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Present-day differential land subsidence risk in the metropolitan cities of Italy

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

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)

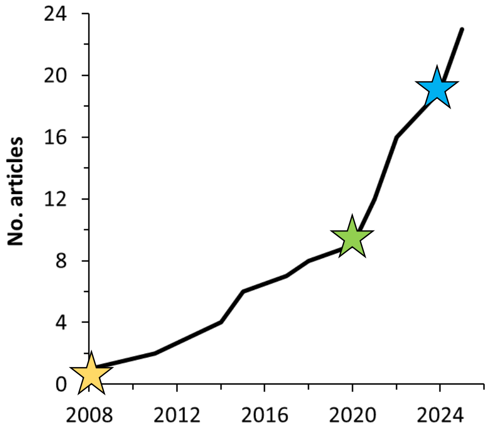
www.subrisk.eu

@SubriskEu

Scientific goals

<u>Trending topic in the InSAR literature</u>

**** 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 <u>hazard</u>

InSAR-based risk assessment workflows based on <u>risk</u> matrices

<u>Exposure</u> 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

→ **<u>Innovating the risk assessment workflow</u>** 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 **<u>land subsidence-induced risk in Italy</u>**, one of the world countries most affected by ground deformation processes

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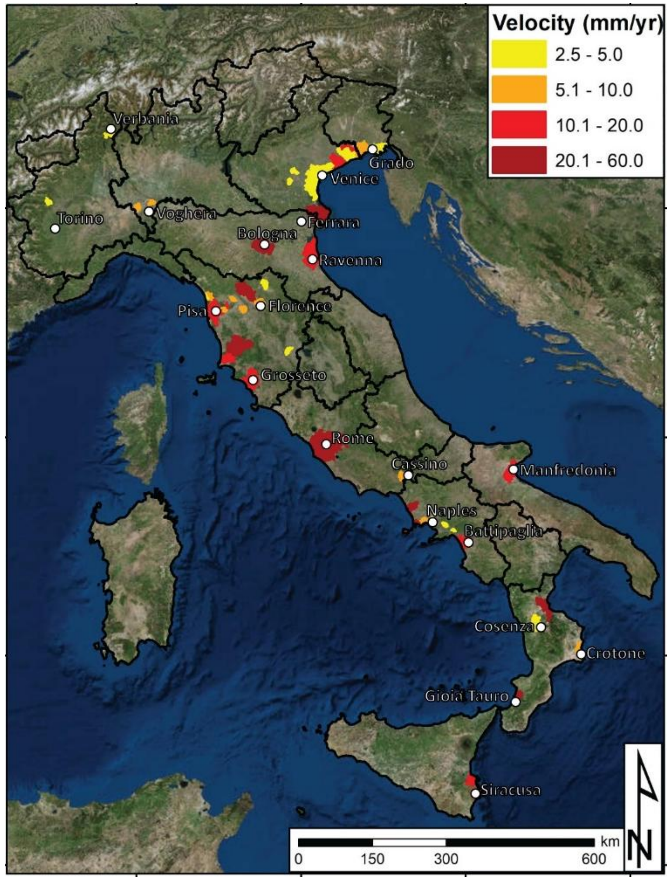
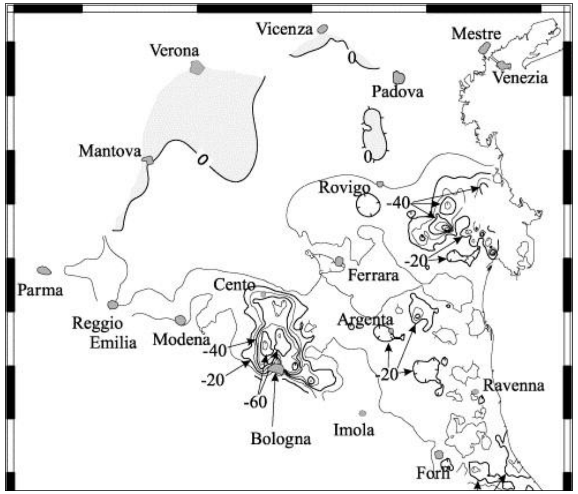
Land subsidence in Italy



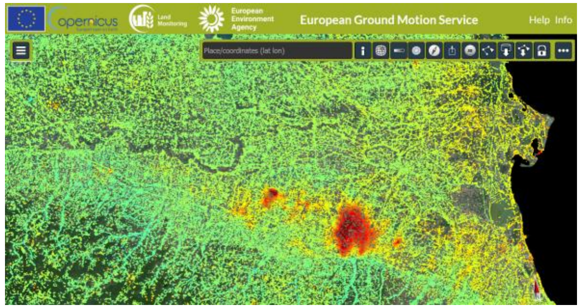
SOLARI *et al.* 2018, doi:10.3389/feart.2018.00149

Po Plain

CARMINATI & MARTINELLI 2002, doi:10.1016/S0013-7952(02)00031-5

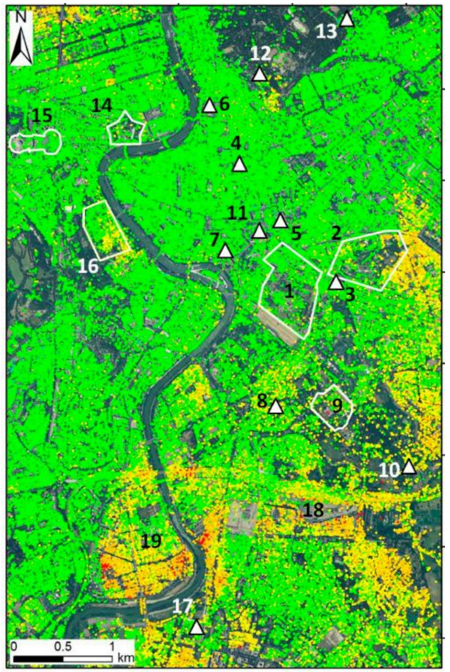


Copernicus European Ground Motion Service (EGMS)



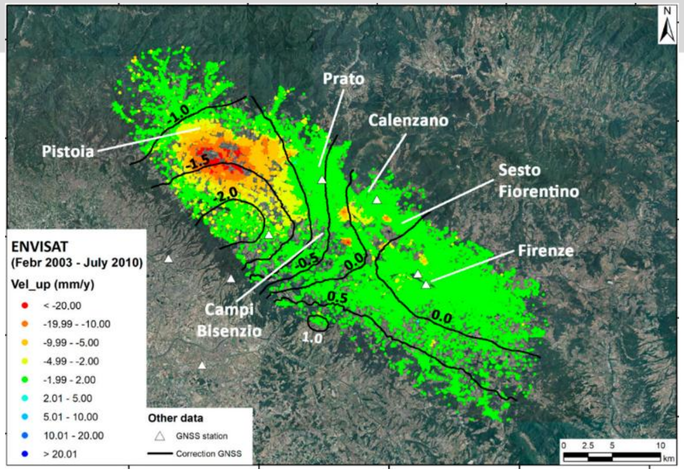
Rome & Tiber River Plain

CIGNA *et al.* 2014, doi:10.3390/rs61212593



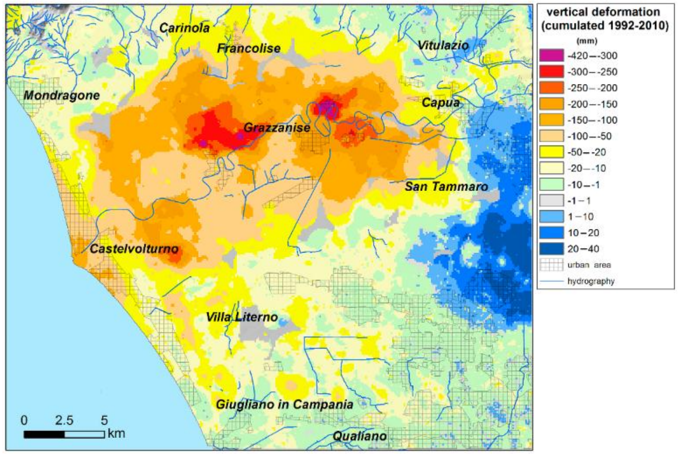
Florence-Prato-Pistoia Plain

DEL SOLDATO *et al.* 2018, doi:10.3390/rs10071146



Volturno Plain

MATANO *et al.* 2018, doi:10.3390/geosciences8010008



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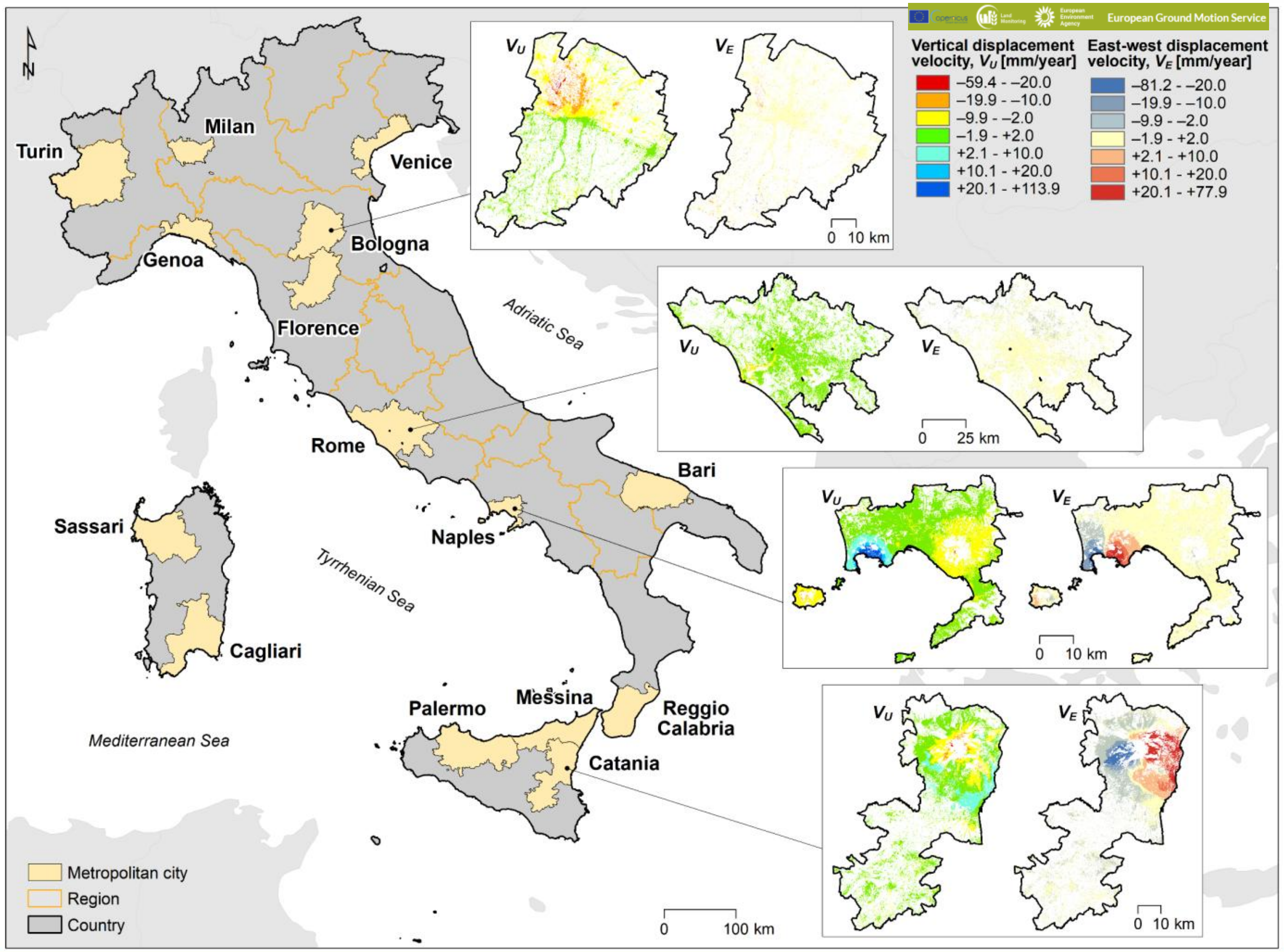
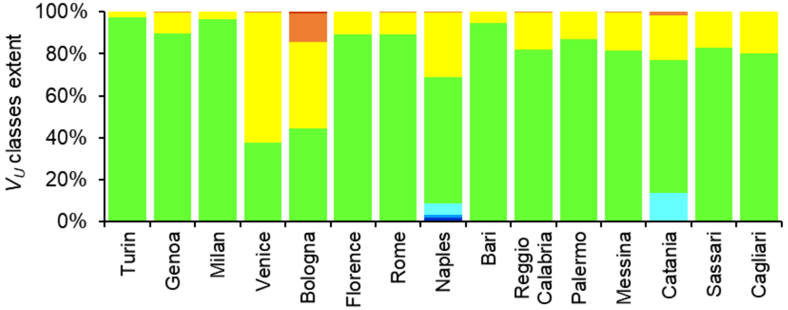
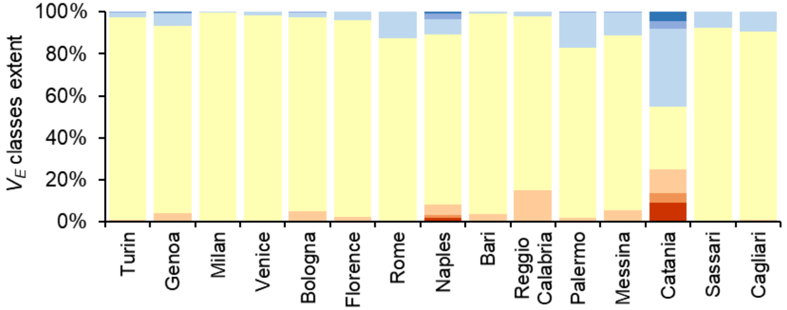
Urban land and population exposed



AOI: **15 metropolitan cities** (54,380 km², hosting > 21.7 M inhab., out of 59 M in Italy)



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%)



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%)

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

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Ground displacement-induced risk

Risk = Hazard x Exposure x Vulnerability

expected loss from a given natural hazard

Hazard: probability of occurrence of a potentially impacting phenomenon

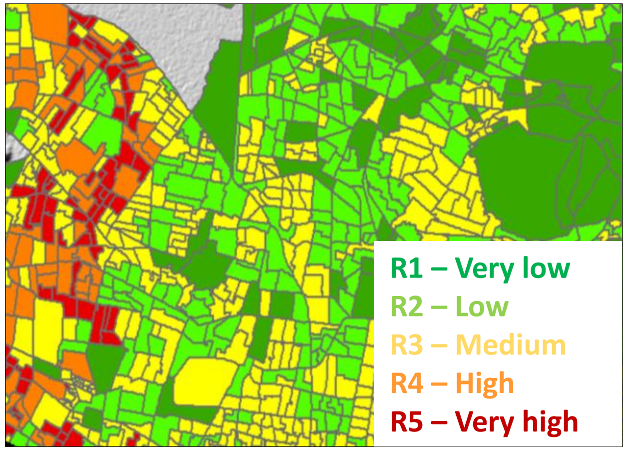
Exposure: location, attributes and value of the assets that could be affected

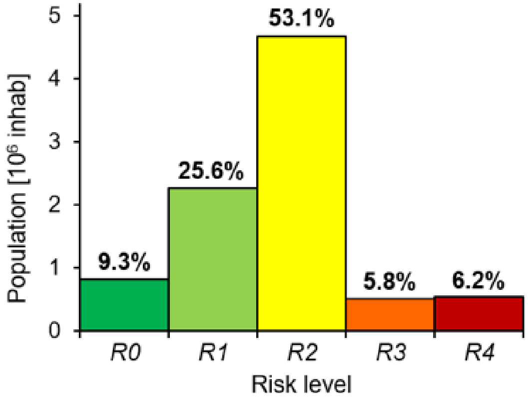
Vulnerability: likelihood that the assets will be affected when exposed to the hazard

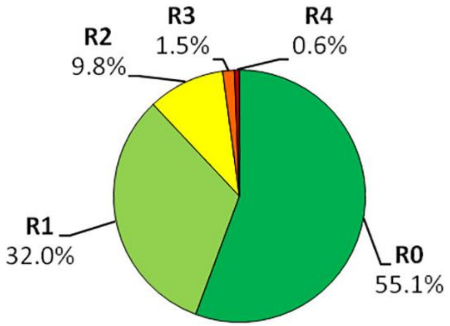
Risk matrix

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

Data analysis – **HAZARD (H)**

Impacts of differential ground displacement
Some examples from Central Mexico

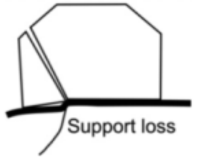
Unlevel sinking and undulating rooflines
(www.sciencemag.org)

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)

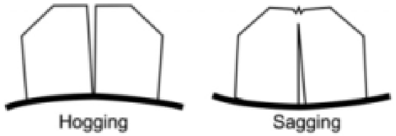


$$\beta = \frac{\Delta d_{Ui}}{l}$$

Δd_{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)



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

Δd_{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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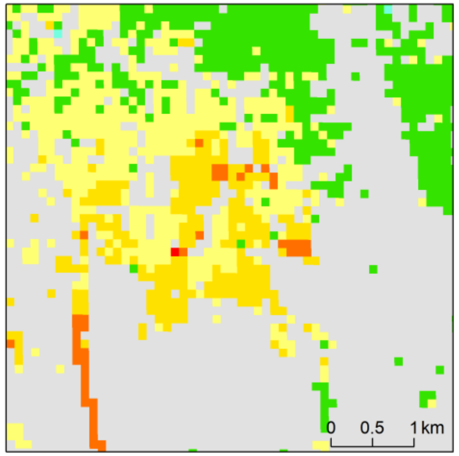
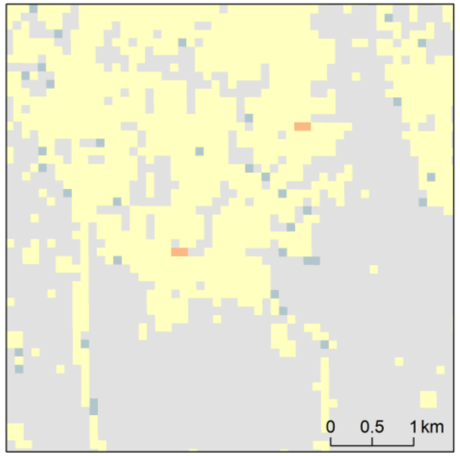
SubRISK+ Data analysis – **HAZARD (H)**

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

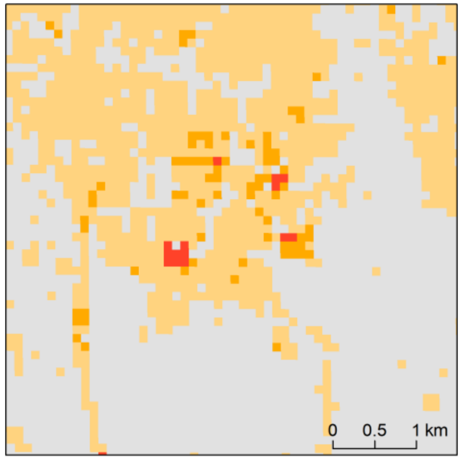


East-west displacement velocity 2018-2022 [mm/year]

- -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

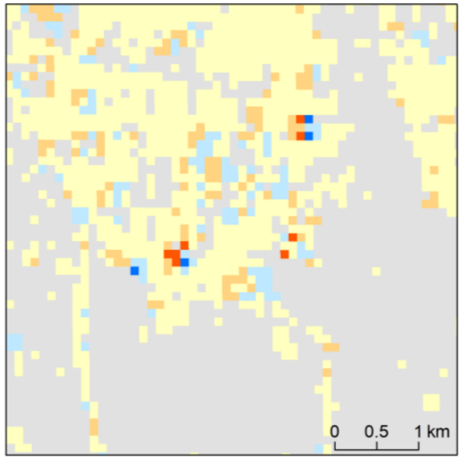
Copernicus Europe's eyes on Earth
Land Monitoring Service

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



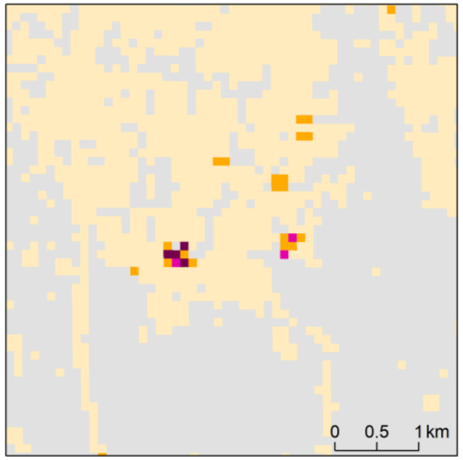
Total horizontal strain [%] 10 years

- -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: $\lvert\varepsilon\rvert < 0.03\%$	Total horizontal strain: $\lvert\varepsilon\rvert \geq 0.03\%$
$\beta \leq 1/3000$	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

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

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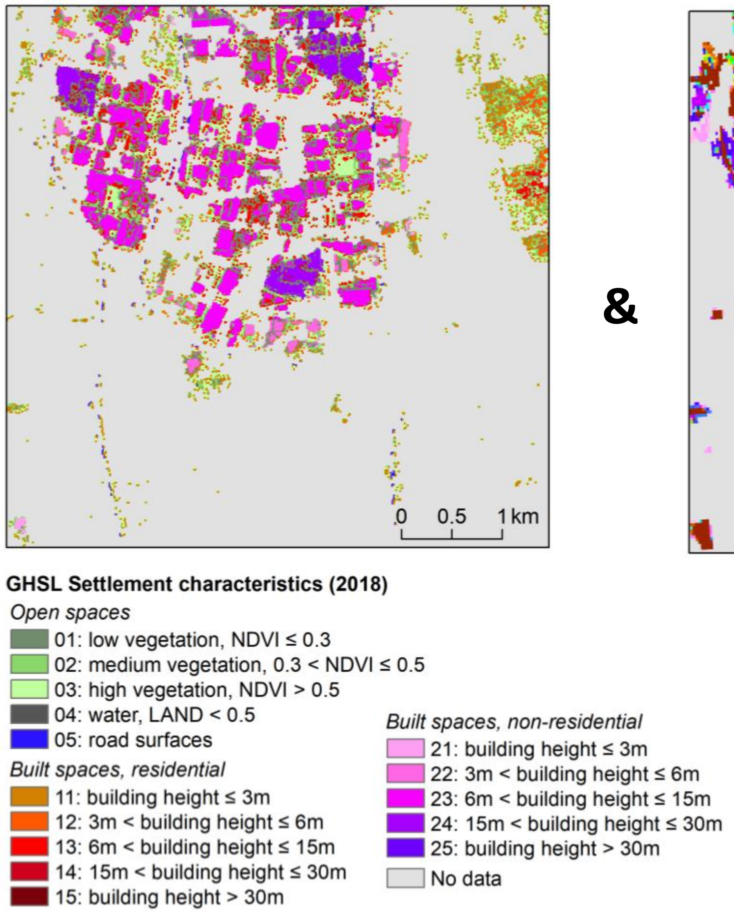
Data analysis – **EXPOSURE-VULNERABILITY (EV)**

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



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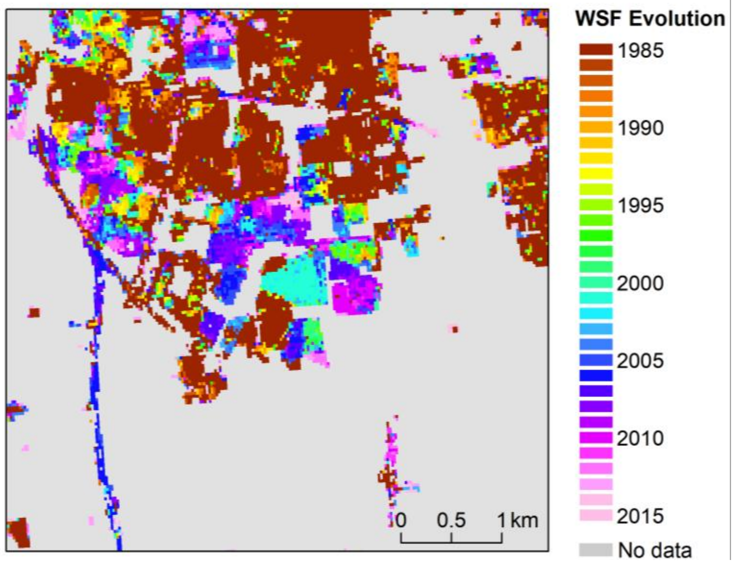
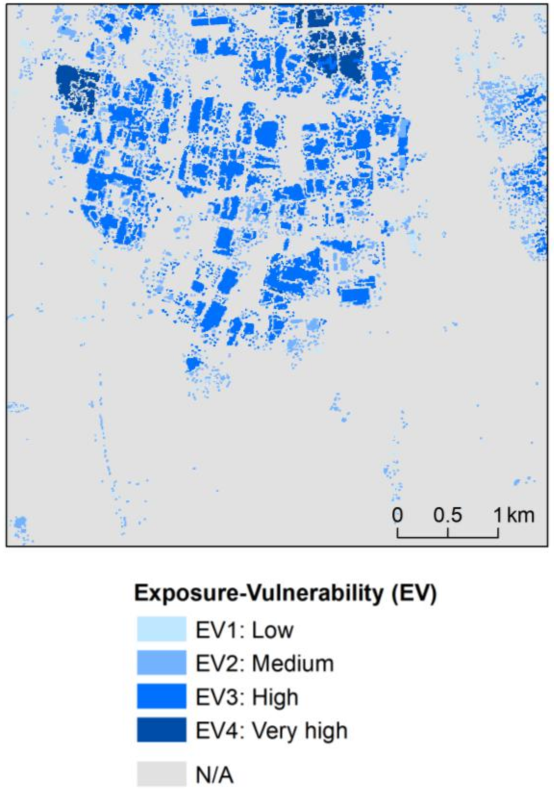


Resulting Exposure-Vulnerability (EV) scoring



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

Data analysis – **RISK (R)**

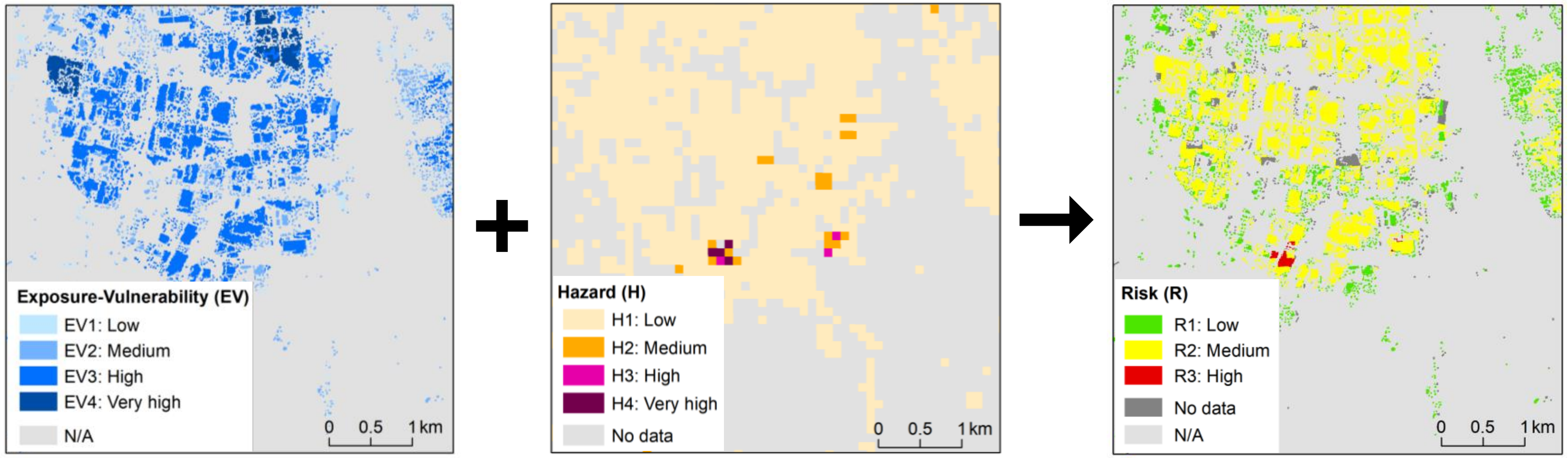
Geospatial combination of H and EV through a tailored risk matrix

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

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

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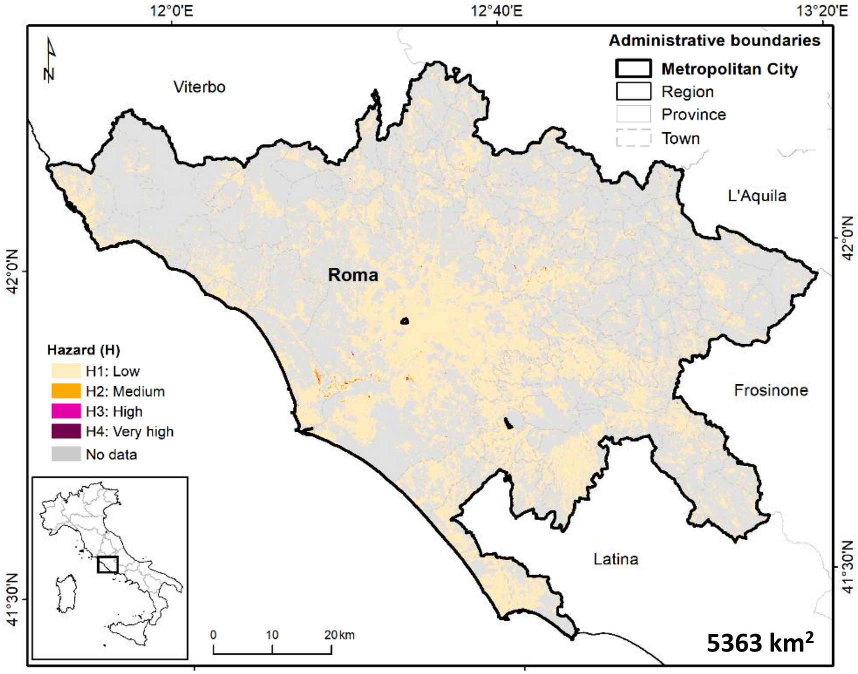
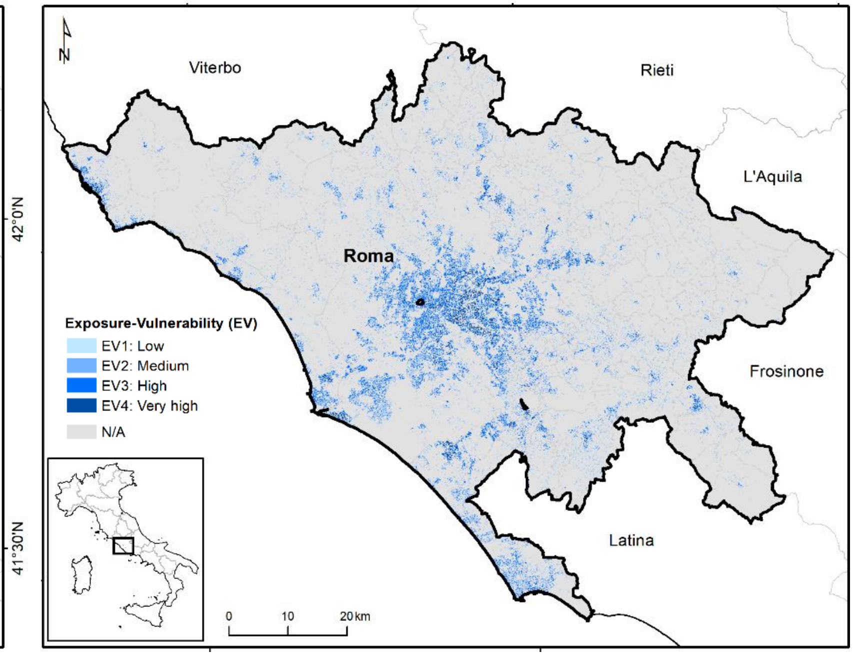
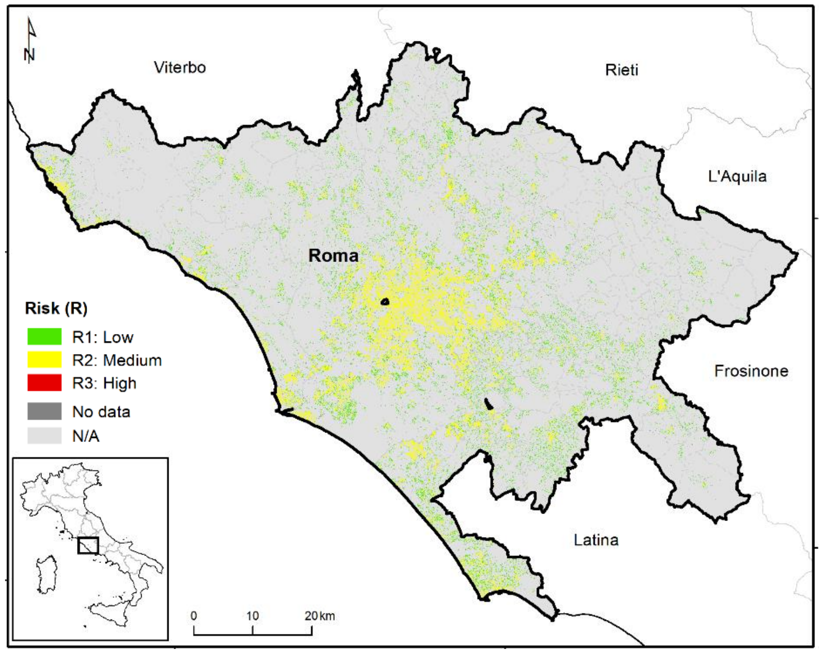
Metropolitan city of Rome

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

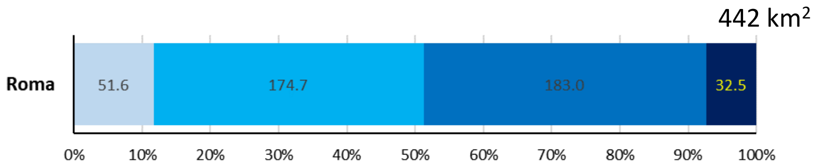




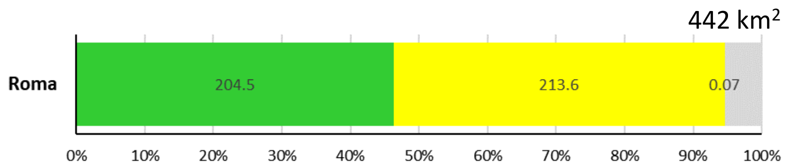


Hazard classes extent [km²]

Exposure-Vulnerability classes extent [km²]



Risk classes extent [km²]



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Overview at the 15 metropolitan cities

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

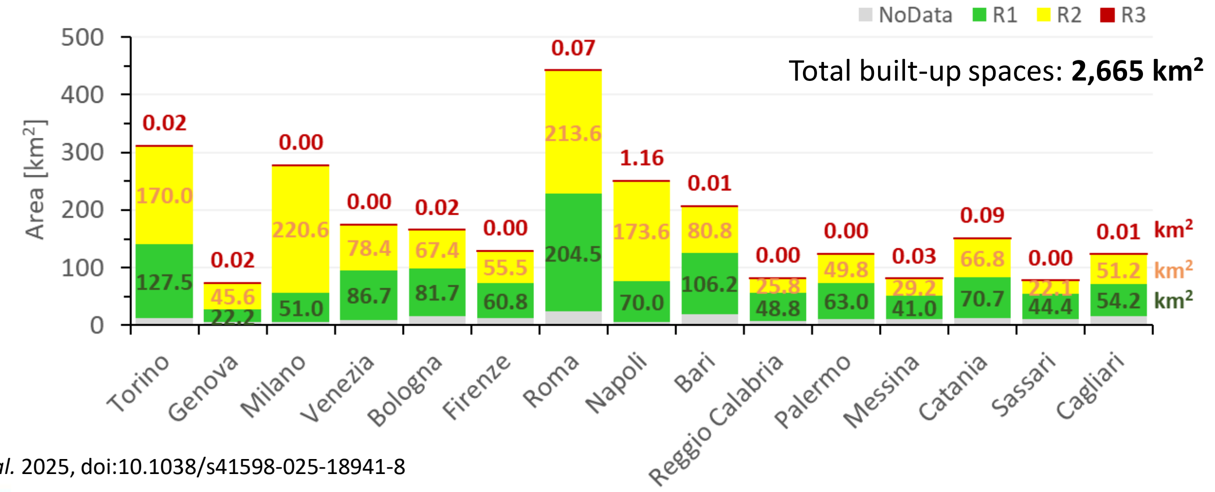
- Narrow sectors with significant *β* (in some cases, an additive threat due to *ε*) over vulnerable infrastructure
- High likelihood of already occurred/incipient structural damage; site inspections of structural health and mitigation measures are recommended

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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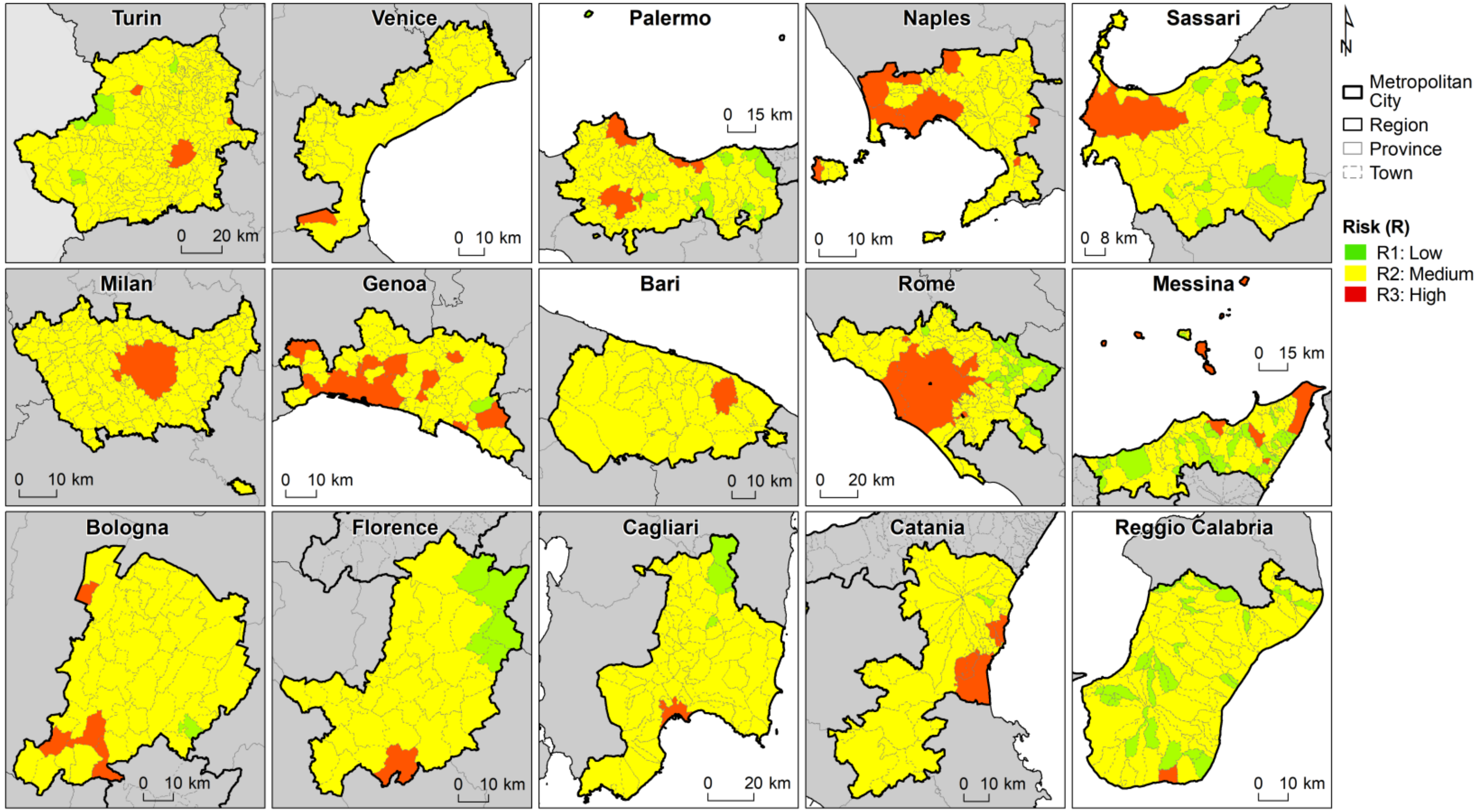
Overview at the 15 metropolitan cities



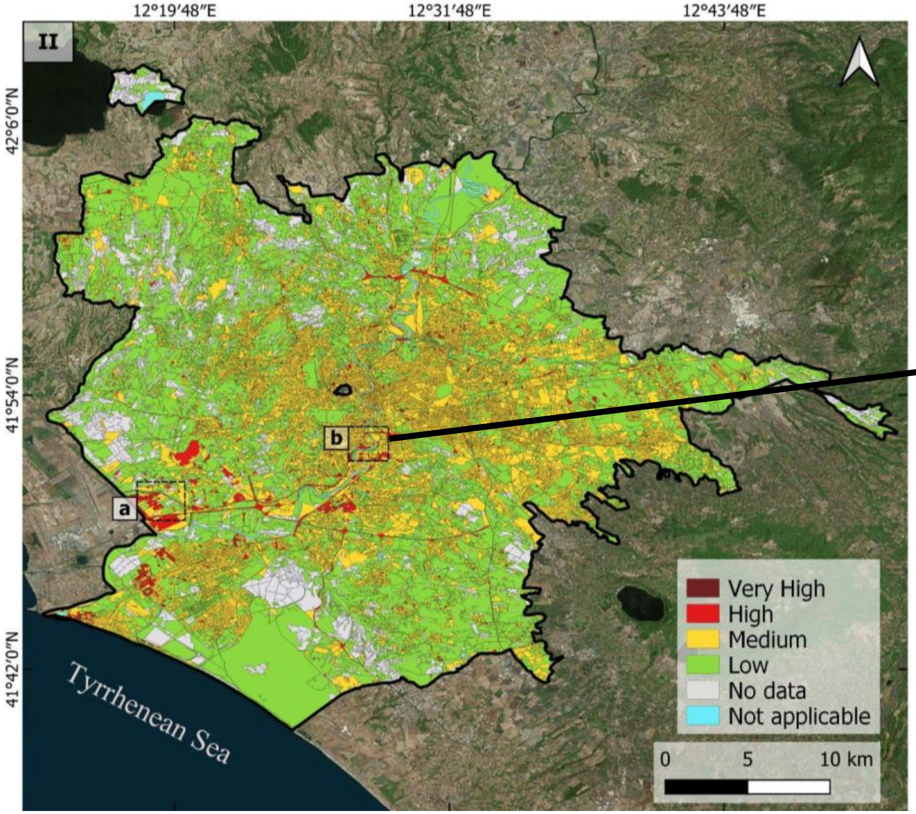
Maximum ground deformation-induced risk at municipality scale within the Italian metropolitan cities

Municipalities split based on the maximum H and R observed within their administrative land

Metropolitan City	Number of municipalities							
	Tot	*H1*	*H2*	*H3*	*H4*	*R1*	*R2*	*R3*
Turin	312	217	63	23	9	9	300	3
Genoa	67	19	28	14	6	1	57	9
Milan	133	112	19	2	0	0	132	1
Venice	44	24	13	7	0	0	43	1
Bologna	55	13	24	16	2	1	50	4
Florence	41	12	20	8	1	5	35	1
Rome	121	72	30	17	2	33	84	4
Naples	92	53	26	10	3	0	85	7
Bari	41	14	17	9	1	0	40	1
Reggio Calabria	97	31	40	24	2	25	71	1
Palermo	82	20	38	20	4	9	70	3
Messina	108	67	27	9	5	36	67	5
Catania	58	17	24	12	5	1	51	6
Sassari	66	42	19	5	0	12	53	1
Cagliari	72	28	32	12	0	3	68	1

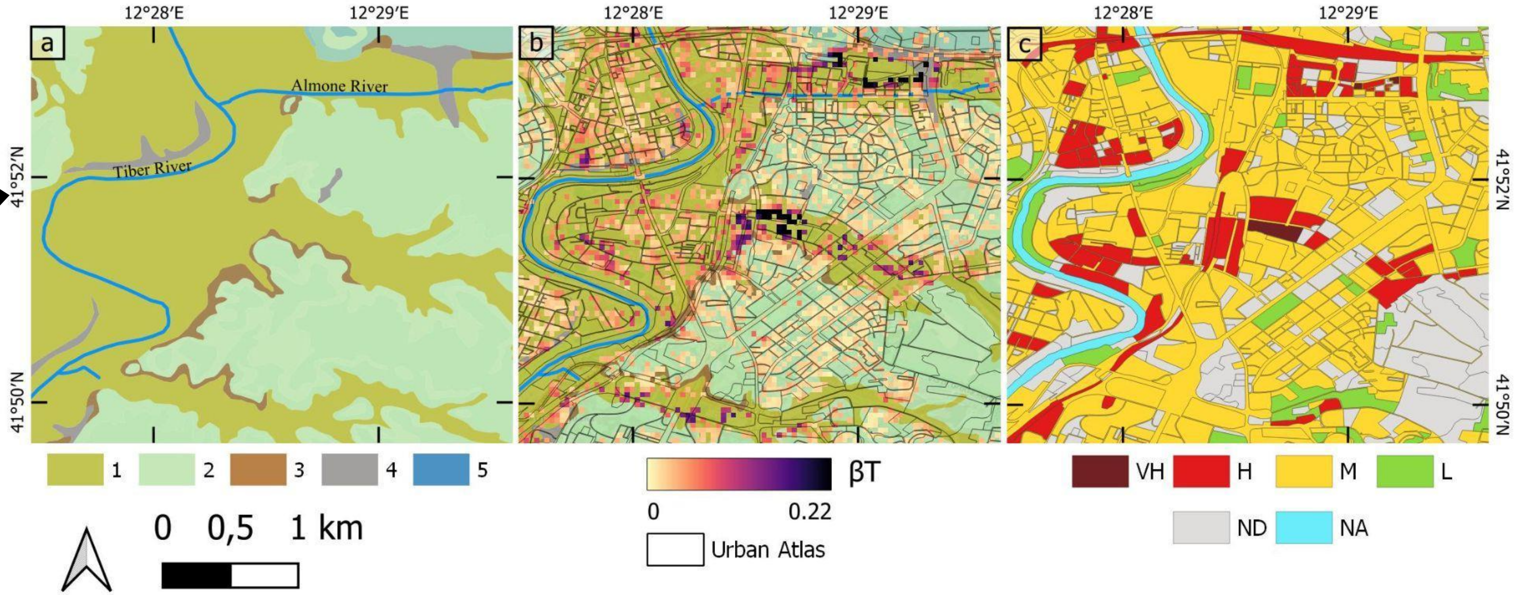
CIGNA *et al.* 2025, doi:10.1038/s41598-025-18941-8

SubRISK+ Multi-decadal city-scale risk assessment in Rome



LENARDON SANCEZ *et al*. 2024, doi:10.3390/land13122103

Combined exploitation of **Copernicus EGMS Sentinel-1** and the Italian **Extraorinary Plan for Remote Sensing** (ERS-1/2, ENVISAT, COSMO-SkyMed) data to derive the total angular distortion <u>cumulated in 1992-2022</u>, and exploiting **Copernicus Urban Atlas**-based exposure vulnerability



Correlation between lithology, subsidence and risk: (a) <u>Lithology</u>: 1, alluvial fan deposits; 2, pozzolana; 3, marginal sandy facies; 4, anthropogenic deposits; 5, river; (b) <u>Total angular distortion</u>; and (c) <u>Risk map</u>

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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

European Ground Motion Service

WORLD SETTLEMENT FOOTPRINT

GHSL - Global Human Settlement Layer

- 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)

- 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 (see Bonì *et al.* talk)

Regione Emilia-Romagna

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Key references


Statistical and Independent Component Analysis of Sentinel-1 InSAR Time Series to Assess Land Subsidence Trends

Multi-Decadal Land Subsidence Risk Assessment at Major Italian Cities by Integrating PSInSAR with Urban Vulnerability

scientific reports

Present-day land subsidence risk in the metropolitan cities of Italy

OPEN ACCESS

CIGNA F., PARANUNZIO R., BONÌ R., TEATINI P. 2025. **Present-day land subsidence risk in the metropolitan cities of Italy**. *Scientific Reports*, 15, 34999. doi:10.1038/s41598-025-18941-8

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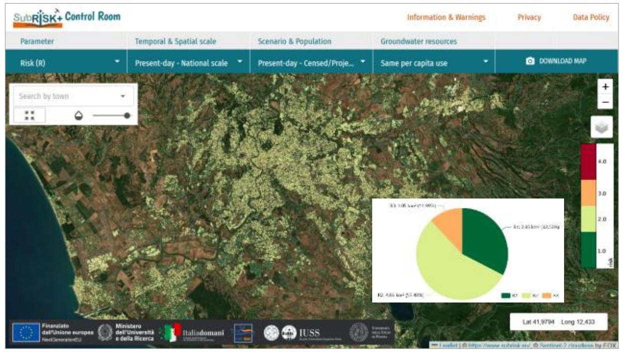

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