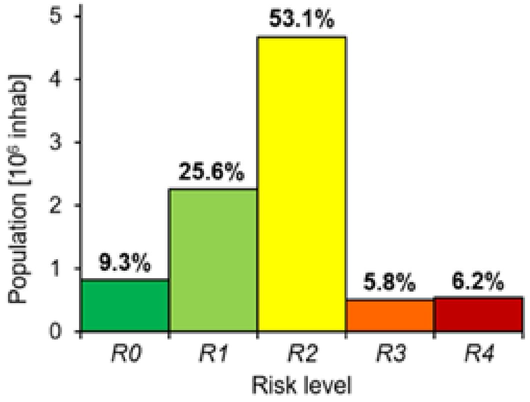
*Hazard*: probability of occurrence of a potentially impacting phenomenon
*Exposure*: location, attributes and value of the assets that could be affected
*Vulnerability*: likelihood that the assets will be affected when exposed to the hazard

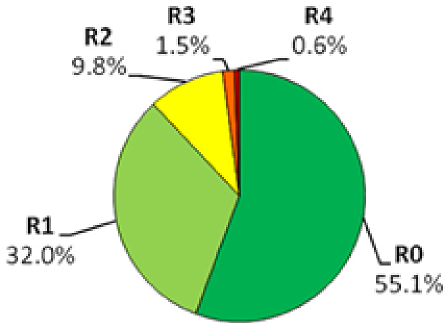
**Risk matrix**

| *Exposure-vulnerability* \ *Subsidence-induced hazard* | low | medium | high | very high |
|---|---|---|---|---|
| low | R1 | R2 | R3 | R4 |
| medium | R2 | R3 | R4 | R5 |
| high | R3 | R4 | R5 | R5 |

**Output risk maps & statistics**




CIGNA & TAPETE 2021, doi:10.1016/j.rse.2020.112161

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# Data analysis – **HAZARD (H)**

**Impacts of differential ground displacement**
*Some examples from Central Mexico*

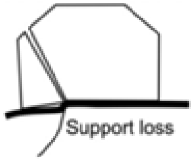

*Unlevel sinking and undulating rooflines*
*(www.sciencemag.org)*

*House fissuring and cracking*
*(FIGUEROA-MIRANDA et al. 2018)*

*Fissured and ramped roads and ground due to surface faulting*
*(©INEGI 2020)*

**A refined hazard assessment based on the quantification of structural stress induced by differential displacement**

## Angular distortion (β)

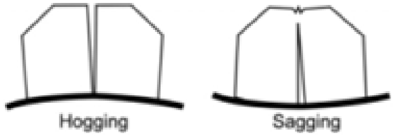



$$\beta = \frac{\Delta d_{Ui}}{l}$$

$\Delta d_{Ui}$ = Vertical differential displacement occurred between the two points
$l$ = distance between the two points

*e.g.* **β = 0.22%** (1/450) refers to a total of 22 cm differential displacement over a 100 m distance

## Horizontal strain (ε)




$$\varepsilon = \frac{\Delta d_{Ei}}{l}$$

$\Delta d_{Ei}$ = E-W differential displacement between the two points
$l$ = distance between the two points

*e.g.:* **ε = 0.15%** (1/670) refers to a total of 15 cm differential displacement over a 100 m distance

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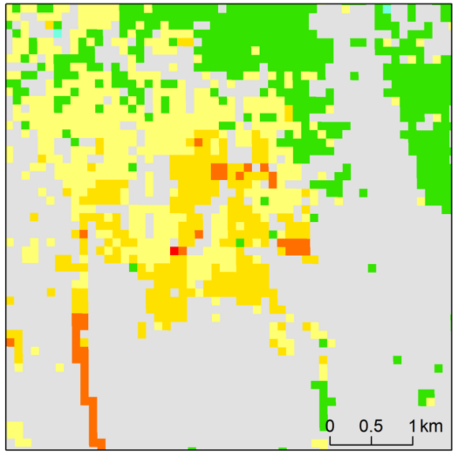
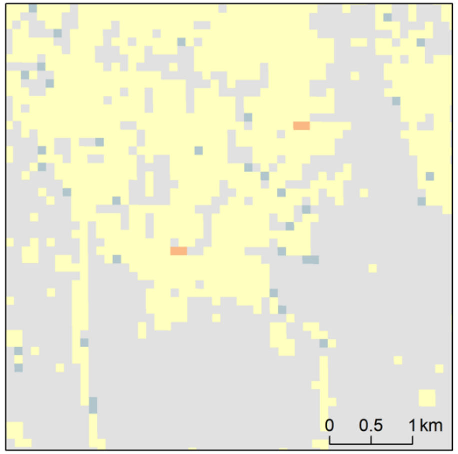
# SubRISK+ Data analysis – **HAZARD (H)**

## INPUT: European Ground Motion Service (EGMS)



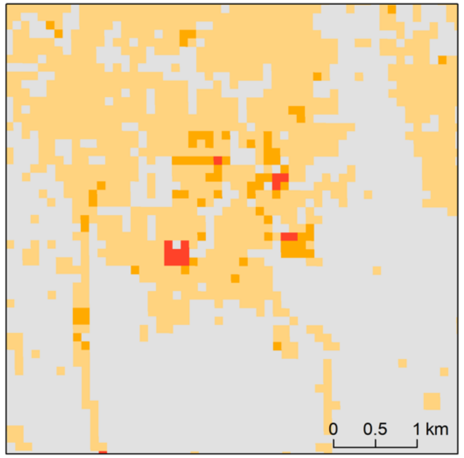

**Vertical displacement velocity 2018-2022 [mm/year]**
- -59.4 - -20.0
- -19.9 - -10.0
- -9.9 - -5.0
- -4.9 - -2.0
- -1.9 - +2.0
- +2.1 - +5.0
- +5.1 - +10.0
- +10.1 - +25.0
- +25.1 - +50.0
- +50.1 - +116.0
- No data



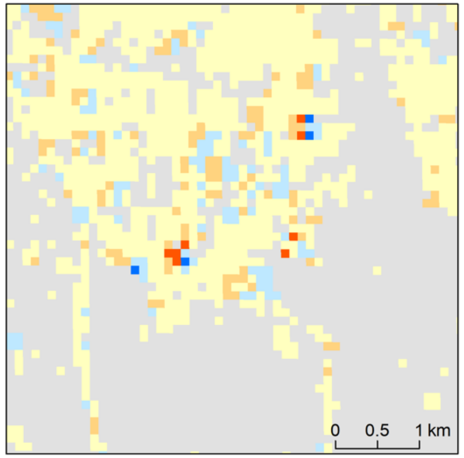

**East-west displacement velocity 2018-2022 [mm/year]**
- -11.13 - -2.5
- -2.4 - -1.5
- -1.4 - -0.5
- -0.4 - +0.5
- +0.6 - +1.5
- +1.6 - +2.5
- +2.6 - +11.9
- No data

Copernicus Europe's eyes on Earth
Land Monitoring Service

## Structural stress due to differential displacement




**Total angular distortion, 10 years**
- 0 - 0.017% (≤1/6000)
- 0.018% - 0.033% (1/6000 - 1/3000)
- 0.034% - 0.067% (1/3000 - 1/1500)
- 0.068% - 0.100% (1/1500 - 1/1000)
- 0.101% - 0.143% (1/1000 - 1/700)
- 0.144% - 0.200% (1/700 - 1/500)
- 0.201% - 0.223% (>1/500)
- No data

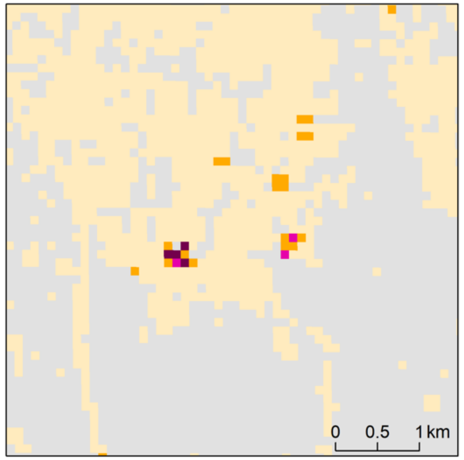



**Total horizontal strain [%] 10 years**
- -0.312 - -0.100
- -0.099 - -0.030
- -0.029 - -0.010
- -0.009 - 0.010
- 0.011 - 0.030
- 0.031 - 0.100
- 0.101 - 0.288
- No data

## Resulting Hazard (H) levels

| Total angular distortion * | Total horizontal strain: $\|\varepsilon\| < 0.03\%$ | Total horizontal strain: $\|\varepsilon\| \geq 0.03\%$ |
|---|---|---|
| $\beta \leq 1/3000$ | H1 | H2 |
| $1/3000 < \beta \leq 1/1500$ | H2 | H3 |
| $1/1500 < \beta \leq 1/500$ | H3 | H4 |
| $\beta > 1/500$ | H4 | H4 |

* *A safety factor of 20% might be applied to reduce the β thresholds and thus ensure a more conservative hazard assessment*




**Hazard (H)**
- H1: Low
- H2: Medium
- H3: High
- H4: Very high
- No data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SubRISK+

# Data analysis – **EXPOSURE-VULNERABILITY (EV)**

**An innovative exposure-vulnerability scoring approach building upon urban settlement characteristics derived from open global datasets**

Input datasets:
- **Copernicus Global Human Settlement Layer (GHSL) BUILT-C** settlement characteristics → [type, height]
- **World Settlement Footprint** (WSF) → [construction year]

Assumptions:
- Non residential buildings are more vulnerable (e.g. hospitals, churches, industrial sheds)
- Older buildings are more vulnerable (by law, new buildings use reinforced concrete vs. masonry/old buildings)

Output EV scores:
**EV1 (low)**
**EV2 (medium)**
**EV3 (high)**
**EV4 (very high)**

| Settlement characteristics | | | Age ≤ 1985 | Age > 1985 |
|---|---|---|---|---|
| Open spaces | 01-05 | low to high vegetation, water and road surfaces | n/a | |
| Built spaces, Residential | 11 | building height ≤ 3 m | EV2 | EV1 |
| | 12 | 3 m < building height ≤ 6 m | EV3 | EV2 |
| | 13 | 6 m < building height ≤ 15 m | EV3 | EV2 |
| | 14 | 15 m < building height ≤ 30 m | EV4 | EV3 |
| | 15 | building height > 30 m | EV4 | EV3 |
| Built spaces, Non-residential | 21 | building height ≤ 3 m | EV2 | EV2 |
| | 22 | 3 m < building height ≤ 6 m | EV3 | EV2 |
| | 23 | 6 m < building height ≤ 15 m | EV3 | EV3 |
| | 24 | 15 m < building height ≤ 30 m | EV4 | EV3 |
| | 25 | building height > 30 m | EV4 | EV4 |

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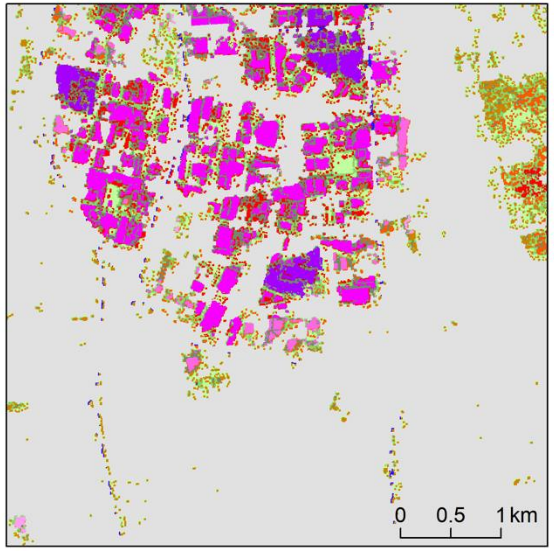
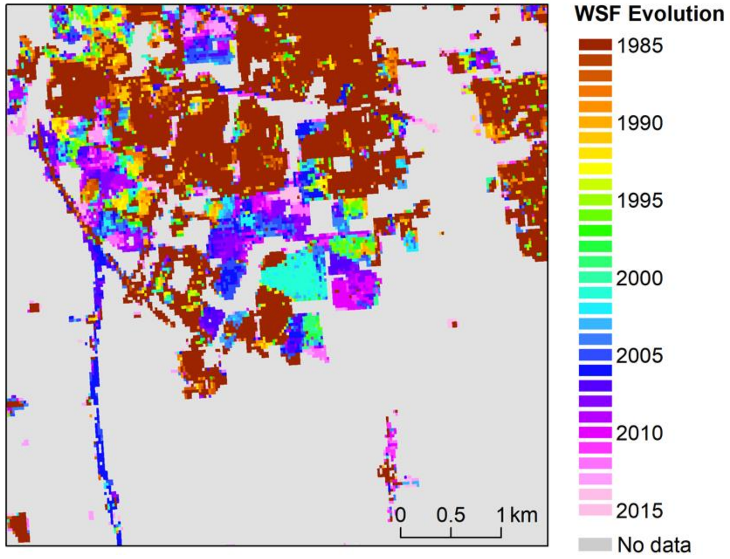
# SubRISK+ Data analysis – **EXPOSURE-VULNERABILITY (EV)**

**INPUT: Global Human Settlement Layer (GHSL) & World Settlement Footprint (WSF)**



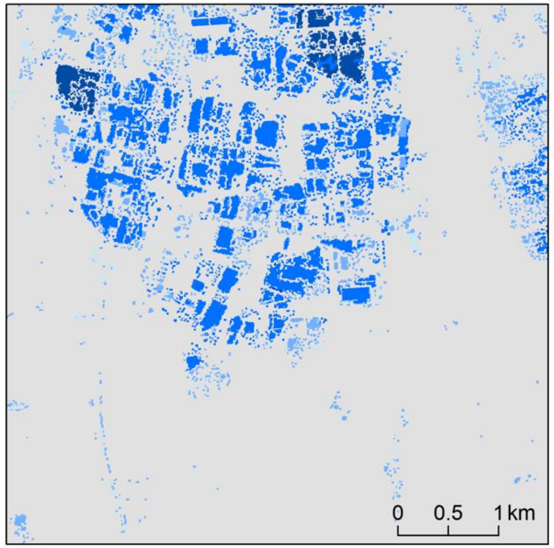

**GHSL Settlement characteristics (2018)**

*Open spaces*
- 01: low vegetation, NDVI ≤ 0.3
- 02: medium vegetation, 0.3 < NDVI ≤ 0.5
- 03: high vegetation, NDVI > 0.5
- 04: water, LAND < 0.5
- 05: road surfaces

*Built spaces, residential*
- 11: building height ≤ 3m
- 12: 3m < building height ≤ 6m
- 13: 6m < building height ≤ 15m
- 14: 15m < building height ≤ 30m
- 15: building height > 30m

*Built spaces, non-residential*
- 21: building height ≤ 3m
- 22: 3m < building height ≤ 6m
- 23: 6m < building height ≤ 15m
- 24: 15m < building height ≤ 30m
- 25: building height > 30m
- No data

**Resulting Exposure-Vulnerability (EV) scoring**




**Exposure-Vulnerability (EV)**
- EV1: Low
- EV2: Medium
- EV3: High
- EV4: Very high
- N/A

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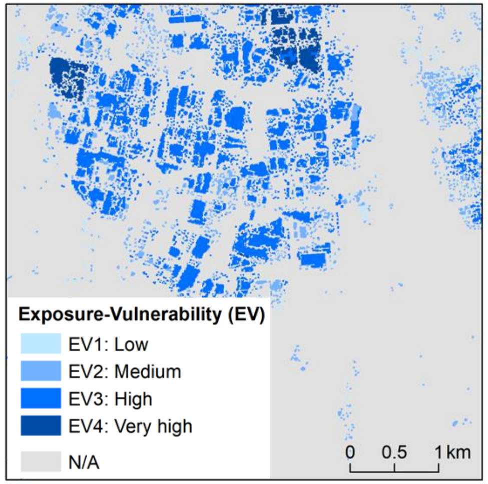
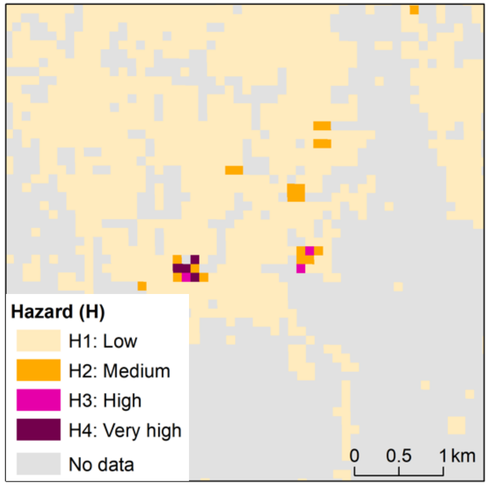
# Data analysis – **RISK (R)**

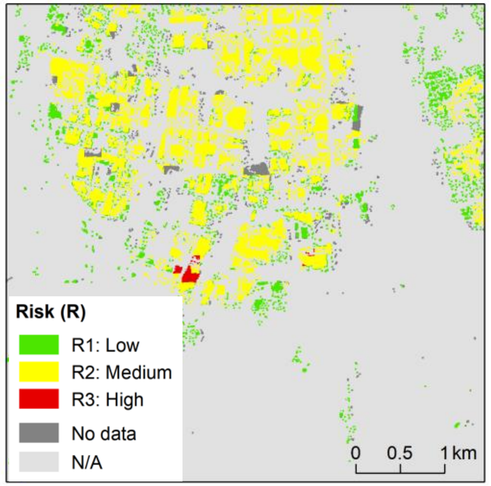
## Geospatial combination of H and EV through a tailored risk matrix

Inputs:
- **Hazard** (H1 to H4)
- **Exposure-Vulnerability** (EV1 to EV4)

Output:
- Risk classes: R1 (low) to R3 (high)
- NoData (no hazard data)
- N/A (unbuilt spaces)




**HAZARD**

| EXPOSURE-VULNERABILITY | H1 | H2 | H3 | H4 |
|---|---|---|---|---|
| EV1 | R1 | R1 | R2 | R2 |
| EV2 | R1 | R2 | R2 | R3 |
| EV3 | R2 | R2 | R3 | R3 |
| EV4 | R2 | R3 | R3 | R3 |

**R1 = low** → Acceptable risk level, no actions

**R2 = medium** → Relevant risk level, potential for structural damage, tailored monitoring is recommended

**R3 = high** → Maximum risk level, high likelihood of occurred/incipient structural damage, site inspections and mitigation measures are recommended at single-infrastructure scale

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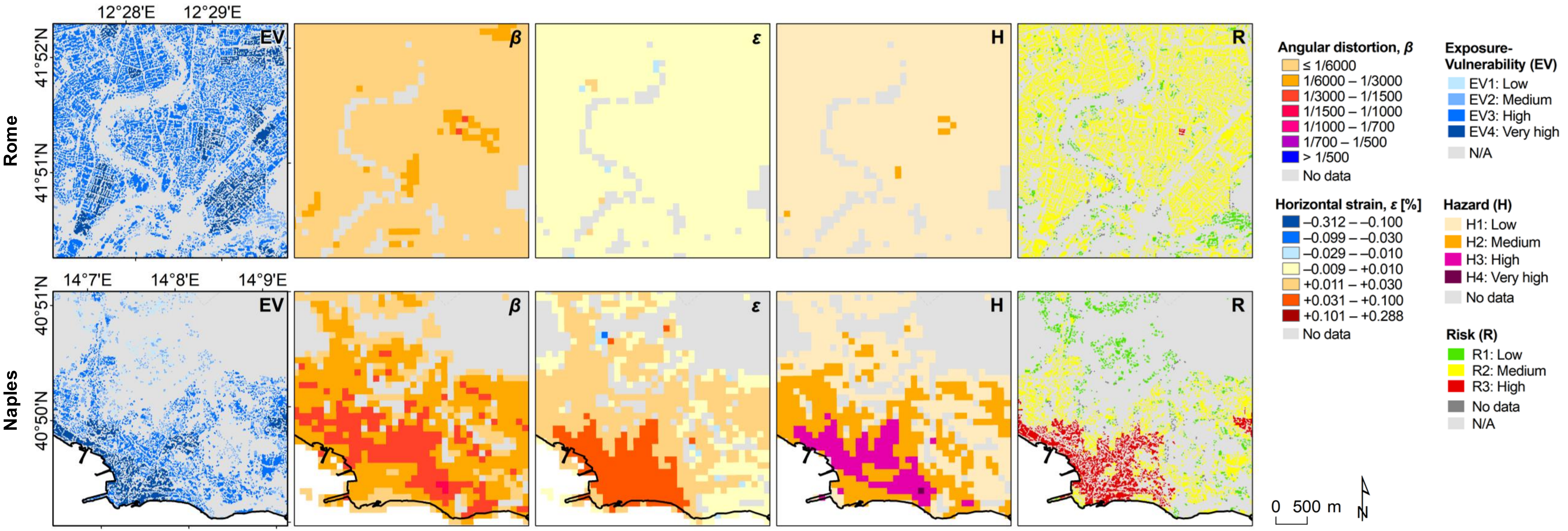
# Data analysis – **RISK (R)**

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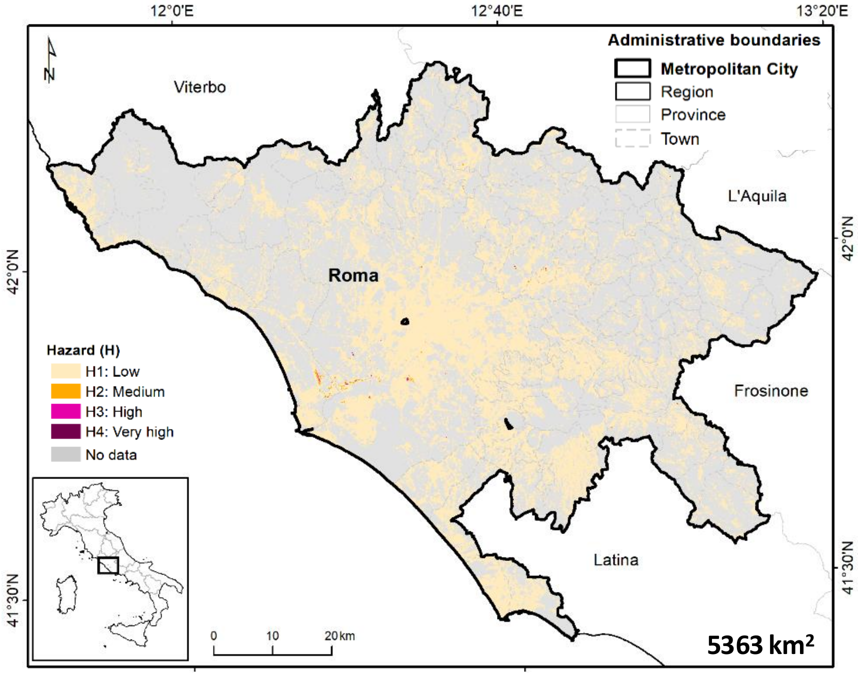
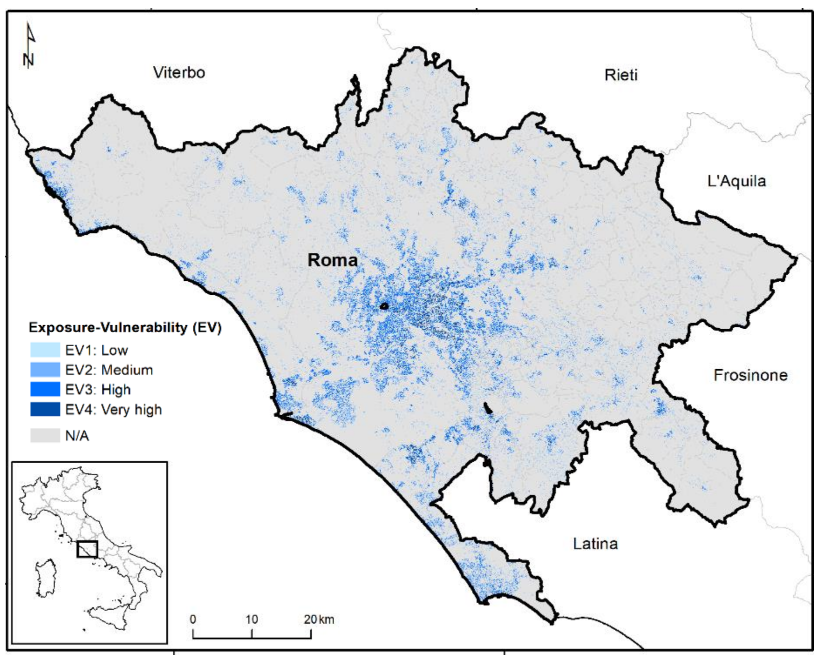
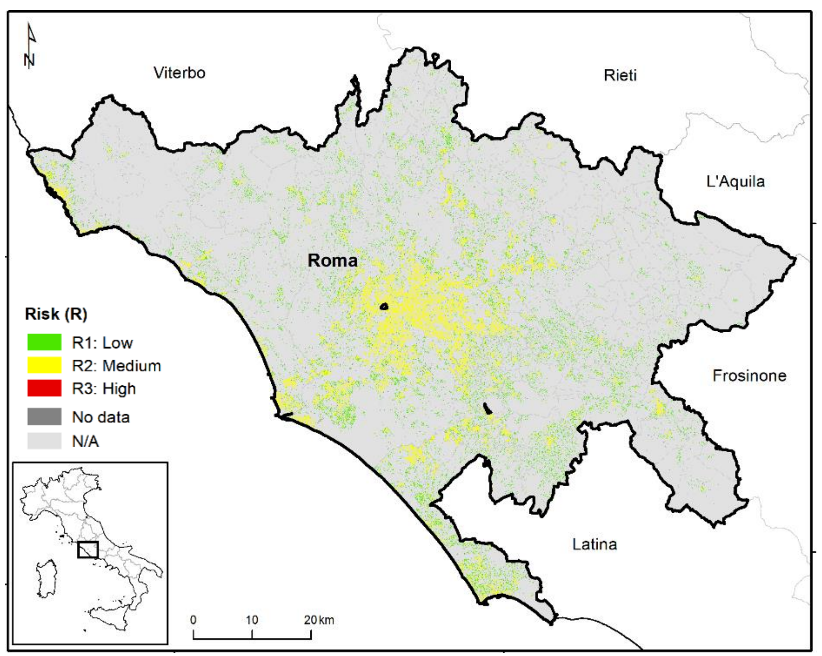
# Metropolitan city of Rome

## Land subsidence-induced hazard due to differential displacement and induced risk for urban infrastructure

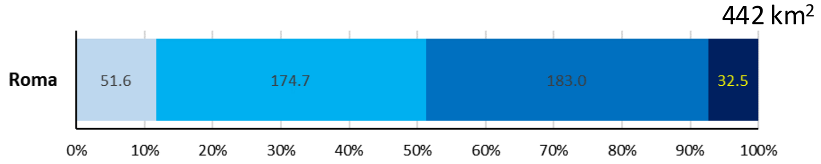


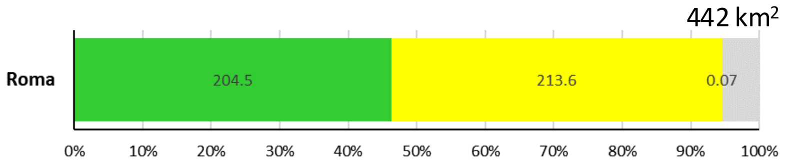




**Hazard classes extent [km²]**


**Exposure-Vulnerability classes extent [km²]**




**Risk classes extent [km²]**

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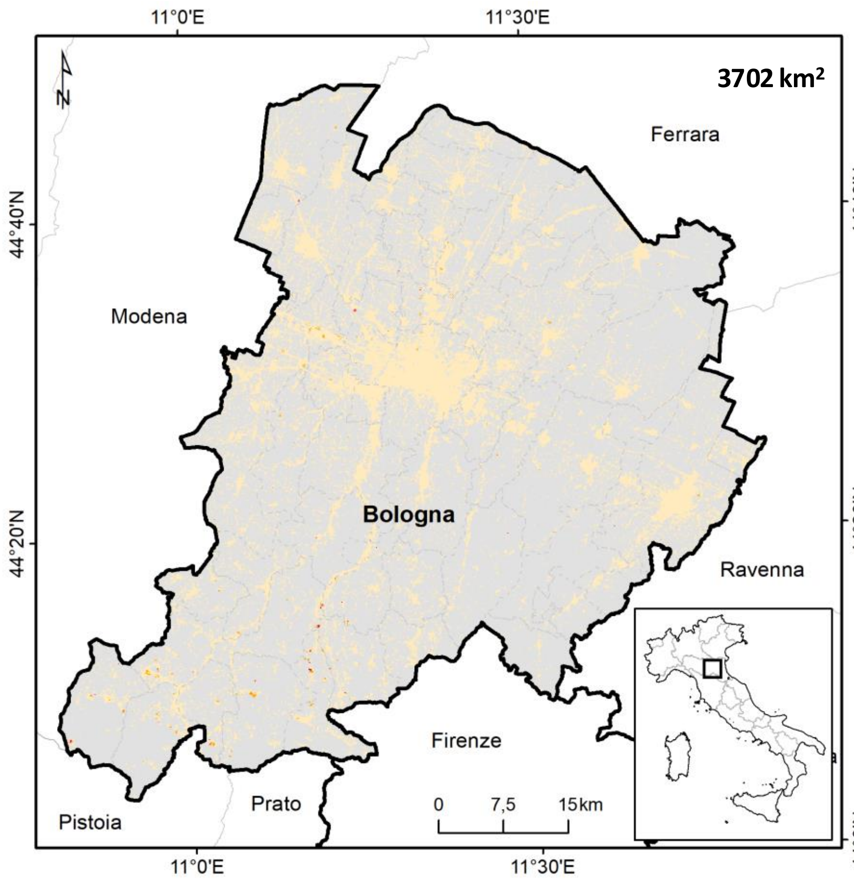
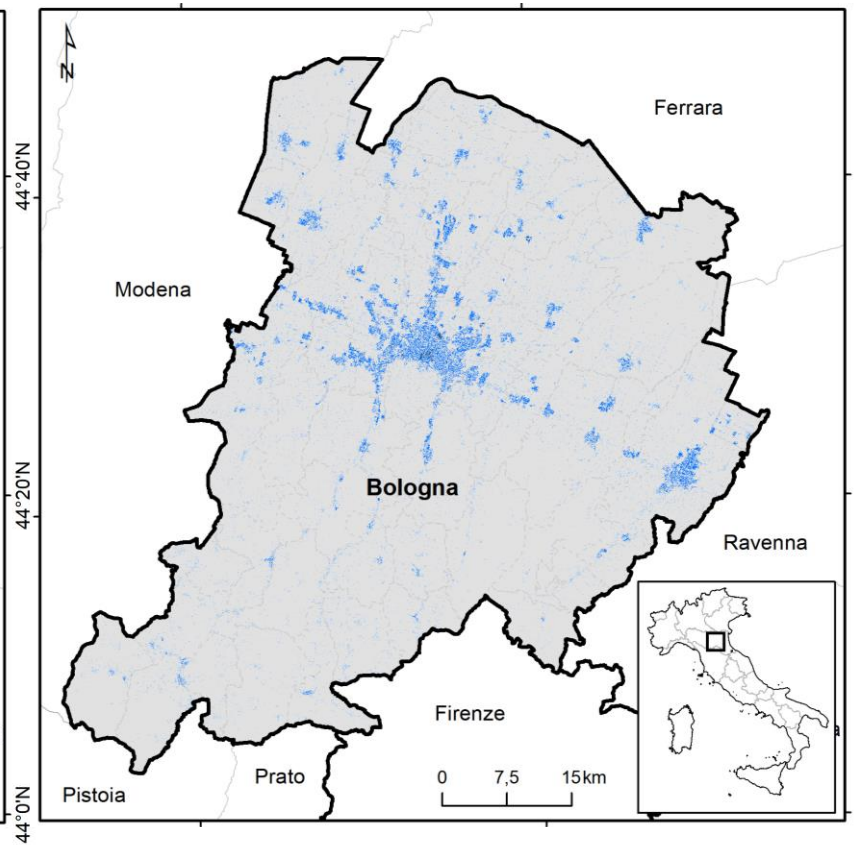
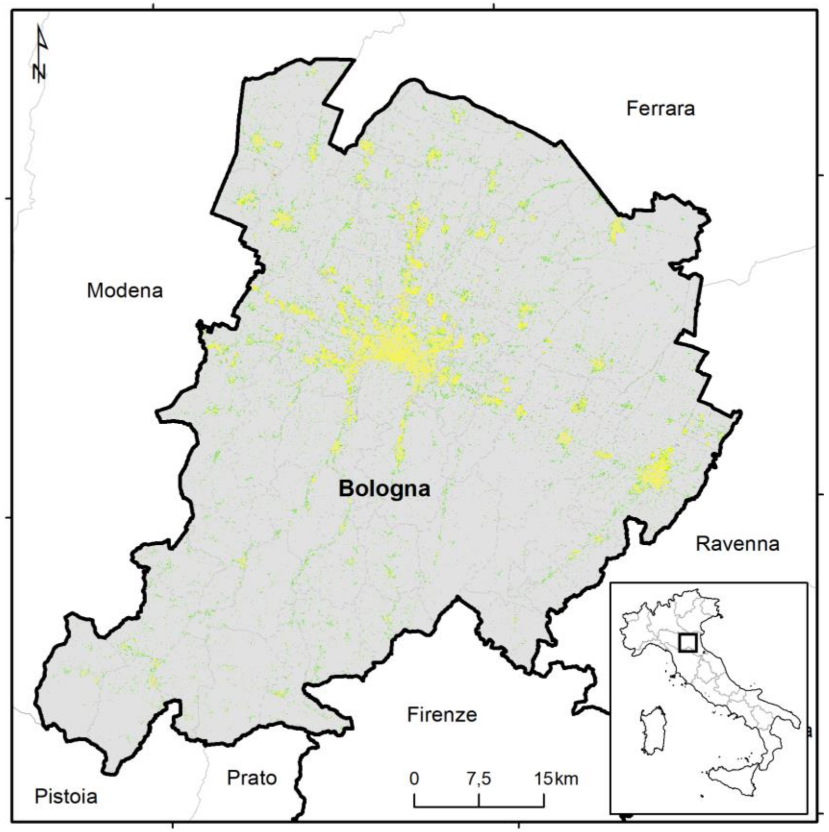
# Metropolitan city of Bologna

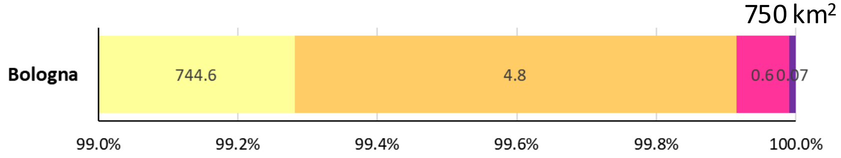
## Land subsidence-induced hazard due to differential displacement and induced risk for urban infrastructure



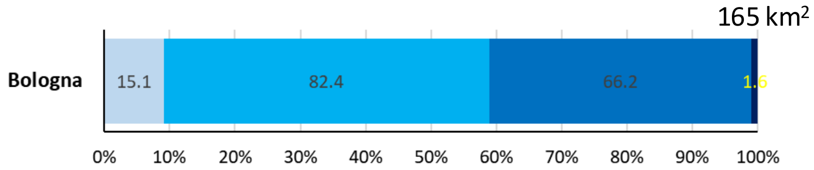



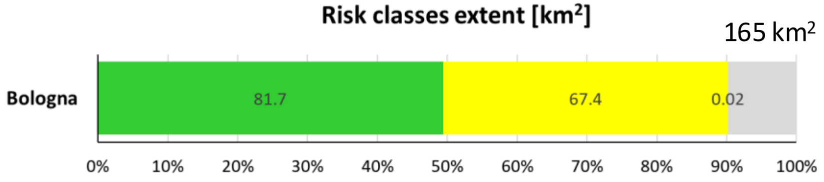

Hazard classes extent [km²]




Exposure-Vulnerability classes extent [km²]




Risk classes extent [km²]



# Overview at the 15 metropolitan cities

**High risk (R3): 1.44 km²  → > 2700 buildings**

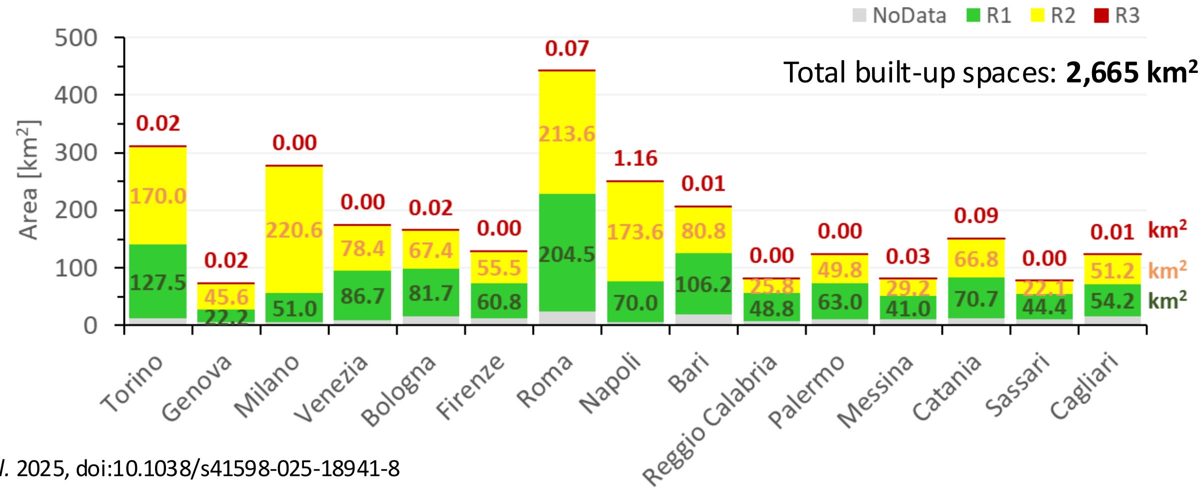
- Narrow sectors with significant $\beta$ (in some cases, an additive threat due to $\varepsilon$) over vulnerable infrastructure
- High likelihood of already occurred/incipient structural damage; site inspections of structural health and mitigation measures are recommended

**Medium risk (R2): 1,351 km² → ~ 2.44 million buildings**

- Potential structural damage might occur at the urban infrastructure involved
- Tailored ground deformation monitoring and derived stress indices is recommended

**Low risk (R1): 1,133 km²  → ~ 2.76 million buildings**

- Acceptable risk level; no specific actions are required




CIGNA *et al.* 2025, doi:10.1038/s41598-025-18941-8

| Metropolitan City | Number of buildings | | | |
|---|---|---|---|---|
| | Total | R1 | R2 | R3 |
| Turin | 733,414 | 410,068 | 323,343 | 3 |
| Genoa | 179,346 | 89,927 | 89,366 | 53 |
| Milan | 429,940 | 121,684 | 308,255 | 1 |
| Venice | 360,661 | 218,347 | 142,314 | 0 |
| Bologna | 286,250 | 175,119 | 111,111 | 20 |
| Florence | 282,671 | 148,901 | 133,770 | 0 |
| Rome | 777,218 | 481,964 | 295,226 | 28 |
| Naples | 363,569 | 125,457 | 236,294 | 1,818 |
| Bari | 349,862 | 246,273 | 103,584 | 5 |
| Reggio Calabria | 224,584 | 170,342 | 54,240 | 2 |
| Palermo | 357,500 | 175,729 | 181,755 | 16 |
| Messina | 270,675 | 168,057 | 102,155 | 463 |
| Catania | 440,943 | 161,409 | 279,202 | 332 |
| Sassari | 59,905 | 37,398 | 22,507 | 0 |
| Cagliari | 85,419 | 33,353 | 52,047 | 19 |
| Total | 5,201,957 | **2,764,028** | **2,435,169** | **2,760** |

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# Future scenarios

**A simple statistical approach that assesses the effects of groundwater withdrawal and changes in climate variables patterns under local climate change based on RCP scenarios**

**GOAL** → To assess future impacts of climate change on land subsidence

**Climate Data**

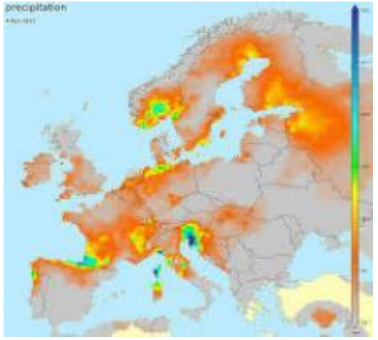
- Historical Reference dataset: E-OBS
  - Spatial resolution: 0.1° x 0.1°
  - Temporal coverage: January 1950 to present
- Regional Climate Models (RCMs): EuroCORDEX
  - European domain: 0.11°x 0.11°
  - Temporal horizon: 2050-2100
  - Scenarios: RCP 4.5 and 8.5

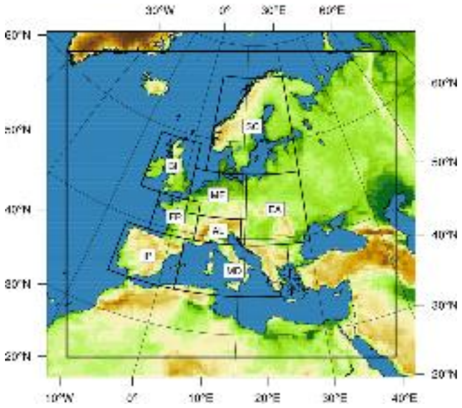
Climate Change Service
climate.copernicus.eu

WCRP CORDEX

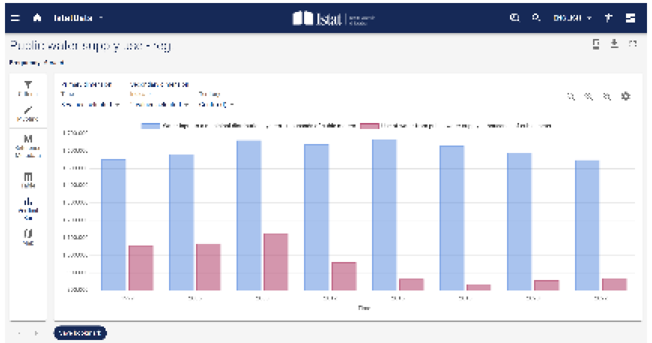
**Other Data**

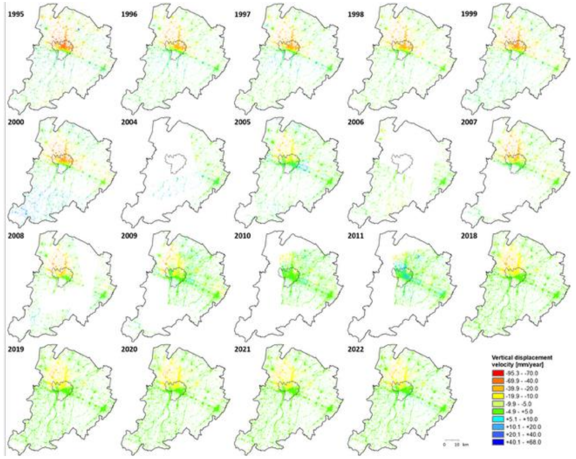
- ISTAT administrative boundaries of the metropolitan cities
- Copernicus EGMS + PST-A InSAR data (L3, ortho, 100 m res.) over 1995–2022
- Groundwater withdrawals (for potable use) over 2008–2024 (ISTAT)



ISTAT public water supply data






Yearly displacement velocity based on PST-A & EGMS InSAR

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SubRISK+

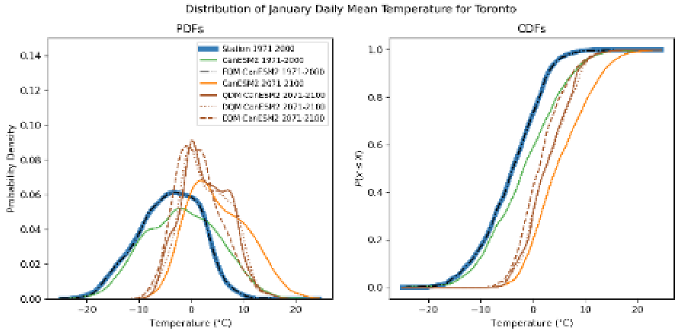
# Future scenarios

## Future Climate Scenario Generation

- Selection of different RCM simulations nested into GCMs are considered to reduce the modelling uncertainties
- Bias Correction Approach (Quantile Mapping)
- Equifeasible Ensembles of Predictions

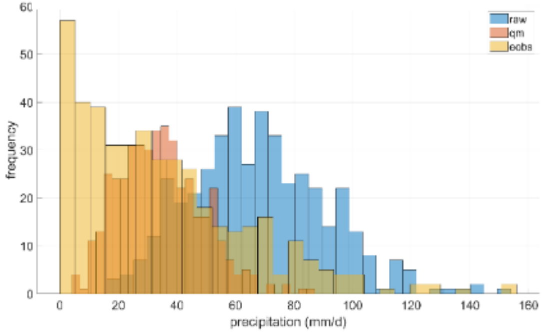
RCMs nested into GCMs selected for this study

| RCM | GCM | | |
|---|---|---|---|
| | CNRM-CM5 | ICHEC- EC-EARTH | MPI-ESM-LR |
| HIRHAM5 | | x | |
| RACMO22E | | x | |
| RCA4 | x | x | x |
| CCLM4-8-17 | | x | x |




Example of Quantile Mapping application

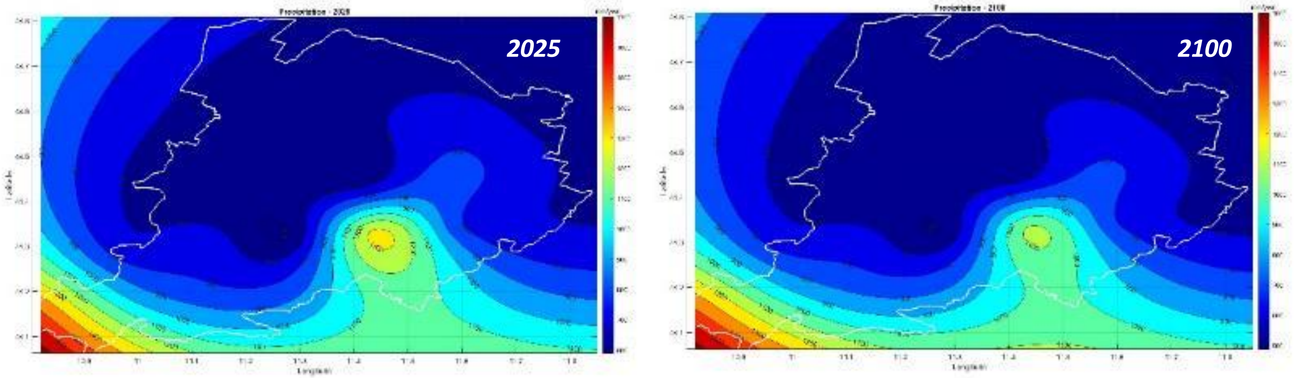
*Bias-corrected pr 1970-2100 RCP8.5*




**PDF pre and post bias-correction using quantile mapping**

## Gridded predictors (pr, tas, et) interpolation

- CRS Reprojection to match EGMS grid
- “Linear” interpolation in the ROI + fallback “nearest” interpolation for missing values in edge regions
- Loop over each time step and interpolate the climate data onto the EGMS grid




**Bias-corrected precipitation in 2025 and 2100 under RCP8.5**

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# Future scenarios

### Linear/polynomial regression with LOOCV

- Every year is used for both training and validation
- Unbiased performance useful when you want to assess model reliability without overfitting
- Evaluation of model robustness (RMSE, Pearson coefficient, $R^2$)

### Extrapolated prediction up to 2050-2100

- Predicting land subsidence every between 2023 and 2050-2100 based on the regression model
- Three water withdrawal (ww) scenarios:
  - +1% increase per year
  - -1% decrease per year
  - historical-trend based scenario

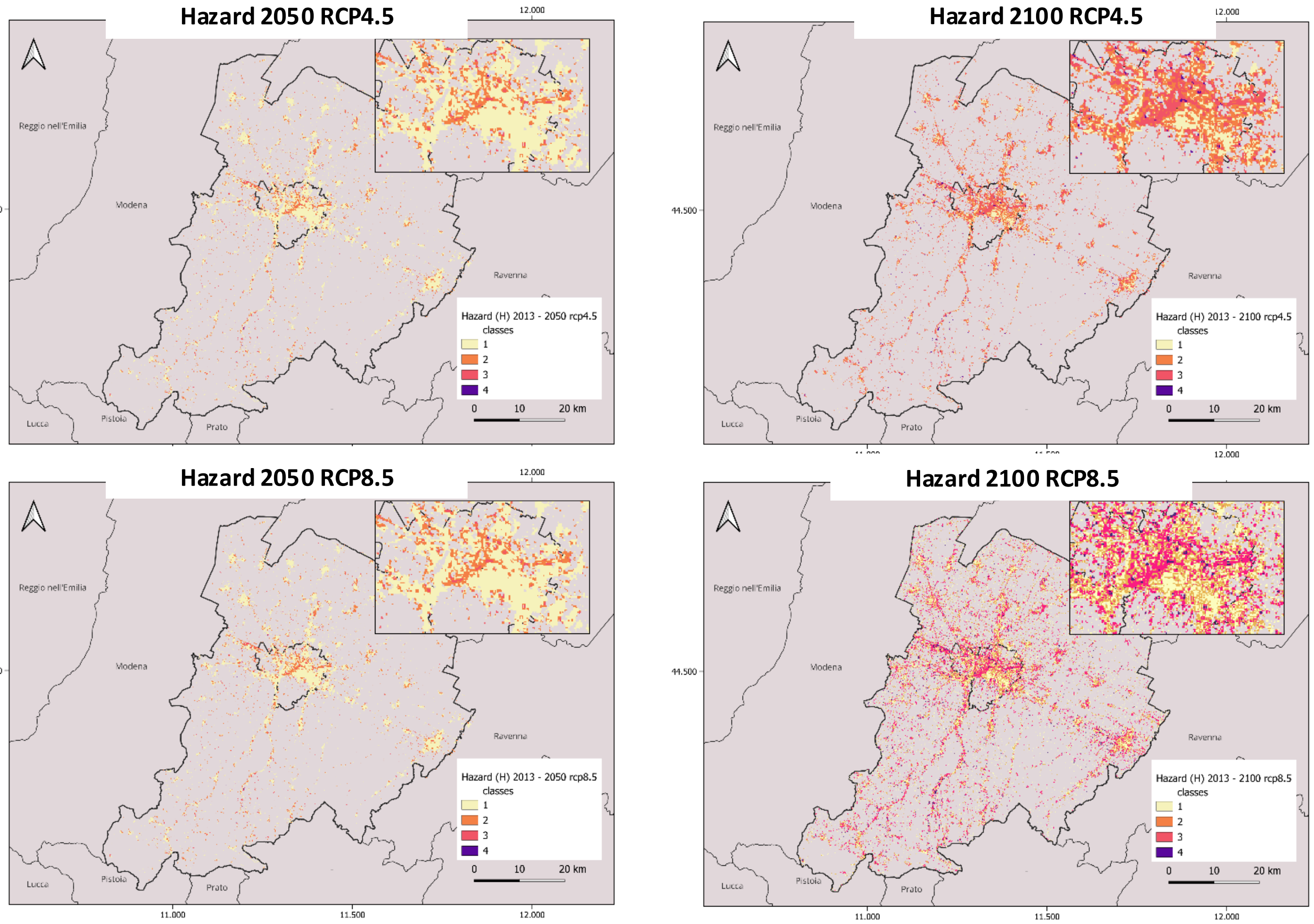
**Hazard Assessment**

***R****isk* = ***Hazard*** *x* ***E****xposure x* ***V****ulnerability*

2050 | 2100

RCP 4.5

RCP 8.5




Scenario ww – historical trend

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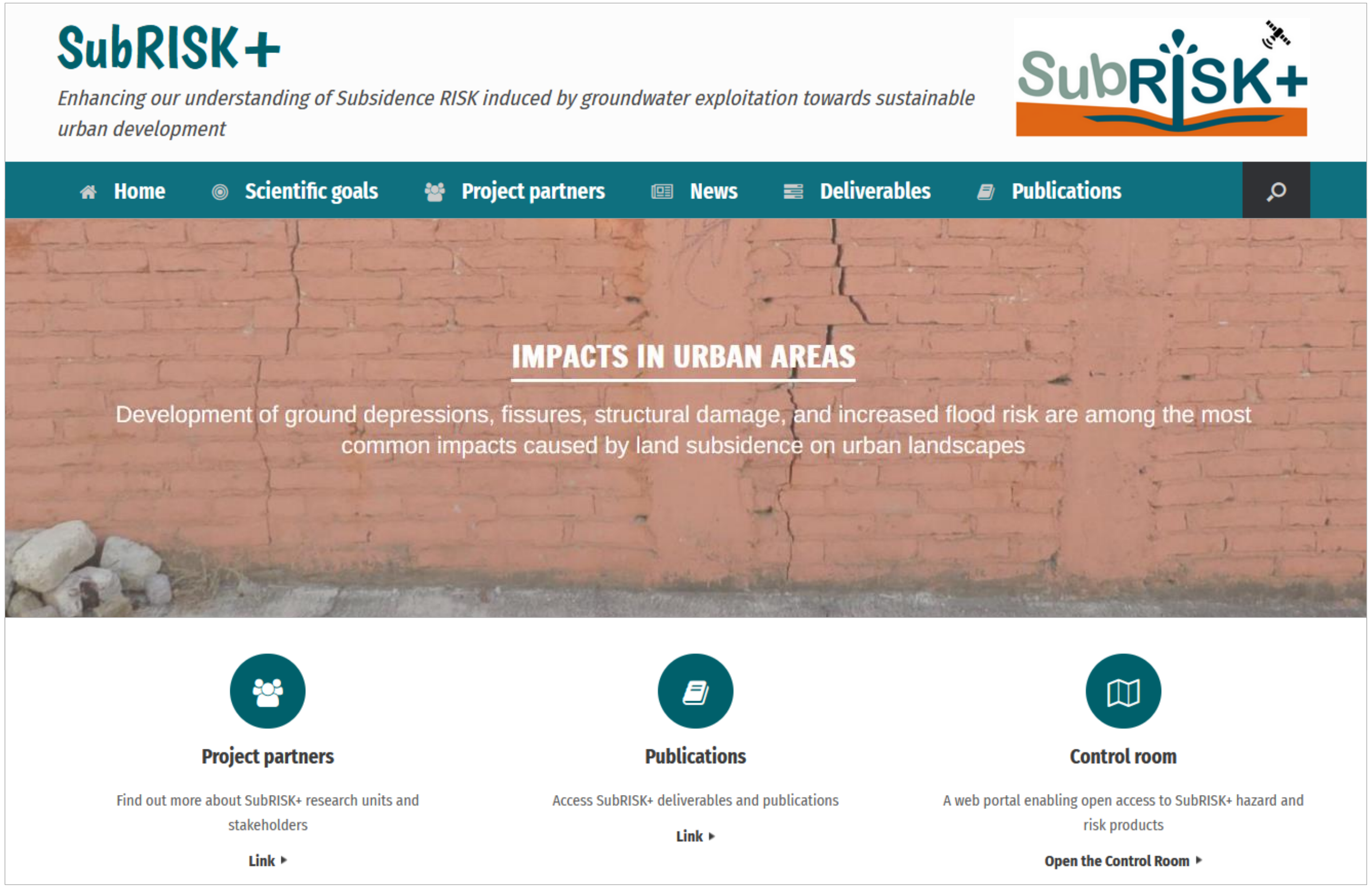
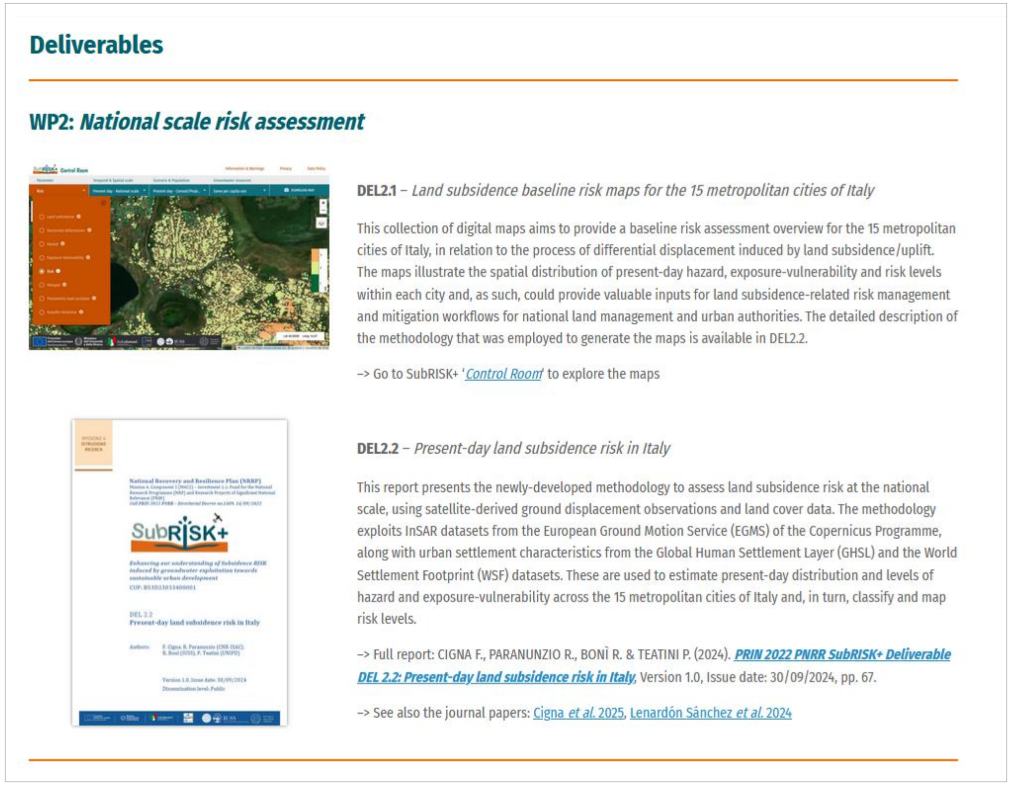
# Project website




https://www.subrisk.eu/

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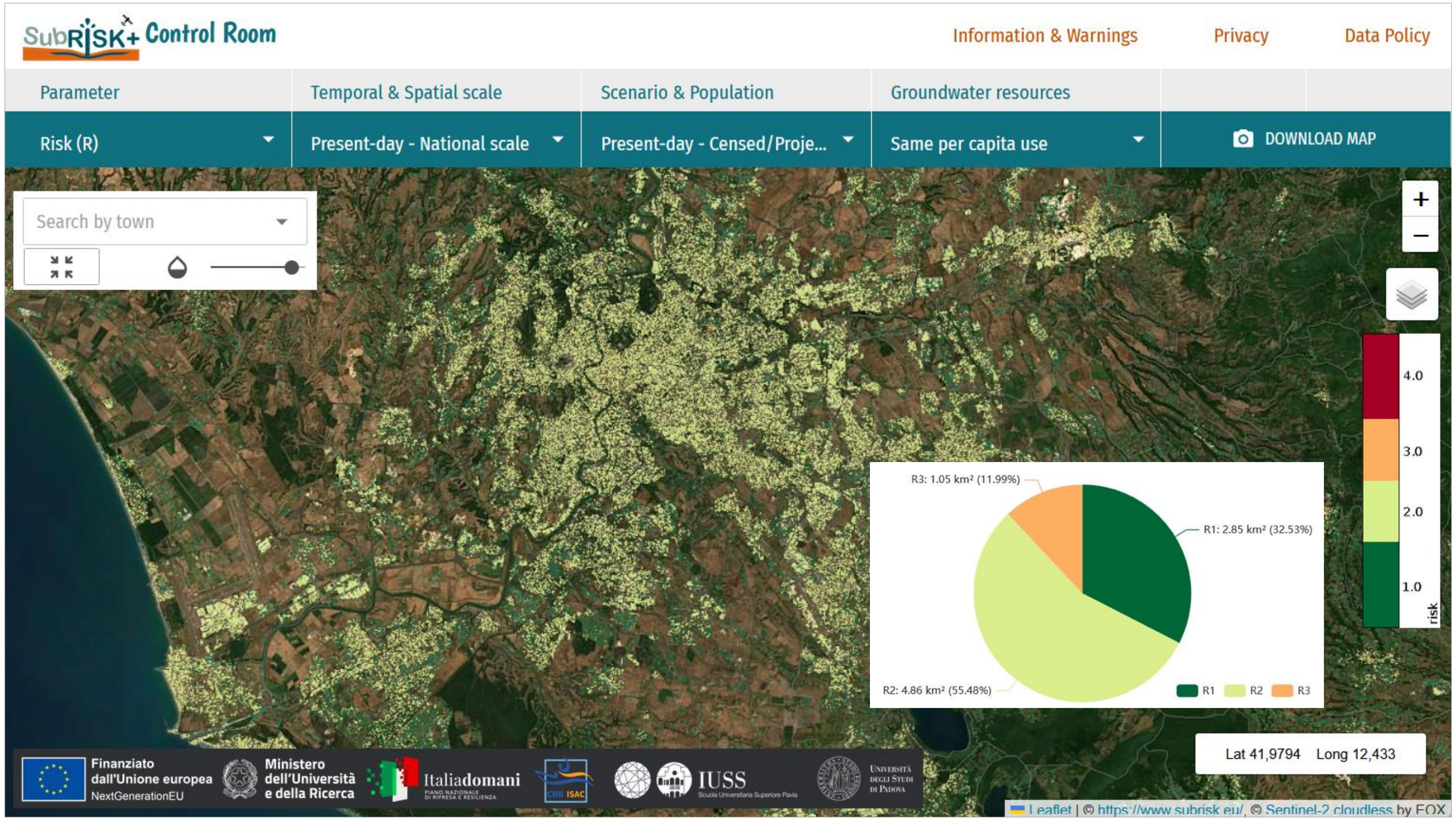
# "Control Room"




A **webGIS** enabling the simulation of future land subsidence risk and impacts by modifying climate, demographic and behavioral factors involved in groundwater availability and exploitation rates

**Land subsidence baseline hazard and risk maps for the 15 metropolitan cities of Italy**

***now available** in*

***** SubRISK+ Control Room *****

https://controlroom.subrisk.eu/

# Conclusions & future perspectives

- The **exposure** of urban land and population to the land subsidence process, ground deformation and its associated **hazard**, and the resulting **risk** to urban infrastructure were investigated
- A reference knowledge-base on **present-day land subsidence risk** to urban infrastructure across the 15 metropolitan cities was developed using the novel InSAR-based workflow
- The work acts as **a baseline for future assessments** to build upon with a look to the next decades and sustainable urban development

- The method **exploits standardised, validated and open EU/global datasets** and, as such, can be exported to other metropolises and countries worldwide
- The risk assessment workflow is to be considered alongside warnings associated with its input datasets and **technical assumptions** (see Cigna *et al.* 2025 paper)

European Ground Motion Service

GHSL - Global Human Settlement Layer

- The work delivers **a significant step forward** from displacement velocity-based approaches that are nowadays common in the literature, **to actionable risk information layers** that are still rare
- The risk mapping outputs have the potential to be **embedded into the risk management and mitigation workflows** of stakeholders, such as those involved in SubRISK+, who contributed to tailor the approach at the regional scale

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# SubRISK+ Key references


OPEN ACCESS


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