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Projected land subsidence risk under climate change and groundwater withdrawal scenarios in the metropolitan cities of Italy

Roberta Paranunzio

CNR-ISAC, Italy

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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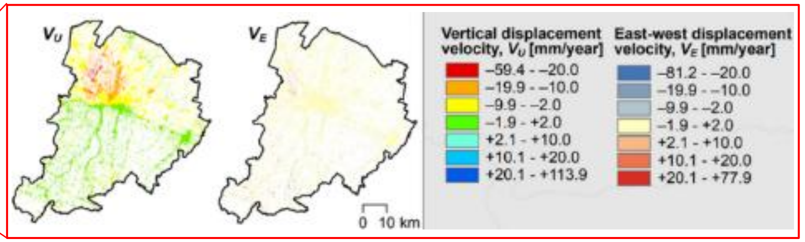
FINAL WORKSHOP

27th February 2026, h. 11:00-16:00 CET

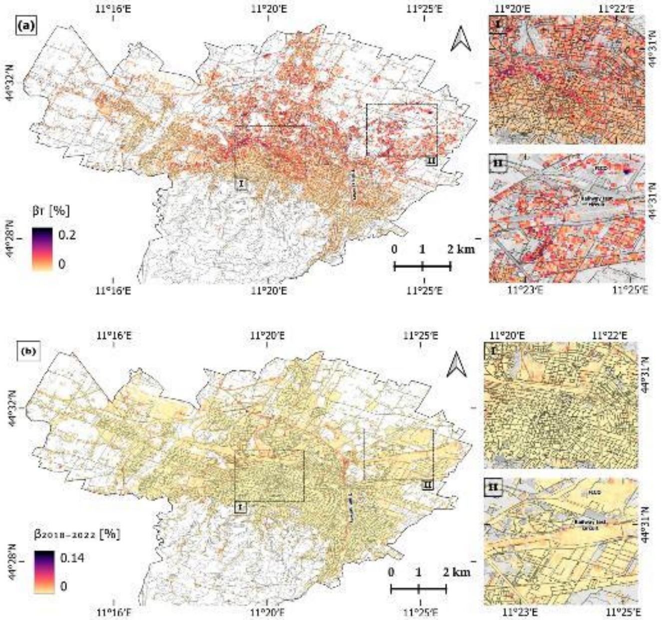
SubRISK+

Future scenario risk assessment

- Future land subsidence, particularly that driven by excessive groundwater extraction, poses a growing threat to urban areas worldwide.
- To assess future impacts of climate change on land subsidence and to support sustainable urban planning, 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 has been proposed. Combined with an exposure-vulnerability scoring approach building upon urban settlement characteristics, it provides a final score of ground displacement-induced risk
- The method has been tested in the Bologna Metropolitan area (Central Italy), which has experienced human-driven land subsidence since the 1960s (Zuccarini et al., 2023) and then applied to the other metropolitan Italian cities



Modified from Cigna et al. 2025

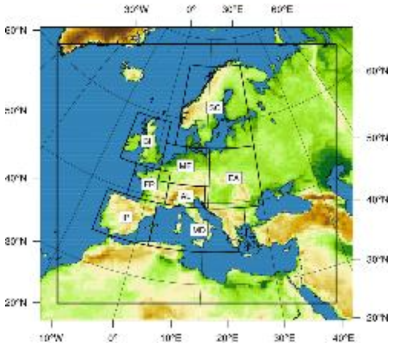


LENARDÓN SÁNCHEZ et al., 2024, https://doi.org/10.3390/land13122103

Hazard - Input Data

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

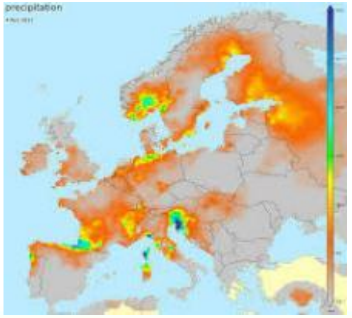


Climate Data

- 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

Other Data

- ISTAT administrative boundaries of the metropolitan cities
- Copernicus EGMS + PST-A InSAR data (L3, ortho, 100 m res.) over 2018–2022
- Groundwater withdrawals (for potable use) over 2008–2024 (ISTAT)

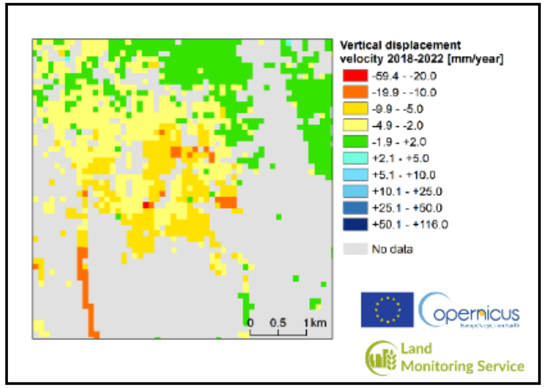


ISTAT public water supply data

Climate Change Service
climate.copernicus.eu

WCRP CORDEX

European Ground Motion Service (EGMS)



Bologna	ERS-1/2	Ascending	October 1995–September 2000	–49.1	+4.3
		Descending	April 1992–December 2000	–55.4	+10.3
	ENVISAT	Ascending	August 2004–July 2010	–24.0	+5.7
		Descending	November 2003–December 2010	–29.0	+4.8
	Sentinel-1	Ascending	January 2018–December 2022	–25.5	+1.4
		Descending	January 2018–December 2022	–24.1	+8.0

LENARDÓN SÁNCHEZ et al., 2024, https://doi.org/10.3390/land13122103

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Hazard - Methodological Approach

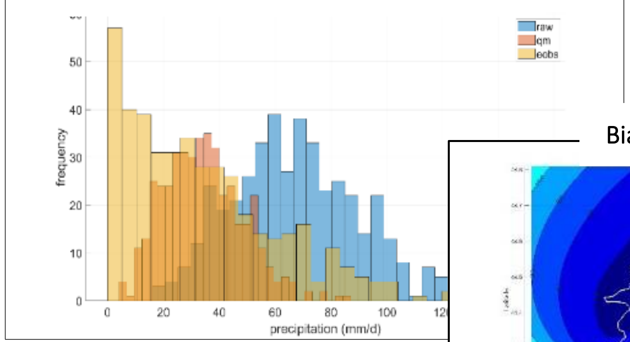
Future Climate Scenario Generation

- Selection of different RCM simulations nested into GCMs are considered to reduce the modelling uncertainties (Collados-Lara *et al*., 2018; 2020)
- Bias Correction Approach (Quantile Mapping)

RCMs nested into GCMs selected for this study

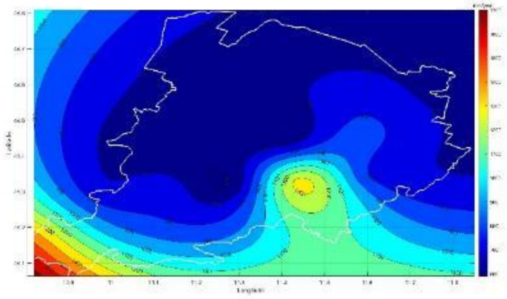
RCM	GCM		
	CNRM-CM5	ICHEC- EC-EARTH	MPI-ESM-LR
HIRHAM5		x	
RACMO22E		x	
RCA4	x	x	x
CCLM4-8-17		x	x

Bias-corrected pr 1970-2100 RCP8.5

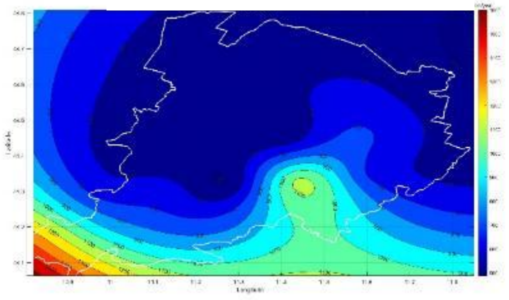


PDF pre and post bias-correction using quantile mapping techniques

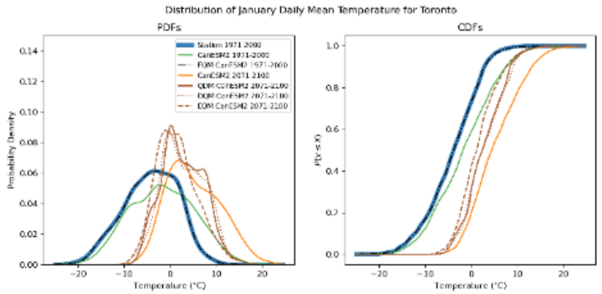
Bias-corrected pr 2025 RCP8.5



Bias-corrected pr 2100 RCP8.5



Bias-corrected precipitation values value over the ROI in 2025 and 2100 under RCP8.5



Example of Quantile Mapping application

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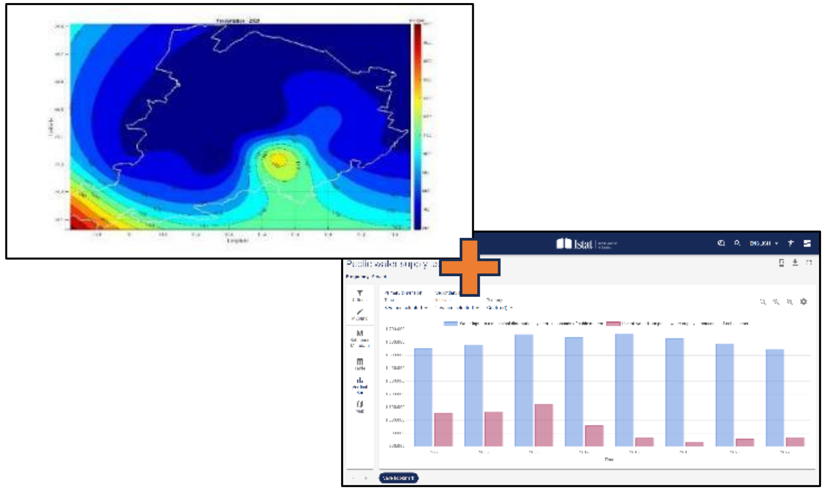
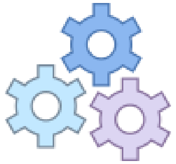
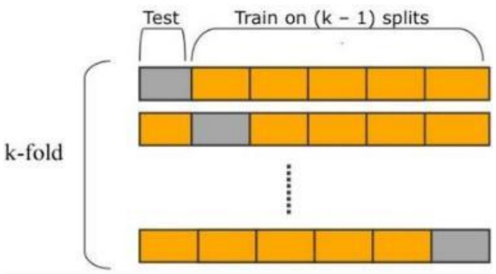
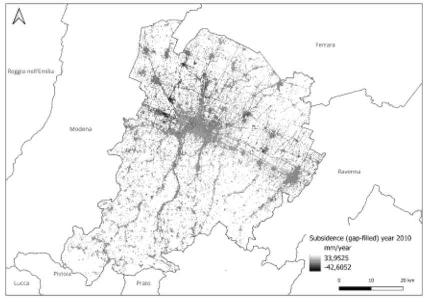
Regression Models to predict vertical ground velocity

- Predictors: ww, pr, et
- Evaluation of model robustness and accuracy
- Selection of the best performing model for each city









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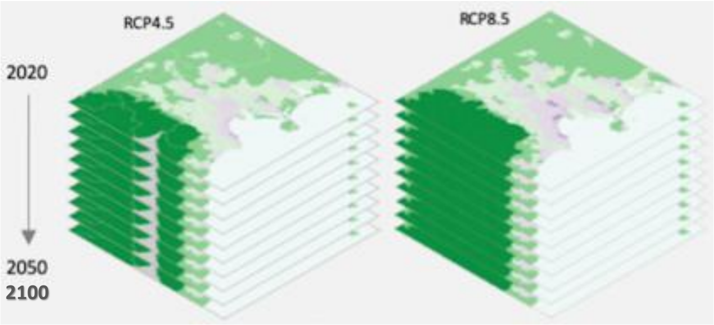
Extrapolated Prediction up to 2050-2100

- Predicting land subsidence every between present-day and 2050-2100 based on the regression model
- Different water withdrawal scenarios: +1% increase per year, -1% decrease per year (Ceccattelli *et al*., 2020) , **historical-trend based scenario.**

+1% per year
-1% per year
Historical-trend



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Hazard Assessment

Risk = Hazard x Exposure - Vulnerability

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*

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

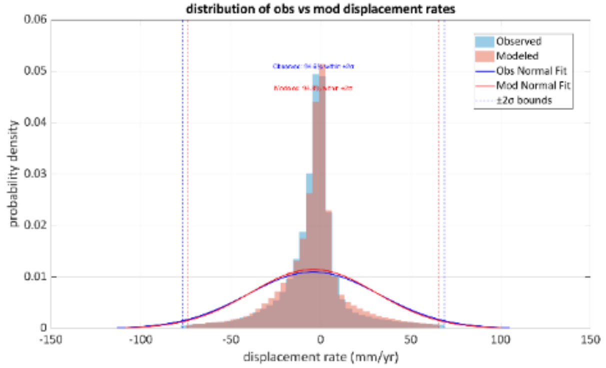
PARANUNZIO et al. 2026

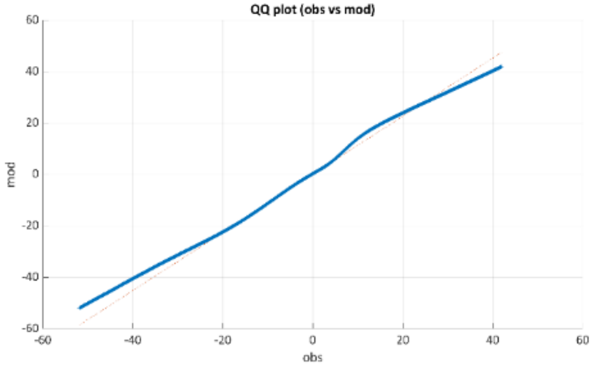
Hazard – Data Analysis

Bologna metropolitan city

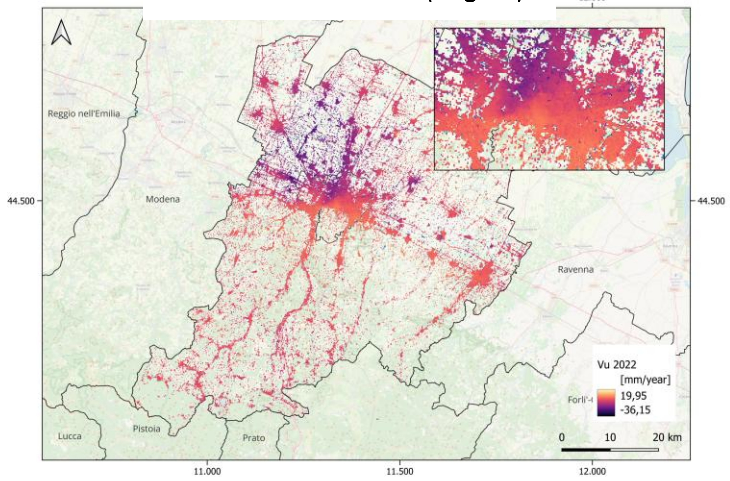
Model	Predictors	Avg. RMSE	Avg. Pearson
'M01_pr_ww_linear'	'pr,ww'	6.3442	0.7148
'M02_pr_ww_poly2'	'pr,ww'	64.0283	0.4153
'M03_pr_et_linear'	'pr,et'	6.1748	0.6881
'M04_pr_et_poly2'	'pr,et'	164.3096	0.0557
'M05_ww_et_linear'	'ww,et'	3.6620	0.8045
'M06_ww_et_poly2'	'ww,et'	79.4822	0.5038
'M07_pr_ww_et_linear'	'pr,ww,et'	27.7907	0.4269
'M08_pr_ww_et_poly2'	'pr,ww,et'	7.3434	0.6606
…	…	…	..

Test summary linear regression models

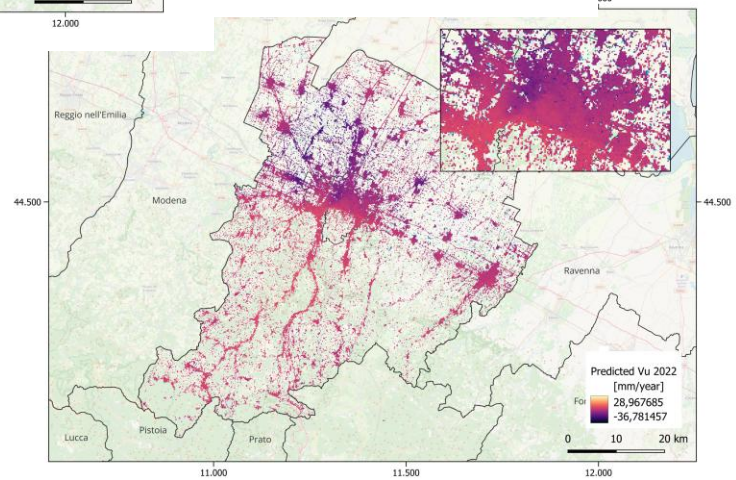




Subsidence Rate 2022 (original)



Subsidence Rate 2022 (modelled)



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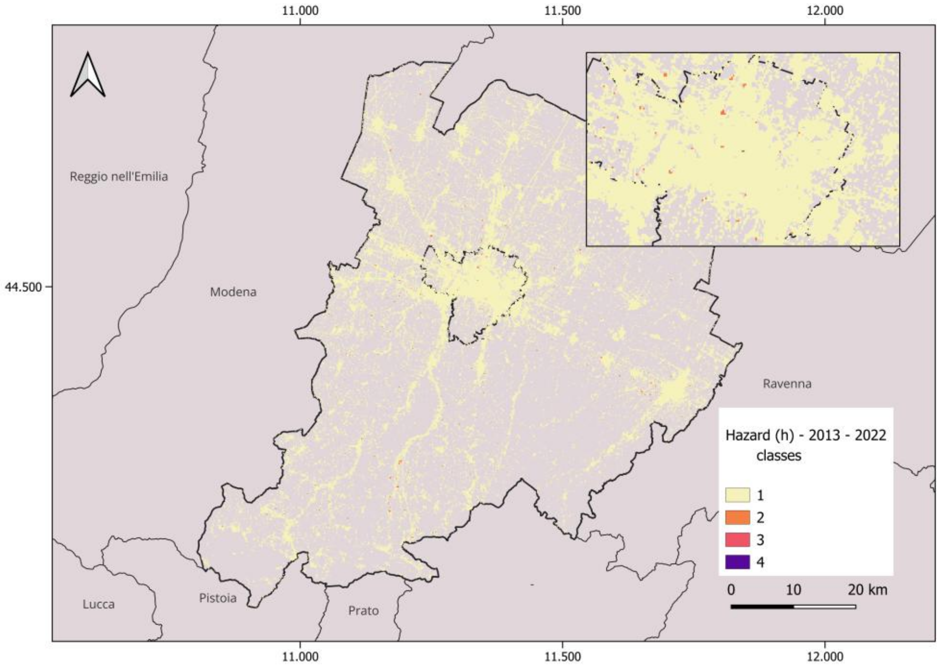
Hazard – Data Analysis

Bologna metropolitan city

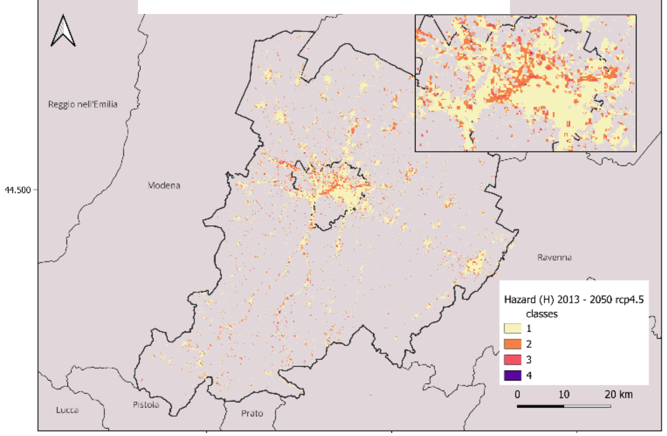


Present-day

2050

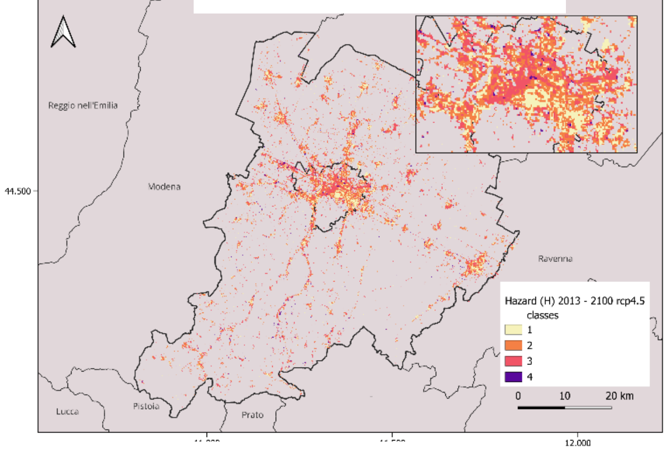
Hazard 2050 RCP4.5

RCP 4.5



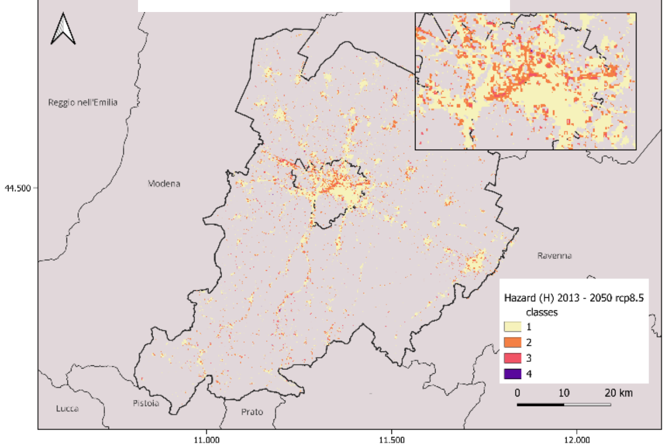
2100

Hazard 2100 RCP4.5

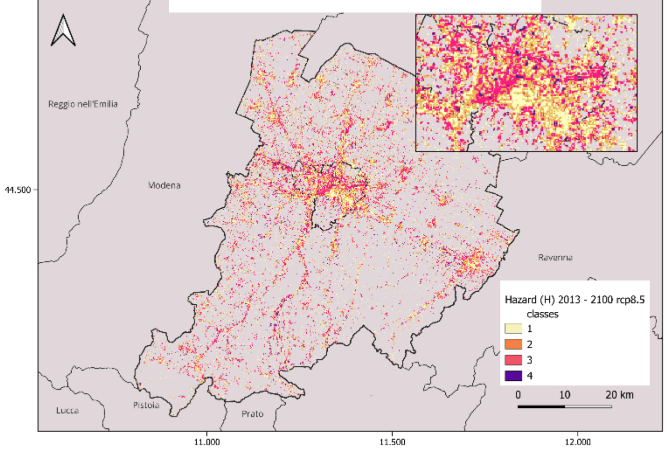


Hazard 2050 RCP8.5

RCP 8.5



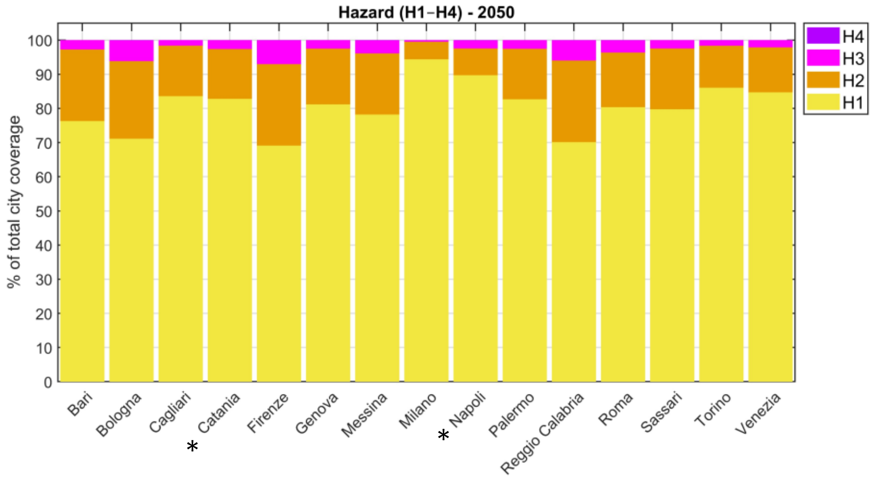
Hazard 2100 RCP8.5

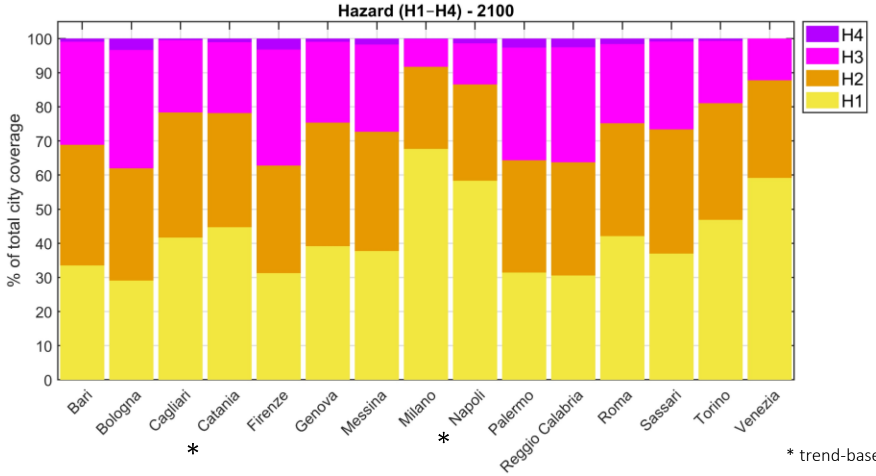


Scenario ww – historical trend

Hazard – Data Analysis

RCP 4.5





* trend-based vertical displacement (subsidence and ground uplift)

Low Hazard (H1)

- Over 69 % of the total mapped land in 2050 within each city
- Relevant reduction in 2100 (range 29 – 68 % in H1)

Medium Hazard (H2)

- Proportion: 5%-24% in 2050 to 24-37 % in 2100 within each city

High Hazard (H3)

- Proportion: 0.5 % to 7 % in 2050 up to 8-35 % in 2100 respectively within each city
- Largest extent in Bologna (~35 %), Firenze (~ 34 %), Reggio Calabria and Palermo (~33 %) in 2100

Very High Hazard (H4)

- Mapped areas in H4 below 0.1 % in 2050 within each city, increase to 3.4 % in 2100
- Largest extent in Bologna and Firenze (~3.4 %) in 2100

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Exposure-Vulnerability - Input Data

A combined metric to quantify the exposure and vulnerability of urban infrastructure to differential displacement in the mid and long-term future based on its spatial distribution, height and age

Input Datasets

- ISTAT administrative boundaries of the metropolitan cities
- Copernicus EGMS + PST-A InSAR data (L3, ortho, 100 m res.) over 1995–2022
- GHSL BUILT-C/S
- World Settlement Footprint
- Corine Land Cover
- Tinitaly DEM
- Open Street Map data

Assumptions for future scenarios

- Precautionary approach: new urban expansion based on non-residential built-spaces (more vulnerable), new development only up to 3% of the existing urbanized territory over the period 2022-2050
- New buildings-height based on Inverse Distance Weighting approach (estimates values at unmeasured locations by averaging measured values surrounding the prediction location)

GHS-BUILT-C Settlement characteristics			WSF Evolution: ≤ 1985	WSF Evolution: > 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

** conventionally, 1 floor = 3 m (approx.)*

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

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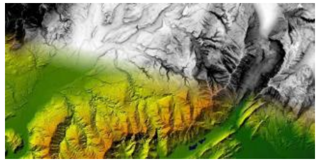
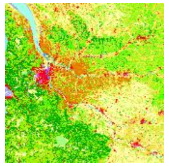
Exposure-Vulnerability assessment approach

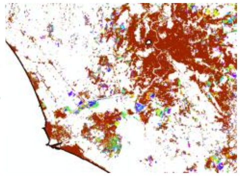
Compute Future Constraints to Urban Expansion
Land cover change and DEM data e.g., distance to buildings, transport network, slope factor, orography

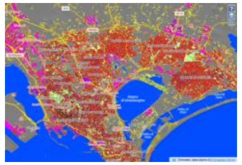




Temporal analysis
Binary classification pre-post 1985 and urban surface classification based on construction year

WORLD SETTLEMENT FOOTPRINT





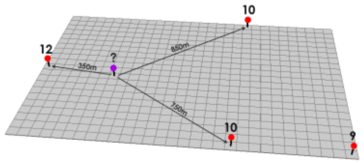
GHS-BUILT-S

Future Urban Expansion Estimation
Annual transition rate calibration from multi-date GHSL and validation
Computational algorithm for land-use expansion model
NB Cautelative approach: non-residential built-up area expansion, new development only up to 3% of the existing urbanized territory

Spatial Interpolation for New Urban Areas
Inverse Distance Weighting approach to estimate heights in new urban zones

New Building Height Growth Assumptions
When determining the **maximum permitted height** for a **new building**, Article 8 of Ministerial Decree 1444/1968 must be applied by **referencing the actual heights of the surrounding existing buildings**.

GHS-BUILT-C



Exposure-Vulnerability Assessment

Risk = Hazard x Exposure - Vulnerability

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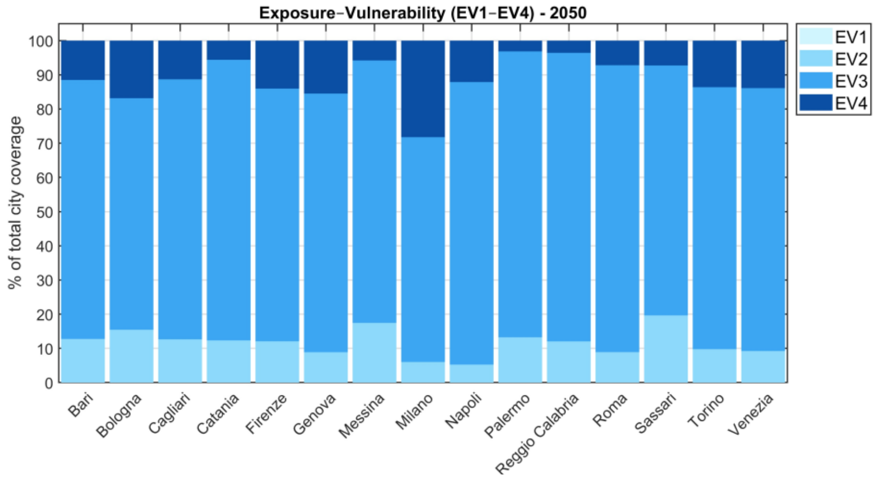
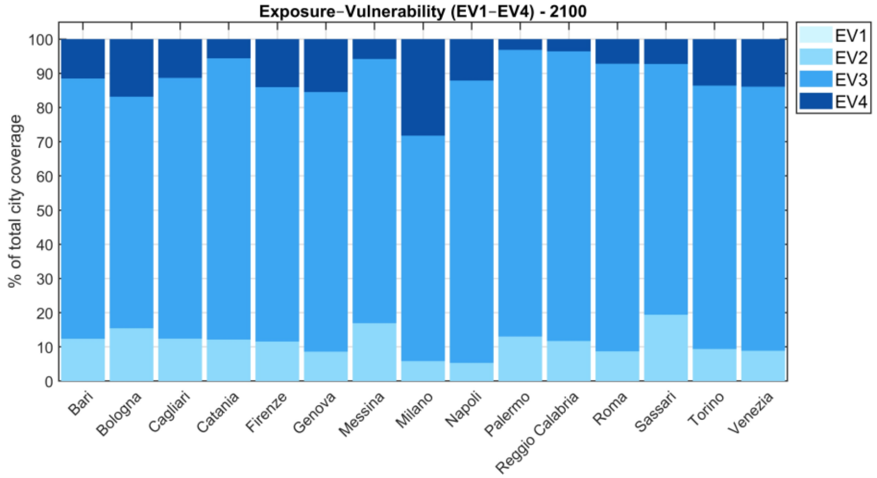
Exposure-Vulnerability- Data Analysis





Low Exposure-Vulnerability (EV1)

- No areas show low EV

Medium Exposure-Vulnerability (EV2)

- Proportion: 5% to 19-5% within each city
- Largest extent in Sassari (~19.5 %) , Messina (~19.5 %) , Bologna (~15.5 %)

High Exposure-Vulnerability (EV3)

- Over 65% of the mapped land within each city
- Largest extent in Rome, Reggio Calabria, Napoli and Palermo (~82-84 %),

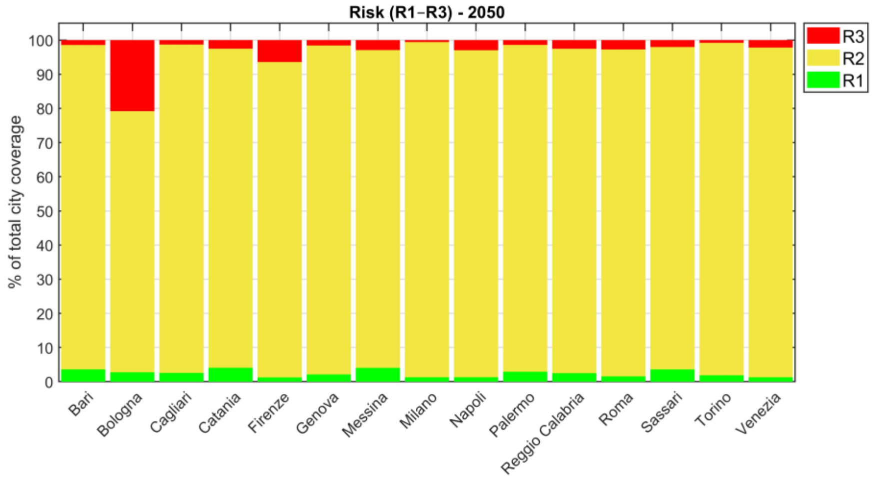
Very High Exposure-Vulnerability (EV4)

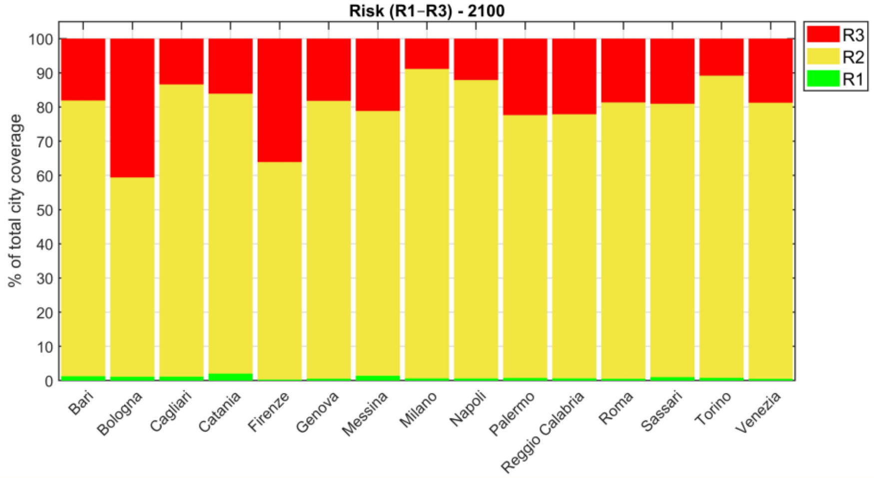
- Proportion: 3% to 28% within each city
- Largest extent in Milano (~ 28%), Bologna (~17 %) and Genova (~15.5 %)

SubRISK+

Risk - Data Analysis

RCP 4.5





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

Low Risk (R1)

- Range between 1-4 % in 2050, decreasing to 0.5-2 % in 2100

Medium Risk (R2)

- Most mapped land in medium risk class (76-98 %) in 2050 and 2100 (76-90 %)

High Risk (R3)

- Range between 0.8-21 % in 2050, increasing to 8.9-40 % in 2100
- Largest extent in Bologna in 2050 (~21%) and ~40% along with Firenze (36 %) in 2100

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

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Conclusions & further perspectives

- Ground deformation and its associated hazard and the exposure and vulnerability of urban land and population to the land subsidence process, along with the resulting risk to urban infrastructure were investigated for near and long-term future, under different emission scenarios.

- A simple approach that, while accounting for climate-change-related uncertainties, can provide a first-order assessment of differential subsidence rates and impacts in the future, especially in regions with limited data availability, has been provided.

- Vulnerability projections for the future are based on a conservative scenario with a maximum 3% urban expansion (2022–2050), mainly in non-residential areas and using estimated building heights. While this ensures a cautious exposure assessment, it introduces uncertainties related to spatial distribution, building types, regulatory changes, and future adaptation. Therefore, results should be interpreted as upper-bound estimates rather than precise forecasts.

- These results indicate that, also under a business-as-usual emission scenario and assuming current trends in groundwater withdrawals, the impacts of climate change on land subsidence would be very relevant, especially for Bologna and Firenze metropolitan areas.

Thank you!

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SubRISK+ references

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