LAND SUBSIDENCE INDUCED BY GROUNDWATER EXPLOITATION: USING SATELLITE INSAR TO ESTIMATE CURRENT AND FUTURE RISK FOR URBAN LANDSCAPES IN ITALY

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Abstract
Italy is among the 15 world countries with the largest estimated groundwater extractions, with a total of 10.4 km³/year (Margat & van der Gun 2013). When groundwater withdrawal and natural discharge exceed recharge rates, aquifer systems are over-exploited (Gleeson *et al.* 2012), resulting in resource depletion, storage loss and compaction of confining clay beds (Galloway & Burbey 2011). The induced land subsidence may cause direct/indirect impacts on urban landscapes (ground depressions, earth fissures, structure damages, increased flood risk, loss of land to water bodies) and economic loss. High to very high subsidence susceptibility and hazard levels characterize many Italian regions (Herrera-García *et al.* 2021), and a number of subsidence hotspots have been observed using satellite Interferometric Synthetic Aperture Radar (InSAR) methods (Rosen *et al.* 2000), such as the Po River and Florence-Prato-Pistoia plains.

The project SubRISK+ (https://www.subrisk.eu) innovates in this field by providing new Earth observation (EO)-derived products and tools aiming to enhance the understanding of subsidence risk in major urban areas of Italy, towards sustainable use of groundwater resources and urban development (Cigna *et al.* 2024; Bonì *et al.* 2024). Started at the end of 2023, the project is funded by the European Union – Next Generation EU, in the framework of the Research Projects of Significant National Interest (PRIN) 2022 National Recovery and Resilience Plan (PNRR) Call.

The project is assessing current and future subsidence risk in Italy using a multi-scale methodology, with implementation spanning from the national to the local scale. Risk is estimated with matrix-based risk assessment approaches (Fig.1) (Cigna & Tapete 2021), embedding InSAR-derived ground deformation observations (e.g. Copernicus' European Ground Motion Service, EGMS; Fig.2), hydrogeological, topographic and land use data. Hazard levels are estimated via computation of angular distortion (Skempton & McDonalds 1956) and horizontal strain (Tandanand & Powell 1991) induced on urban infrastructure, as derived from InSAR datasets. Exposure and vulnerability are assessed based on type and height of urban infrastructure, and geospatially combined with hazard information via a risk matrix to derive risk levels, from very low to very high (e.g. R1 to R5; Fig.1). Statistics on the population living within the various risk categories are finally extracted. At regional scale, accurate detection of hotspots and drivers is enabled by implementing advanced geostatistics and exploiting time series analysis tools (Bonì *et al.* 2016, Abdollahi *et al.* 2019), including Independent Principal Component Analysis (IPCA) and Optimized HotSpot Analysis (OHSA).

An advanced numerical model coupling 3D transient groundwater flow and geomechanics of heterogeneous aquifer systems (Teatini *et al.* 2016; Bonì *et al.* 2020) will also be developed to quantify the effects of groundwater usage to land deformation, and estimate uncertainties at local-scale in a highly vulnerable city. The output from the groundwater flow model will serve as input in the deformation model, utilizing the same computational grid and distribution of mechanical parameters to create a consistent flow-deformation model. A calibration procedure will be implemented where uncertainties associated to available piezometric records and InSAR measurements and from modelling approach are integrated to estimate the parameters of both the groundwater flow and deformation models.

The calibrated (and validated) models will be subsequently employed to forecast the consequences of future hydrological regime and pumping scenarios associated to climate change. The potential increase in uncertainty over longer prediction time spans will be properly quantified through the proposed approach.

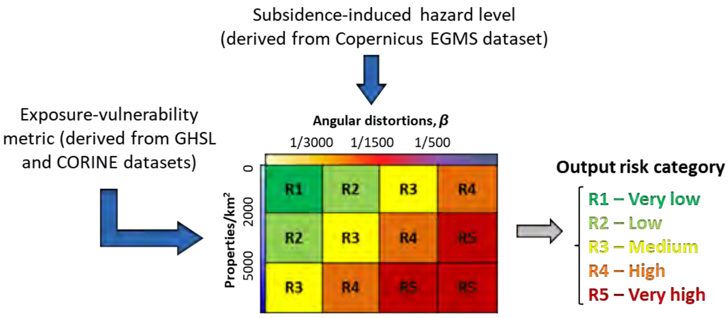

Fig.1: Matrix-based subsidence risk assessment approach adopted by the SubRISK+ project, following the methodology developed by Cigna & Tapete (2021).

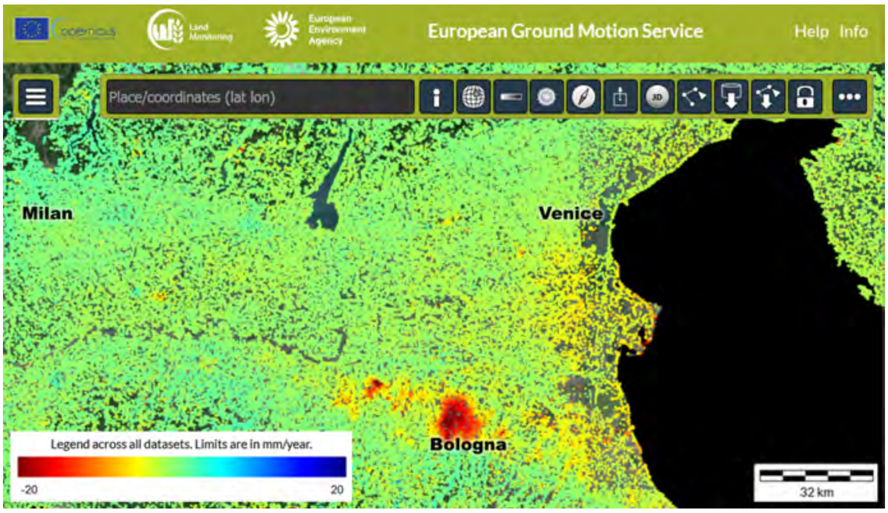

Fig.2: Zoom onto the Copernicus' European Ground Motion Service (EGMS) dataset (Crosetto et al. 2020) showing vertical land deformation in 2018-2022 over northern Italy. Contains modified Copernicus Sentinel-1 data 2021.

A tailored socio-economic impact analysis will be developed to quantify market and non-market direct/indirect losses at national, regional and local scale (Hallegatte 2014), based on affected areas' exposure, vulnerability and resilience. Future subsidence risk by 2050 and 2100 under climate change (RCP4.5/8.5, medium/high emissions), demographic and urban development, will be assessed for the metropolitan cities and, locally, by adapting the numerical model to support long-term risk predictions under different scenarios. Predictions of future land use changes using socioeconomic and environmental parameters will contribute to an integrated, indicator-based approach at city scale (Jiang *et al.* 2022, Meroni *et al.* 2017) that will enable assessment of urbanization patterns and identification of potential areas prone to future subsidence (Birkmann *et al.* 2021, Paranunzio *et al.* 2022).

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