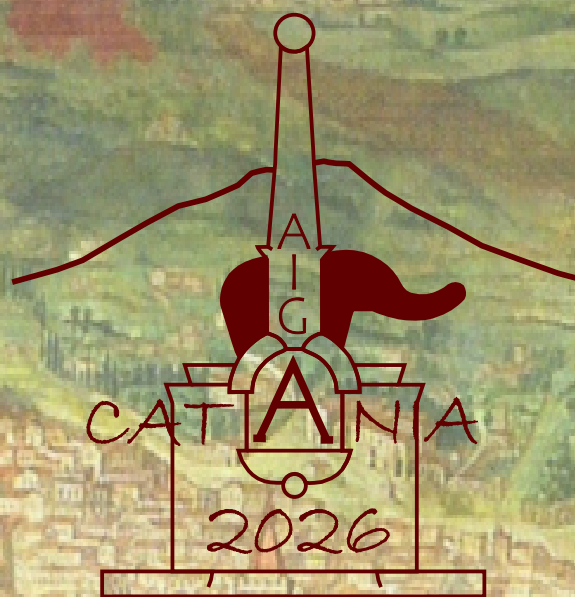


XIII Convegno dei Giovani Ricercatori di Geologia Applicata

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ABSTRACT BOOK

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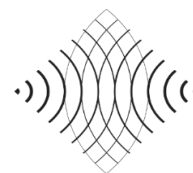


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Kinematics of the rock spreading of Lauria historical town (southern Italy)

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Abstract. Many historical towns scattered across the Apennine mountain range are at risk from landslides that, over time, have damaged buildings and roads, thus contributing to the gradual depopulation and loss of cultural identity. To deal with this issue, the PRIN 2022 LIVES project is focused on the study of landslides affecting historical towns based on joint geological and geotechnical analyses of slope stability as well as societal impacts. The scopes of the project are the reconstruction of evolutionary scenarios and the design of suitable mitigation actions.

The ancient center of Lauria (Basilicata region, southern Italy) was identified as representative of the unstable historical towns of the Apennines, because it has been affected in the last centuries by severe slope instability phenomena. The ground movements phenomena involve the Lanzo's cliff, formed by a highly fractured carbonate rock mass, upon which historical residential buildings, infrastructures and places of worship were built. Over the centuries, the slope movements were characterized by several episodes of sudden acceleration. Some of these phases were recorded in 1740 and 1820, leading to the collapse of buildings and even to casualties, while others were reactivated by intense external forcing such as the 1998 Lauria earthquake (Mw 5.7).

Relying on previous geological investigations, including field and topographic surveys, boreholes campaigns with piezometric and inclinometer data, carried out between 1980 and 2012, an engineering-geological model of the fractured unstable Lanzo's rock mass was reconstructed. Moreover, satellite Sentinel-1 InSAR data (2019-2025) were gathered and analyzed for the comprehension of slope kinematics.

Among the main results, Lanzo's carbonate rock mass was recognized as a fragmented rock block overlying the argillaceous basin series of the Nemoli heterogeneous complex. The geometric spatial reconstruction allowed the assessment of Lanzo's rock block thickness as varying from 20 to 80 m. Moreover, the rock block was recognized as disarticulated in minor blocks by major active fractures, caused by a spreading mechanism which determines differential ground movements and morphological trenches.

The most unstable sectors of the historical center are located along the slopes overlooking the Caffaro gully and the Noce Valley, where open fractures dislocate and subdivide the Lanzo rock mass into multiple adjoining blocks. In this sector, damaged buildings are distributed in clustered patterns depending on differential movements occurring across zones with higher spatial concentration of open cracks and trenches.

Topographic and Sentinel-1 InSAR data showed a continuous and constant slow movement of the slope with a steady velocity varying from about 15 mm/y, in the inner sector of the Lanzo's settlement, to 35 mm/y, close to the outer edge. These slow-moving movements appear correlated to seasonal rainfall patterns rather than high-intensity daily events. The actual slow-moving kinematic stage can be considered as intermediate between paroxysmal phases, the last of which occurred in 1998.

The findings of this study may serve as a foundation for future studies aimed at defining future scenarios and mitigation strategies for the protection of cultural heritage in landslide-prone areas.

Numerical modelling or conventional analyses? When an integrated approach becomes fundamental in understanding slope failure mechanisms

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Abstract. Conventional kinematic and limit equilibrium analyses represent the first and fundamental steps in the analysis of slope stability, especially when the geometry and geology of the study area are relatively simple. When the structural setting or slope geometry is complex, it is often important to integrate conventional analyses with numerical modelling.

Numerical techniques, such as finite element, finite difference and distinct element modelling, allow for the simulation of stress-strain evolution and the characterization of progressive or composite failure mechanisms that cannot be adequately captured by conventional limit equilibrium analyses. When properly calibrated, these methods greatly enhance the interpretation of slope behaviour, particularly in structurally intricate geological environments.

In this research a comprehensive approach based on the integration of conventional and numerical methods is presented. The case study used at this purpose is the Monte Conero (Ancona, Marche Region, Central Italy), a coastal slope characterized by a highly complex structural framework and articulated morphology. This area is of particular concern due to the presence of vulnerable touristic and accommodation structures located close to potentially unstable rock masses, which are exposed to toppling and rockfall hazards.

A multidisciplinary methodology was adopted, combining engineering geological and geomorphological field surveys with remote sensing investigations through UAV-based photogrammetry. These activities enabled a detailed reconstruction of the slope geometry and discontinuity network, providing the basis for subsequent kinematic and limit equilibrium analyses. Although these analyses offered a preliminary understanding of potential instability mechanisms, they were unable to fully reproduce the failure kinematics observed in the field.

To overcome these limitations, numerical modelling was performed to simulate different geological and mechanical scenarios. The numerical approach successfully reproduced the observed deformation patterns, providing a more comprehensive understanding of the controlling factors and failure mechanisms.

This work discusses in detail the advantages and limitations of adopting an integrated methodological framework for slope stability studies. Particular attention is devoted to the challenges inherent in numerical modelling, including the selection and calibration of model parameters, the definition of boundary and initial conditions, the choice of appropriate constitutive laws, and the validation of numerical results. Addressing these aspects is crucial to ensure that simulations yield realistic and reliable interpretations of slope behaviour.

3M-approach to managing large-slow-moving landslides

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Abstract. Large, slow-moving landslides are complex geomorphological phenomena that are often characterized by deep-seated deformation, long-lasting activity, and intricate interactions with geological, hydrological, and anthropogenic factors. Given their scale and kinematic complexity, the 3M-approach (Monitoring, Modelling, Mitigation) emerges as a sustainable and effective strategy. The 3M framework facilitates enhanced landslide dynamics representation through the integration of long-term, high-resolution monitoring data, including ground displacements, hydrological parameters, and environmental triggers, with both numerical and data-driven modeling techniques. This understanding provides evidence-based insights for designing effective risk mitigation strategies. This contribution focuses on case studies of the Passo della Morte landslide and highlights how continuous monitoring is not just a preliminary step but a central component of the modeling process. In essence, the 3M-approach underscores the necessity of employing monitoring techniques to ensure the sustainable management of persistent large-scale landslides within a changing environment.

Prediction of rainfall-induced shallow landslides at a geographical scale using Deep Learning: an application to the Liguria Region (NW Italy)

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Abstract. The occurrence of rainfall induced shallow landslides produces significant impacts on the environment and society worldwide, causing extensive damage to infrastructures, buildings, croplands, and woodlands, thus representing a serious source of risk in hilly-mountainous areas. The prediction of these peculiar ground instabilities is a challenging task because of their complex nature. For these reasons, research to increase the quality of their prediction is of great importance in the frame of geo-hydrological risk including mitigation strategies, land-use and urban planning, and of the development of early warning systems for civil protection purposes. The present work deals with the implementation of a deep learning model aimed at the spatial-temporal prediction of rainfall induced shallow landslides at geographic scales. The methodological approach consists of two main phases. The first phase, based on statistical analysis and machine learning, is aimed at building a predictive neural network. By using the ITALICA database (Peruccacci et al. 2023), which catalogues rainfall induced shallow landslide events in Italy, and a 20-year pluviometric dataset collected from the rain gauges of the national civil protection network, the probability for rainfall induced landslide initiation at the location where rainfall is available is estimated. In the second phase, the rainfall-based probability is spatialized and coupled with landslide susceptibility, namely the spatial variable that considers the influence of geological and geomorphological characteristics of the territory. Two spatial distribution modelling techniques were used: a deterministic approach based on the Voronoi tessellation and a stochastic model using the MUSE (Modeling Uncertainty as a Support for Environments) software (Miola, 2025). The developed spatial-temporal forecasting model has been tested over the entire Liguria region, whose territory is highly prone to be affected by rainfall induced shallow landslides. The outcomes of the model application showed that the integration of both temporal and spatial variables proved effective in landslide forecasting. The proposed model can represent a useful tool for civil protection activities in the frame of weather-hydrological event management as well as the mitigation of risks associated with the occurrence of rainfall induced shallow landslides.

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Sinkhole time-magnitude hazard scenario evaluation in the city of Naples using machine learning and Poisson distribution

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Abstract. Sinkholes, cylindrical or funnel-like three-dimensional depressions or collapses, are a widespread phenomenon in the Italian peninsula. A sinkhole diameter and depth can vary from sub-metrical up to several tens of meters, potentially causing serious damage to historical buildings or even causing the loss of human lives. In the underground of historical cities like Rome, Palermo, and Naples, there is often a huge network of underground man-made cavities that have been used for multiple purposes (aqueducts, catacombs, air-raid-shelters, etc.). The collapse of these cavities, or the formation of new ones due to pipeline leakage, can lead to the triggering of an anthropogenic sinkhole.

Using machine learning algorithms such as Random Forest, Gradient Boosting Machine, and Maximum Entropy, different anthropogenic sinkhole susceptibility scenarios based on magnitude were produced, followed by temporal occurrence analysis. From the machine learning models, the so-called ensembles are built using different algorithms and different input datasets. The first step to assess different scenarios is the partitioning of the anthropogenic sinkhole inventory based on magnitude and the implementation of different sets of pseudo-absence (for Random Forest and Gradient Boosting Machine) or background point sets (for MaxEnt), thus varying both the algorithms and the input data. After generating a reasonable number of models, they were validated using the ROC performance scores and combined to build the ensemble, using a weighted average combiner and considering only the models that exceeded the 0.75 ROC threshold. Three susceptibility maps based on three different magnitude scenarios were obtained. This approach allows the user to retrieve important information even if the three resulting scenarios appear similar, providing useful data on possible interactions between the sinkhole magnitude and specific zones of the area of interest.

Regarding the temporal occurrence analysis, the Poisson distribution was employed to obtain the probability of a new sinkhole occurrence at 1, 3, 6, and 9 months (assuming that each sinkhole is independent from one another). Combining the three spatial occurrence scenarios (the susceptibility maps) with the four temporal occurrences, twelve hazard scenarios were obtained, based on different magnitudes and time intervals, achieving the intended goal of this methodology.

Combining the spatial and the temporal occurrence assessment, the user can use this tool to add the temporal factor to the analysis and study the evolution of the three magnitude scenarios over time. Due to the statistical approach used in this methodology, there are limitations related to the absence of data within the study area, for example, the lack of a detailed sinkhole inventory containing information about magnitude or date of occurrence. The amount of data in the inventory is also an important factor, as the reliability of statistical methods decreases when there is less available data.

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Kinematic rock slope hazard assessment using UAV photogrammetry, mobile and terrestrial laser scanning: a quantitative comparison

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Abstract. This study compares three close-range surveying techniques: terrestrial laser scanning (TLS), mobile laser scanning (MLS) and unmanned aerial vehicle digital photogrammetry (UAV-DP), in order to assess their performance in kinematic rock slope hazard analysis. The case study was an abandoned marble quarry in Tuscany, Italy.

Three georeferenced point cloud datasets were analyzed to extract and compare kinematic analysis outputs. TLS served as the reference method for its geometric accuracy and precision. MLS, based on a simultaneous localization and mapping (SLAM) system, was evaluated for its efficiency in rapid data collection, while UAV-DP was used to reconstruct high-resolution surfaces from an aerial view.

Results show that TLS ensures the highest precision but is limited by occlusions and logistical constraints. UAV-DP provides wide coverage and detailed surface information, though it depends on appropriate ground control points reference and lighting conditions. MLS data are generally noisier but allow fast and flexible mapping when processed through a dedicated workflow. A specific procedure is proposed to enhance MLS point cloud usability for kinematic analysis, focusing on noise filtering and point density optimization.

The comparison demonstrates that variations in point cloud quality could affect the interpretation of structural features and potential instability mechanisms. However, all three methods, when properly processed, can deliver reliable inputs for preliminary hazard assessment. The choice of the most suitable technique should take into account not only accuracy requirements but also the availability of time and resources, site accessibility, and project objectives. It should also be noted that survey costs are not always directly proportional to the practical usefulness of the geomechanical information obtained.

Sinkhole Susceptibility Analysis using machine learning algorithms and ensemble modeling in Enemonzo (Northern Italy)

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Abstract. Sinkholes are ground instabilities, often circular-shaped and characterized by a depression that, as the name suggests, leads to ground and water sinking towards the center of the depression. In extreme cases, they can lead to collapse, thus posing a serious threat to both infrastructure and human lives. Karst areas (carbonates and evaporites) due to the presence of diffuse voids, are the ideal environment where sinkhole can occur. In the area of the Enemonzo municipality, within the Tagliamento Valley (Friuli Venezia Giulia region, NE Italy), sinkholes are very common due to the widespread presence of Triassic evaporites, mantled by extensive cover deposits.

Since, sinkhole geohazard pose critical problems to the urban fabric, a susceptibility map represents a useful tool for local governments. Among the various statistical approaches for susceptibility analysis, machine learning is nowadays widely used. In particular, to evaluate sinkhole susceptibility in the Enemonzo area, the Random Forest, Gradient Boosting Machine, and Maximum Entropy machine learning algorithms were applied. Among the predisposing factors variables employed, there are continuous ones representing the density and distance of certain variables (tectonic lines, aqueduct and sewer networks, and hydrographic networks) and some others categorical (land use, geology, and geomorphology). The predisposing factors are natural and anthropogenic: slope, elevation, cover thickness, road network, used to simulate the presence of the secondary aqueduct and sewer networks.

Using the available sinkhole inventory, multiple sinkhole susceptibility maps were obtained by combining different input datasets and algorithms. After evaluating their performance using the ROC score and the k-fold cross-validation technique, different models were combined using the weighted mean, obtaining a final ensemble model. To evaluate the ensemble and avoid any positive bias that could affect the performance, the initial susceptibility inventory was divided into two subsets: 70% for training and validation of the singular models and 30% used for testing the ensemble model using the ROC/AUC technique.

The good performance obtained for the resulting map makes it a useful new tool towards a better understanding of sinkhole susceptibility assessment and to help local administrations and stakeholders in urban planning and to mitigate the risk.

Integrating RGB and Infrared Thermography for Multitemporal 3D Monitoring of Coastal Landslides

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Abstract. Landslide characterization and monitoring require tools capable of providing quantitative information with high spatial and temporal resolution. The integration of RGB photogrammetry and infrared thermal imagery acquired from UAV platforms represents a significant advancement in surveying techniques, particularly in coastal environments characterized by high geomorphological complexity.

In this framework, Infrared Thermography (IRT) offers strong potential for detecting thermal anomalies associated with instability processes—such as fractures, wet zones, altered surfaces, or detachment areas—but its traditional use has been often limited to two-dimensional, non-metric representations. To overcome this limitation, a dedicated thermal processing tool (IRT-PC) has been developed, enabling the conversion of 2D thermograms into 3D thermal point clouds containing georeferenced surface-temperature values (Caliò et al., 2025). The tool adapts conventional photogrammetric algorithms used for RGB imagery and integrates specific radiometric calibration modules to ensure both geometric and thermal consistency among the images.

The RGB-IRT integrated close-range monitoring was applied to the Timpa di Acireale cliff (eastern Sicily, Italy), an impressive volcanic escarpment affected by recurrent gravitational processes. UAV surveys conducted between 2023 and 2025, within the framework of the PRIN 2022 LINAR project, included multitemporal daytime RGB and nighttime IRT acquisitions. The generated 3D models allowed for the identification of landslide signs, structural discontinuities and thermal anomalies. Moreover, the multitemporal comparison between dense point clouds enabled the detection of those evolution feature triggered by the rainy season, including new landslides. The quantitative analysis of the digital models allowed also the precise estimation of mobilized volumes, which is essential for the coastal evolution monitoring. The results confirm the effectiveness of the IRT-PC tool and the proposed workflow, which represents a replicable, non-invasive, and quantitatively reliable methodology particularly suited for integrated monitoring and evolutionary analysis of unstable slopes in complex geomorphological settings.

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Probabilistic landslide risk assessment for the road network at the regional scale

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Abstract. As the climate continues to change, extreme rainfall events are becoming more frequent, leading to a sharp rise in landslide occurrences, often numbering in the hundreds or even thousands during a single episode. Over the past three years, the Italian regions of Marche, Emilia-Romagna, and Tuscany have experienced severe rainfall events that triggered widespread landslides and floods, causing fatalities and significant damage. From a geological perspective, these events share a common feature: the triggering of fast-moving shallow landslides that have severely affected the road network. Although significant progress has been made in small-scale landslide risk assessment, especially regarding building vulnerability and loss estimation, methods for analysing the road network vulnerability to landslides, and the associated risk, are still scarce in the literature. In light of these considerations, we present a probabilistic landslide risk assessment for the road network at the regional scale, using Tuscany as study area. We propose a methodological framework that is easily replicable and updatable. Notably, the proposed landslide risk assessment relies on three key components: landslide susceptibility, landslide intensity, and vulnerability of the road network. Landslide susceptibility across Tuscany is estimated using an interpretable machine learning model. We define the vulnerability of the road network as a function of landslide intensity and functional resistance, which represents the ability of a road segment to maintain its functionality in the case of a landslide. Specifically, vulnerability is defined through a semi-quantitative approach based on three scenarios of landslide intensity. These scenarios are derived from a magnitude-frequency analysis of past landslides. Functional resistance of each road segment is determined by combining several attributes: road type, width, pavement characteristics, and state of activity. Ultimately, landslide risk for the road network is expressed in terms of functionality losses arising from potential road interruptions. Preliminary results identify critical sectors along the Apennine chain and demonstrate the potential of this approach to support regional risk management practices.

From Seismic Trigger to Deep-Seated Creep of the Complex Monte Saresano Landslide

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Abstract. The Monte Saresano landslide in Tavernola Bergamasca (BG, Lombardy) is a large rockslide affecting an old quarry slope that has underwent at least three historical reactivations since the 1900s. Geomorphological, structural, and geomechanical evidence suggests the presence of a large slope instability extending well beyond the limits of the present-day active sector.

In February 2021, a significant acceleration of the movement was recorded following a seismic event of $ML = 2.2$ that occurred 2km east of the municipality of Viadanica (BG), around 7 km to the west of the landslide site. Displacement rates surged to 2.3-5.0 mm/day immediately after the event, rising from a mean background rate of approximately 0.1-0.2 mm/day. Fractures were observed almost along the entire perimeter of the rockslide, affecting local and provincial roads. Following this acceleration, a long-term phase of progressive slowdown was observed with minor effect of rainfall on the displacement rate only at the ground surface.

This study integrates data from a comprehensive monitoring network (active mostly since 2017) comprising optical targets, GNSS, borehole extensometers, inclinometers, multiparametric probes, and ground-based InSAR. We combined this with a laboratory geomechanical characterization of the materials, including triaxial and direct shear tests on basal shear zone materials, and creep tests for the carbonate rocks belonging to the “Domaro Limestone Formation”. Compositional investigations (XRF, XRD, thin sections) defined the lithology as limestone and marly limestone.

The integration of geophysical and borehole data highlighted complex dynamics characterized by deformations distributed over a wide thickness. We identified a deep sliding shear zone system isolating a 2.6 million m³ mass, potentially extending to 4.45 million m³ if the unstable mass is extended to embrace the entire cataclastic basal layer that reach about 10 metres in thickness. HVSR measurement campaigns at 50 stations enabled, through the use of Nakamura’s approach, the reconstruction of rockslide depth by calibrating the material parameters at the station points.

Finally, 3D Finite Element Modeling (FEM) was employed to analyze the slope stability. Static analyses and Strength Reduction Factor calculations allowed us to estimate the critical cohesion and friction angle values. The numerical results, which closely match the observed basal shear zone depth, suggest that diffuse fracturing and severely weakened cataclastic levels, resulting from prehistorical activity, were exploited both during the reactivation and also by disturbance originated by recent quarrying and blasting activities, controlling the recent landslide evolution, while the 2021 seismic event acted as a critical trigger. These insights will support future risk mitigation strategies as well as the design and validation of stabilization works. Furthermore, new data from the monitoring network and geomechanical testing will enable more advanced numerical modelling efforts.

MERCURIO: sisteMa di monitoraggio intElligente e multiplaattafoRma per la siCUREzza dell'Infrastruttura ferrOviaria

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Abstract. L'obiettivo del progetto MERCURIO è lo sviluppo di un sistema innovativo di monitoraggio multiplaattaforma a supporto del processo di ispezione e manutenzione delle infrastrutture ferroviarie regionali. MERCURIO integrerà in un singolo strumento di supporto alle decisioni il risultato di una catena di elaborazione avanzata che, attraverso l'uso intensivo di tecniche di Intelligenza Artificiale, implementerà una strategia di data fusion, modulare e scalabile in grado di supportare una gestione intelligente degli asset. MERCURIO fa propria la necessità di dotare le infrastrutture ferroviarie regionali di uno strumento flessibile, che risponda alle criticità specifiche dei territori sui quali insistono, ottimizzando le procedure di manutenzione, prevenendo così, in maniera repentina, situazioni di criticità che possono incidere sulla sicurezza dei passeggeri e sui costi dettati dal fermo della linea e dagli interventi di ispezione in loco. Nello specifico, in questa nota saranno presentati i risultati preliminari ottenuti da un lato, a seguito delle installazioni in sito di sensori (inclinometri, piezometri, martinetti piatti, sonde capacitive, fessurimetri e assestimetri), dall'altro, ottenuti dalle elaborazioni di immagini satellitari SAR, capaci di monitorare differenti tipologie di fenomeni franosi che potrebbero interagire con l'infrastruttura ferroviaria.

Sinkhole risk assessment in an underground gypsum quarry through full-3D Electrical Resistivity Tomography

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Abstract. The mitigation of geological risks associated with mining exploitation generally requires accurate investigations and monitoring. Excavation changes the state of stress of the rock masses and can worsen the mechanical properties of rock volumes, often triggering instability phenomena. If the exploitation is performed in highly soluble rocks (e.g., limestone or gypsum), specific problems may be associated to the development of karst processes and related morphologies, including the opening of sinkholes or dolines at the surface.

The present study proposes the description of a case occurred in the underground gypsum quarry of Murisengo, near Turin. During spring 2025, a sinkhole of about 80 m in diameter formed at the surface of the quarry area, requiring dedicated investigations aimed at a description of the occurred phenomenon and at assessment of the sinkhole risk associated with the further advancement of the exploitation.

To achieve this aim, we planned a coarse, rapid, large-scale on-site geophysical survey. In detail, we chose to use Electrical Resistivity Tomography (ERT) technique since past research had demonstrated its potentiality in the identification of the contact between shallow sediments and the exploitable gypsum unit and produced solid correlations between electrical resistivity and compositional (and, in turn, mechanical) properties of gypsum.

Different from traditional 2D ERT routinary applied in several contexts, we employed the ERT in a full-3D mode, in order to investigate the whole 20-hectare area of the quarry in a unique survey. We then interpreted the results in the light of geological maps of the underground quarry deriving from previous traditional surveys, allowing for a calibration and a reliable interpretation of geophysical data.

The obtained 3D resistivity volume effectively located the sinkhole as a low-resistivity anomaly that extended several meters in depth. Other conductive areas were also correlated to previously documented sinkholes and lower-quality gypsum volumes.

Overall, the adopted approach demonstrated its effectiveness in the characterization of the gypsum unit, giving good results particularly in the identification of the main predisposing factors for the development of new sinkholes, being in detail the geometry of the articulate morphology of the top of the gypsum unit and the local variations of the mechanical properties of the gypsum unit itself.

The approach showed therefore good potentiality as a monitoring strategy since it was fast and accurate enough to effectively assess the emergency situation, detecting the main areas at risk, to be further investigated with geological and geotechnical studies.

Multi approach for monitoring landslide-induced displacements of the Gimigliano urban area (Calabria, South Italy) through in-situ investigation and SAR interferometry measurements

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Abstract. The reconnaissance, mapping, and monitoring of landslide-prone areas are crucial sources of data for evaluating the kinematic features and assessing the risk of landslides. Synthetic Aperture Radar Interferometry (InSAR) offers a valuable tool for quantitatively measuring long-term ground surface deformations induced by landslides. The technique provides highly reliable data, with millimetre precision, mostly in urbanised areas affected by slow ground displacement. The in-situ static monitoring sensors, such as inclinometers, represent a further technique that enables a valuable estimation of continuous deep displacements, providing a helpful integration with the previous ones. This approach is particularly effective in Calabria (southern Italy), where many urbanised areas are affected by diverse types and sizes of landslides, linked to rugged topography, tectonics, river deepening, rainfall regimes, and intense weathering processes.

The research aims to investigate the instability phenomena involving part of the Gimigliano village, in Catanzaro province (Calabria, southern Italy). The study was based on a geological and geomorphological field survey, integrated with InSAR remote sensing techniques, inclinometer sensor data, and borehole investigations. The topographic landscape is characterised by elevations ranging from 450 to 700 m a.s.l., with steep slopes carved by the Corace drainage network. The site lies within the “Sila Piccola” structural geological framework including both Liguride Complex (Jurassic–Cretaceous remnants of the Tethys Ocean) and Calabride Complex (late-Hercynian continental crust, locally with Meso–Cenozoic sedimentary). In particular, the Gimigliano surroundings are dominated by Liguride terranes, composed of serpentinite and greenschist rocks with a cover of metalimestones, marbles, metarenites, and metapelites. The Liguride terranes are overthrust by the Calabride terranes including schists and paragneiss.

The study area is also affected by intense tectonic deformation, responsible for significant fracturing, enhancing the weathering and degradation processes of the rocks. These processes cause physical and mechanical property decay of the rock masses, favouring the predisposition to instability in the area. The geological framework inevitably influences groundwater circulation due to the significant differences in permeability and fracturing of the rocks. Thereby, widespread landslides of different sizes, depths and states of activity characterise the Gimigliano municipality area. Sentinel-1 datasets, processed using both the SBAS and PS InSAR techniques, were employed to measure the preliminary displacement time series for the interval 2019-2024. The acquired data showed a ground movement rate ranging from 15 to -28 mm/yr and from 18 to -16 mm/yr for vertical and east components, respectively. Furthermore, InSAR data show a prevalent vertical and horizontal deformation in correspondence of landslide head and toe respectively. Inclinometer monitoring, used to measure deep displacements, recorded values up to 7 cm at a depth of 59 m. Finally, an analysis of rainfall data was performed to find a correlation between the last one and landslide activity. The complete integration of multi-source data enabled the construction of reliable landslide modelling.

A new low-cost inclinometer for landslide related structural health monitoring

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Abstract. Monitoring activities represent a crucial factor in assessing the evolution of slopes and the safety of infrastructures exposed to landslide risk. However, professional instruments may require significant economic investment; for this reason, building a dense sensor network to collect distributed data can often be challenging. A low-cost Arduino[®]-based 3-axis inclinometer has been developed with the aim of providing a valuable alternative to professional solutions, especially when widespread monitoring activities on low-budget projects are required. This sensor was designed to perform structural health monitoring (SHM) in diversified contexts and detect the damage level and its temporal evolution by measuring the angular rotations of structures. In particular, the device – characterised by a very compact size and low power consumption – can take tilting angle measurements along three directions (x, y, and z-axes) in a full range of rotation. These specifications offer significant advantages over most professional inclinometers, which typically detect angular rotation along one or two directions within a limited range. The proposed instrument is equipped with capacitive 3D-MEMS technology (Micro Electro Mechanical Systems) and features a SPI (Serial Peripheral Interface) digital interface chip, an online data transmission system, and local data storage. These features, in combination with the open-source Internet of Things (IoT) approach, allow for the low-cost inclinometer to fit in multiple monitoring environments. Preliminary field tests were performed in various landslide contexts to evaluate the reliability and versatility of use of the device.

Thermal Effects on Soil Water Repellency: Implications for Post-Fire Slope Stability

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Abstract. Wildfires are among the most impactful natural phenomena affecting ecosystems. Their increasing frequency and intensity, largely driven by climate change and human activity, have raised growing concern within the scientific community and among environmental protection organisations. Beyond the immediate destruction of vegetation, wildfires trigger a series of cascading effects within the environmental system, significantly modifying shallow processes. In mountainous regions, where hydrological and geomorphological vulnerability is already high, these processes can severely compromise slope stability and the safety of local communities.

Wildfires significantly alter the hydrological and geo-mechanical properties of soils, often increasing the susceptibility of slopes to shallow landslides and debris flows. Several authors have reported that, among the fire-induced alterations associated with slope failure predisposition, the development of soil water repellency plays a crucial role in controlling post-fire infiltration dynamics and runoff generation. However, depending on vegetation coverage and organic matter content, soil water repellency may already characterize slopes prior to wildfires. Laboratory studies have shown that the onset of soil water repellency is strongly influenced by temperature, soil composition and organic matter content, whereas its breakdown occurs at higher temperatures. Yet, the direct contribution of temperature-induced changes in soil water repellency to slope failure processes remains unclear.

The present study investigates how temperature the development and breakdown of soil water repellency, and how this property influences infiltration. Laboratory experiments were conducted on both homogeneous and heterogeneous soil samples subjected to controlled thermal treatments within temperature ranges recognised as representative of soil water repellency initiation and degradation under wildfire conditions. The tested materials included a commercial quartzose sand (non-repellent), natural soil collected from a conifer-forested slope in Sorico (Northern Italy, water-repellent), and their mixtures. After heating, the hydrophobic behaviour was assessed through water drop penetration time (WDPT) tests, while the hydraulic conductivity was evaluated using a permeameter. Unheated samples were used as reference to quantify the temperature-induced variation.

Results reveal a temperature-dependent response only in samples containing organic matter: moderate heating promotes the development of soil water repellency, while higher temperatures lead to its degradation through the thermal breakdown of organic compounds responsible for hydrophobicity. Moreover, differences in thermal conductivity among the tested materials produced heterogeneous responses to heating, suggesting a non-uniform reduction of repellency even after prolonged exposure to elevated temperatures.

These findings indicate that temperature exerts a complex control on soil wettability and, consequently, on post-fire infiltration behaviour.

Italy-Wide Landslide Susceptibility from Regional Random Forest Models: Upper Oglio Basin Case Study

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Abstract. The assessment of landslide susceptibility is a key aspect of territorial risk management and is crucial for the planning and maintenance of safe infrastructure. Among the different types of landslides, soil slips and debris flows are the most challenging to predict and monitor, due to their rapid onset and strong dependence on local geological and hydrological conditions and are therefore particularly hazardous to infrastructure. In this study, a landslide susceptibility map covering the entire Italian territory was developed using the Random Forest algorithm with cross-validation, a statistical resampling technique that assesses model performance by repeatedly training and testing the model on different subsets of the data. To account for local variability, separate models were trained for each region and then combined to produce a consistent national-scale susceptibility map.

In addition to conventional predictors such as geological and geomorphological characteristics, the model incorporates the Curve Number parameter to account for maximum soil infiltration capacity, thereby integrating hydrological behaviour into the susceptibility assessment. The National Landslide Inventory (IFFI) was used for model training and validation, including translational and rotational slides, complex movements, earth flows, and shallow landslides. IFFI polygons classified as “debris flows” were excluded from the training and validation datasets, as they generally represent accumulation areas rather than source zones. Since the inventory contains only manually mapped landslides, areas not included in it should not be interpreted as non-landslide-prone, but rather as unclassified. The algorithm’s output then quantifies how closely each pixel resembles the characteristics of known landslides.

The resulting susceptibility map provides a robust framework for identifying areas potentially prone to landslides, supporting risk mitigation strategies and infrastructure planning at both regional and national scales. To evaluate the map’s effectiveness, the upper Oglio River catchment (Val Camonica valley, northern Italy) was analysed. This area, crossed by a railway line repeatedly affected by debris flows, was subdivided into sub-catchments where the Melton Index, quantifying gravitational energy, and Bovis classification, describing debris supply conditions, were computed. The comparison of susceptibility results with historical events and the analysed indices confirmed the map’s ability to highlight areas most prone to debris-flow initiation, providing valuable information for assessing infrastructure exposure.

Optimizing Landslide Susceptibility Mapping Units Through Slope-Area Process Domain Analysis

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Abstract. Slope units are geomorphological subdivisions of the terrain bounded by drainage, designed to maximize internal homogeneity and external heterogeneity across distinct morphological units. They are commonly used in landslide susceptibility mapping under the assumption that the complete landslide kinematics - initiation, propagation, and accumulation - occur within a single unit. However, slope units can be too large, or too small, to accurately envelope the entire landslide dynamics, based also on their different types. Moreover, non-optimal slope unit delineation may over-smooth terrain variables, leading to misleading zonal statistics; for instance, averaging slope gradients can obscure sharp transitions that are critical for landslide triggering.

This study introduces a methodology to optimize the internal partitioning of slope units using the Slope–Area (S–A) relationship, a well-established geomorphological proxy for identifying local process domains. The S–A plot, derived from high-resolution digital elevation models (DEMs), expresses the empirical relationship between local slope (S, m/m) and contributing area (A, m²), allowing a process-based reclassification of the landscape. An additional innovative component of this approach is the inclusion of spatial rainfall variability by computing a rainfall-weighted S–A function, where flow accumulation is multiplied by the precipitation rate (R, m yr⁻¹) to approximate discharge (A·R, m³ yr⁻¹). This enables the derivation of both unweighted and precipitation-weighted drainage networks for each catchment.

The resulting S–A diagrams reveal five distinct scaling regions, each associated with a characteristic geomorphic process domain. This analysis allowed the identification of the S–A domains most frequently associated with landslide initiation and deposition, for each landslide type, enhancing the evaluation of landslide susceptibility across different parts of the slope.

The methodology was applied to a sub-portion of the Emilia-Romagna region using a 5-meter pre-event DEM and the 2023 landslide inventory (Berti et al., 2025). Both weighted and unweighted flow accumulation values, derived from May 2023 precipitation data, were considered to refine the S–A characterization and improve the spatial representation of landslide-prone areas.

Integrating Field Monitoring and Remote Sensing for Assessing Soil Moisture Dynamics in Volcanic Mountain Environments

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Abstract. Mountain slopes mantled by pyroclastic soils are highly susceptible to intense rainfall events, which can induce shallow landslides through rapid changes in near-surface hydrological conditions. Understanding the temporal evolution of soil moisture is therefore crucial for assessing slope stability and improving landslide hazard evaluation.

Although in-situ measurements provide precise insights into soil hydrology, their spatial coverage is inherently limited. In contrast, remote sensing offers extensive spatial information but requires ground-based validation to ensure accuracy. This study integrates field monitoring data with multispectral satellite observations to investigate the spatial and temporal variability of soil moisture across two experimental sites in the Lattari Mountains (Southern Italy).

Long-term hydrological datasets and spectral information from Sentinel and Landsat imagery are employed to analyze several vegetation - and water-related indices, assessing their sensitivity to hydrological changes in volcanic soils.

Preliminary results reveal strong correlations between remote-sensing indices and field-based measurements, indicating that multispectral data can effectively capture short-term variations in near-surface soil moisture. The proposed framework offers a scalable and cost-efficient method to enhance rainwater infiltration and consequently slope stability assessments with the final aim to support early-warning systems for rainfall-induced landslides.

DEM resolution effects on landslide susceptibility mapping: a multi-method comparison in Oregon study area

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Abstract. Landslides are among the most destructive natural processes on Earth and represent a constant threat to communities and local economies. Spatial and temporal prediction of landslide occurrence is a major challenge in slope instability analysis and risk mitigation. In recent decades, research has focused on developing different methods to analyze the factors involved and improve landslide susceptibility, hazard and risk models. This study focuses on landslide susceptibility assessment in Oregon state, using a multi-method comparative approach and integrating two digital elevation models (DEMs) of different spatial resolutions. The work is part of RETURN project, which stands for multi-Risk sciENCE for resilienT communities under a changiNg climate, specifically the VS2 Spoke, which deals with the analysis of ground instabilities. The aim is to understand the influence of DEM resolution on the accuracy and spatial detail of susceptibility mapping, as well as the comparison between the results obtained through the different approaches and those deriving from the use of a VS2 tool (the “WP2-box”), which estimates the susceptibility. The analyses were carried out using spatial data, in particular two DEMs with resolutions of 30 m and 10 m, and several predisposing and preparatory factors, including morphological, geological, hydrological, environmental and climatic parameters, and a landslide inventory map. A multi-method approach, integrating statistical analysis, multi-criteria decision techniques and machine learning algorithms, was applied to generate landslide susceptibility models for both DEM resolutions. The methodologies were Weight of Evidence (WoE), Analytic Hierarchy Process (AHP), and Random Forest (RF), subsequently combined to develop an ensemble susceptibility model. Two of these approaches are also included in the aforementioned “WP2-box”, thus, this tool was employed to execute the models, and the resulting outputs were subsequently compared to highlight possible discrepancies. The results indicate that susceptibility maps derived from the same technique, but with different DEM resolutions, show general consistency in the identification of susceptible areas, although some variations emphasize the influence of spatial resolution. Some models gave the most accurate results, with areas of susceptibility closely matching the position of landslide bodies. Moreover, as regards the comparative analysis, many differences were noted between the various maps, despite both validations being correct and returning good AUC values. In conclusion, it can be stated that these results underline the key role of susceptibility patterns and spatial input data type in providing essential information for effective spatial planning and risk management, especially in built-up/urban areas.

The real length of the infinite slope: the critical L/H threshold

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Abstract. The Infinite Slope Method (ISM) is widely used in geotechnical engineering to provide a quick and practical calculation of slope stability. However, its accuracy is fundamentally conditional on a key geometric assumption: that the landslide length (L) significantly exceeds its thickness (H). This study addresses a question fundamental to this main assumption: how long a slope must be, to be effectively considered "infinite". To precisely quantify this threshold, we propose an innovative and easily applicable extension of the Infinite Slope Method, based on the evaluation of the stress in the slope. This simple, but innovative approach is specifically designed to determine and quantify the stabilizing impact of the landslide toe on the overall factor of safety (FS). The model was validated against real-world field data, enabling a comparison between the results obtained from the proposed model and field observations. A comprehensive sensitivity analysis was then performed with the explicit aim of defining the critical L/H ratio beyond which the slope effectively behaves as an infinite slope, and the influence of its finite length can be considered negligible. Results provide a clear quantitative boundary: for landslides with an L/H ratio below 25, the stabilizing contributions of the finite length are significant. Keywords: Toe landslide, Infinite slope, Slope Stability, L/H ratio.

Landslide - infrastructure interaction: the case history of a bridge on river Lao (Calabria Region – Southern Italy)

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Abstract. Slow gravitational slope deformations pose a significant and complex geomorphological hazard, with direct implications for the stability of critical road infrastructure, particularly bridges. This study investigates the slow gravitational deformation process that affected a bridge over the Lao River close to the bound between Calabria and Basilicata regions. The area is characterized by slow movements that are not always immediately detectable, which can be indicators of broader-scale instability, often related to the intrinsic dynamic context of the territory. These complex dynamics also interact with the Lao River, leading to the diversion of its course. To analyze these dynamics, a combined approach was used, integrating differential analysis of Digital Elevation Models (DEMs), geological analysis, and morphological interpretation of the area. The position and the presence of vegetation made it non possible the use of SAR-based interferometry, available through the European Ground Motion Service (EGMS) portal (<https://egms.land.copernicus.eu>). The used methodology are classic in-situ geological and geomorphological surveys combined with modern geomorphometric analyses based on the processing of LiDAR data. This allows for highlighting and quantifying slow, but persistent annual displacements affecting the portion of the territory interacting with the infrastructure, confirming a continuously evolving dynamic. This research contributes significantly to the understanding of slow deformational activity of slopes and their interaction with infrastructure, offering crucial insights for geo-engineering and geotechnical risk management, especially regarding slope-bridge interaction. Keywords: Slow Gravitational Deformation, Slope Stability, bridge-landslide interaction, LiDAR data.

Unsupervised classification of Ground Displacement Time series Patterns Using an Autoencoder-Based Approach

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Abstract. Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) has become a crucial technique for monitoring ground deformation, with broad applications in landslide detection, land subsidence assessment, and infrastructure stability evaluation. Existing products, such as the European Ground Motion Service (EGMS), provide detailed Sentinel-1-based measurements for millimetre-scale ground monitoring across almost the European continent. However, processing large-scale InSAR datasets in an automated way remains difficult. Efficient automated methods are needed to transform vast amounts of ground motion data into information that is easily interpretable and accessible to nonexpert users and end-users.

There are three main challenges in our application. First, it is practically infeasible to manually label a sufficient amount of true deformation data. Second, most models require complete and regular time series, but in practice some data are missing due to snow cover, atmospheric disturbances, or operational issues. Third, the time series itself contains multiple superimposed components, including seasonal variations, long-term trends, which complicate modeling and analysis.

In this study, we investigate the application of unsupervised methods combined with deep learning to analyze large-scale InSAR displacement time series. To handle missing data, a dedicated module is incorporated into the model. Specifically, we design an autoencoder network that compresses each time series into a lower-dimensional latent representation. The latent features capture the main temporal patterns while reducing noise and redundancy. The latent representations are then used for clustering, allowing the identification of distinct ground deformation behaviors directly from the data. The resulting clusters are first interpreted qualitatively by comparison with regional event inventories. Subsequently, quantitative analysis is performed using time series decomposition to examine the temporal characteristics of each cluster and better understand the underlying deformation processes.

This study demonstrates the potential of unsupervised learning for automatic analysis of ground deformation, providing a useful tool for future geological investigations and risk assessment.

Assessment of slope processes in a deep-seated rockslide-earthslide by integrated investigation and monitoring: Brugneto case study (Northern Apennines, Italy)

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Abstract. The analysis of long-term slope deformation processes and their controlling factors in large deep-seated complex landslides holds relevance with respect to hazard and risk assessment and for the identification of possible mitigation measures. The Brugneto landslide (Northern Apennines, Piacenza province, Italy), is a remarkable example of a complex deep-seated slope failure transitioning from rock sliding in the upper sector to earth sliding at the toe. The landslide area extends over 118308 hectares and is classified at high hydrogeological risk zone under Law 267/98. As a matter of facts, slope movements have periodically accelerated over the last decades, most recently in 2008 and 2015, damaging the Brugneto village as well as another minor hamlet and local roads.

To achieve a comprehensive understanding of its internal structure and of the active slope dynamics, a multi-source data integration approach was adopted. The analysis combined different surface investigation methods, such as geological-geomorphological surveys, supported by high-resolution LiDAR-derived DTM (2022), continuous GNSS monitoring (from 2023 until nowadays), site-specific InSAR data analysis (including multitemporal interferometry and interferogram stackings, from October 2014 to March 2024). Furthermore, it also considered subsurface data obtained by geophysical investigations and boreholes, as well as by inclinometers (2024-2025). Rainfall records from a nearby gauge complete the dataset, allowing for an analysis of the rainfall-displacements correlation.

The integrated approach resulted in the identification of two main distinct morpho-kinematic sub-units, moving at velocities ranging from 2 mm/yr to 30 mm/yr, both showing a limited variability of movement rates during the year. The main sub-units can be further subdivided into elements on the basis of surface and subsurface features, showing that multiple sliding governs the evolution along the slope. All the available information, have been summarized into reference longitudinal cross sections, which depict the shape and extent of sub-units and elements, which are separated by multiple sliding surfaces extending down to the depth of 70 m.

This study provides a robust geological interpretation of the Brugneto landslide, and it demonstrates how its complex internal structures controls its multi-mechanism behaviour. The findings offer also a critical reference for similar slope deformation processes in the Northern Apennines, or similar phenomena elsewhere and provide a solid geological basis for improved hazard assessment and targeted mitigation strategies in this and in other comparable geological contexts.

Challenges in 3D subsurface reconstruction and geotechnical characterization for 3D slope stability evaluation in urban areas: a case study in Chieti's Hill (Abruzzo, Italy)

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Abstract. In recent years, 3D Engineering Geological Models (EGMs) have been increasingly developed to support slope stability analyses by managing the complexity of geological conditions through an integrated framework that enables volumetric visualization of subsurface geometries and geotechnical properties. When accurately constructed, based on multidisciplinary investigation campaigns carried out by geological surveys, geophysical prospections, borehole logs, laboratory analyses, and in-situ hydro-geotechnical tests, 3D EGMs allow a digital realistic reconstruction of the subsurface geological setting. Despite their advantages, EGMs still face several challenges, particularly in urban environments, where restricted accessibility and pronounced anthropogenic disturbances hinder effective data acquisition and model reliability.

The present study aims at investigating the sliding mechanisms of the northwestern zone of Chieti's hill (Abruzzo Region - Central Italy) to perform a 3D static and dynamic slope stability numerical analyses. From a geological point of view, the study area is characterized by the Mutignano Formation (FMT), a thick succession of marine deposits (clays, sands, and conglomerates) dating from the Upper Pliocene to the Middle Pleistocene. Above the FMT, quaternary deposits such as fluvial, alluvial, eluvial-colluvial, and landslide soils are visible along the hillsides as geomorphological features of detachment and accumulation. The large unstable slope is highly anthropized, which greatly restricts the availability of natural outcrops for direct geological observations of the active gravitational movements of complex genesis.

The landslide-affected areas were also delineated by identifying damaged buildings and analyzing satellite imagery, especially Sentinel-1 InSAR data from the Copernicus European Ground Motion Service.

The mechanical behavior of the soils subjected to landslides was defined through the geotechnical parameters gained by laboratory and in situ testing. Where direct experimental data were lacking, reference values were obtained from international scientific literature and Seismic Microzonation (SM) studies conducted in the municipality of Chieti. A robust geotechnical characterization was achieved by balancing experimental data with literature values.

A comprehensive sensitivity analysis was carried out on the main geotechnical and hydraulic parameters that control slope stability, with particular attention to effective cohesion, friction angle, and pore-water pressure, as these variables exert the greatest influence on the overall stability framework.

The results highlight that adopting a homogeneous model, in which average parameters values are uniformly assigned to the entire slope mass, leads to an oversimplification of the problem. In contrast, the heterogeneous model, which incorporates for the spatial variability of material properties and hydraulic conditions, offers a more realistic representation of slope behavior. This model captures the complex distribution of stresses and strains, allowing the identification of zones that are more susceptible to deformation and failure.

Monitoring and FDEM numerical modelling of tuffaceous coastal cliffs: the case study of Ventotene Island

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Abstract. Tuffaceous cliffs represent common geological systems in Italy, and they are particularly vulnerable to degradation processes induced by meteo-climatic factors. Despite their relevance, the mechanisms governing the evolution of these systems remain partially unexplored.

This research focuses on the case study of the Punta Eolo cliff (Ventotene, Italy), a coastal promontory composed tuffs subject to frequent collapse phenomena.

To quantitatively characterize the interrelations between climate forcing and cliff evolution, a multi-parametric monitoring system named “Ventotene Field Laboratory” (VFL) was inaugurated in May 2024. The VFL represents one of the first applications of continuous integrated monitoring on coastal cliffs. The system continuously records: (i) the deformative response of the rock mass; (ii) subaerial forcing; (iii) marine forcing through an Acoustic Wave and Current profiler (AWAC) and dynamic pressure transducers installed on the submerged cliff face.

The VFL dataset has been integrated with an advanced numerical modelling framework based on the Finite-Discrete Element Method (FDEM), specifically designed to simulate Progressive Rock Failure (PRF) mechanisms in fractured rock masses. The FDEM approach, implemented in Irazu software, allows explicit representation of fracture initiation and propagation within initially intact rock, capturing the transition from continuum to discontinuum behavior that characterizes tuff cliff failures. Thermo-mechanical coupled analyses reproduced the propagation of daily and annual thermal waves through the rock mass, while dynamic analyses incorporated wave-induced pressure distributions derived from monitoring data to assess the mechanical response to marine forcing.

In this research a novel methodological contribution was implemented by using S-N fatigue degradation curves within the FDEM framework to simulate the cumulative effect of cyclic environmental stressors on mechanical property decay of the tuffs. This approach couples progressive basal notch excavation, calibrated through Sunamura's erosion model, with time-dependent strength reduction of overlying parietal portion of the cliff. The degradation process involves the progressive decay of different rock mass strength properties as a function of loading cycles, representing the integrated effect different climatic stressors. Simulations spanning approximately 200 years of evolution demonstrate that the system requires roughly 80 years to reach initial destabilization, manifested by basal collapses, followed by detachment of 2-4 m wide rock blocks through toppling kinematics at recurrence intervals of 40-50 years—timescales consistent with historical records for the Ventotene cliffs.

To further constrain the fracture mechanics parameters required by FDEM modelling, a laboratory program consisting in tensile and three-point bending tests is currently underway. This experimental framework represents a crucial advancement in parameterizing FDEM models for soft pyroclastic rocks, where direct fracture mechanics data remain scarce in the literature.

The integrated approach demonstrates that climate-related factors act as preparatory mechanisms operating over pluriannual timescales, progressively weakening the cliff system through distributed damage accumulation. The FDEM method successfully reproduces realistic PRF sequences without requiring predefined discontinuity networks or unrealistically deep basal notches. The Ventotene case study establishes a replicable methodological framework applicable to analogous coastal contexts worldwide, particularly relevant for Mediterranean volcanic coastlines and potentially transferable to other lithologies with appropriate site-specific calibration.

Multi-scale numerical modelling of tunnels intersecting large and active landslides

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Abstract. The interaction between landslides and transportation infrastructure represents a critical challenge in mountainous regions worldwide, with significant implications for public safety, economic stability, and regional connectivity. This work addresses this issue by focusing on a persistent research gap termed the multi-scale challenge: the difficulty of simulating localized infrastructure damage induced by large-scale landslide processes within computationally feasible frameworks.

Commonly, numerical modelling of landslide-infrastructure system (LIS) interaction sacrifice resolution for one system component (landslide or infrastructure) to improve computational efficiency for the other. Landslide-centric models, for instance, allow sophisticated slope analyses to be performed, but treat infrastructure as simplified boundary conditions. On the other hand, infrastructure-centric models attain high structural resolution but prescribe landslide-induced actions as uniform loads, oversimplifying complex slope processes. Even systemic approaches, which explicitly incorporate both elements, face computational constraints in terms of mesh resolution, often focusing on smaller landslides or specific interaction mechanisms rather than complete LIS behavior. To overcome this limitation, this research developed a comprehensive multi-scale modelling approach, adapting nested modelling principles to geomechanical and structural engineering applications. The approach explicitly separates spatial scales while establishing rigorous procedures for mechanical data transfer. A landslide-scale model captures bulk slope behavior and stress distributions, while a infrastructure-scale model focuses on detailed structural response. Custom Python and FISH scripts are used to extract velocity fields and stress tensors, which are then transferred from the landslide- to the infrastructure-scale model, enabling infrastructure boundary conditions to be derived directly from landslide simulations.

The methodology is validated through application to the Passo della Morte landslide in the Carnian Alps of Friuli-Venezia Giulia region, Italy. This site is characterized by a 24-million-cubic-meter active rock-block slide (moving 2-3 cm/year) affecting a 2200-meter road tunnel supported through a segmented pre-cast concrete lining. The case provides extensive geological characterization, several years of monitoring data (inclinometers, GNSS, crackmeters), and detailed site documentation, both essential prerequisites for developing the multi-scale framework. The landslide-scale model, developed using FLAC3D, encompasses the entire slope with strategic mesh refinement within the “extraction volume” surrounding the tunnel, with a progressively coarser discretization towards model boundaries. The model successfully reproduces observed displacement gradients, with good comparison against inclinometer profiles and GNSS measurements. The infrastructure-scale model, implemented in 3DEC, focuses on a 108-m-long section of the tunnel, which includes the most severely damaged segments. This configuration enables analysis of intra-segment deformation and inter-segment joint behavior, critical for evaluating the effectiveness of the segmented lining design in accommodating landslide movement. The multi-scale numerical analysis shows that the tunnel model develops roto-translational deformation patterns consistent with field observations and measurements.

This research establishes that the multi-scale challenge can be effectively addressed through nested modelling strategies maintaining both computational efficiency and physical accuracy. The methodology represents a solid pathway demonstrating technical feasibility and identifying requirements for advancing landslide-infrastructure interaction analysis toward mature frameworks supporting evidence-based infrastructure management in landslide-prone regions.

InSAR Analysis of Ground Displacement at the Hatfield Moors Underground Gas Storage Site: Implications for Future Carbon Capture and Storage Applications

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Abstract. Underground Storage Systems (USS) are increasingly recognised as critical infrastructures in the global energy transition towards net-zero Carbon Dioxide (CO₂) emissions, as emphasised by the Intergovernmental Panel on Climate Change (IPCC). Among these, Underground Gas Storage (UGS) and Carbon Capture and Storage (CCS) play complementary roles: UGS ensures a reliable gas supply during the transition period, while CCS provides a long-term solution for carbon sequestration. This study uses free and open-source advanced spaceborne remote sensing data, provided by the European Ground Motion Service (EGMS), to investigate ground displacement processes associated with UGS operations at the Hatfield Moors site (United Kingdom). The aim is to support environmental integrity assessments for future CCS deployment. Hatfield Moors is a depleted natural gas reservoir that was converted for UGS in 2000 and is located beneath a sensitive peatland ecosystem. The site provides a valuable opportunity to assess the potential of UGS facilities as prototypes for CCS, highlighting the importance of robust monitoring methodologies. Operations involve cyclical gas injection and withdrawal to meet seasonal energy demands, generating measurable surface displacements caused by poroelastic responses in the reservoir, which are subsequently transferred to the surface. It is important to detect and interpret these deformations in order to interpret reservoir behaviour and understand how such motions might be used in a CCS context to ensure regulatory compliance. Interferometric Synthetic Aperture Radar (InSAR) is a powerful tool for detecting millimetre-scale ground displacements with high spatial and temporal resolution. The InSAR analysis performed over Hatfield Moors reveals clear seasonal patterns in ground displacement above the reservoir. However, these patterns are not correlated with the operational cycles of gas injection and withdrawal. Specifically, uplift is observed during withdrawal phases, while subsidence occurs during injection periods, the opposite behaviour to that expected from reservoir pressure variations. This discrepancy suggests that displacement signals are primarily governed by external environmental factors rather than UGS-induced operations. Cross-correlation analyses between InSAR-derived displacement time series, piezometric data, and regional precipitation records show a strong relationship between surface movements and groundwater level fluctuations. Periods of increased rainfall and rising groundwater correspond to surface uplift, whereas dry periods and declining groundwater level result in subsidence. These results emphasise the dominant role of hydrological dynamics in controlling surface displacement in peatland environment. Integrating InSAR observations with environmental and operational datasets improves the reliability of deformation interpretation and supports the development of robust monitoring frameworks for both active UGS sites and prospective CCS projects. The study also highlights the dual importance of peatlands as both vulnerable environments and critical carbon sinks. Maintaining stable groundwater levels is essential to prevent peat oxidation and subsidence, processes that release stored carbon and compromise ecosystem services. In this context, InSAR monitoring not only may support geotechnical safety but also contributes to peatland conservation and climate mitigation strategies. The methodologies developed at Hatfield Moors provide a scalable framework for evaluating ground displacement and environmental integrity in future CCS projects, demonstrating the broader potential of Earth observation in supporting sustainable underground resource management.

Methodological Approach for Special Inspections and Level 4 Assessments in the Context of the study of slope–Bridge Interaction according to the Italian Guidelines for the Classification and Risk Management of Existing Bridge

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Abstract. The Guidelines for the Classification and Risk Management, Safety Assessment, and Monitoring of Existing Bridges (Ministerial Decree No. 204/2022) establish a multilevel (from Level 0 to Level 5) and multidisciplinary framework for managing the risk associated with road infrastructures. This framework is based on the definition of “attention class” for different types of risk, including structural, hydraulic, and seismic hazards, as well as risks related to slope–bridge interactions.

Levels 0 to 3 outline a preliminary knowledge-gathering process aimed at defining an attention class for each of the risks considered. This process identifies the bridge that requires further investigation and more detailed safety assessments, which are developed through Special Inspections and Level 4 Assessments. These represent the most advanced stages of the knowledge and verification process, aimed at achieving an accurate evaluation of the interaction between bridges and slope instability phenomena.

In the Guidelines Special Inspections are well defined for structural risk, while for the other risk it is precise that they must also be carried out for bridges located in areas subject to flood, erosion, or landslide processes, or in zones recognized as having a high hydrogeological risk, where potential interference with the structure is evident. However, the specific conditions under which such inspections should be undertaken, as well as the procedures to be followed, are not yet clearly defined as for structural risks. The Level 4 is implemented through the (Project of knowledge), an integrated process that combines document analysis, in-situ and laboratory investigations, detailed geological and geotechnical modelling, and numerical analyses aimed at the quantitative estimation of the safety of the slope–infrastructure system. This stage enables the progressive development of increasingly reliable knowledge models, supporting risk mitigation and management decisions.

The paper aims to illustrate the methodological approaches that the authors have used working in the context of the activities developed within the GEO-Poliba group of the Fabre Consortium to define when and how to develop Special Inspections and Level 4 Assessments.

Technical satellite for natural Hazard in the internal area of Basilicata region (Southern Italy) – The case history of Stigliano town

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Abstract. The inland areas of the Basilicata Region are particularly exposed to natural hazard phenomena related to slope instability due to the intrinsic geological and geomorphological dynamics that led to their generation. Satellite observation techniques and remote sensing applications allow for an objective evaluation of ongoing ground deformation processes, providing valuable support for decision-making aimed at territorial risk mitigation and land preservation.

The research activity focused on a specific case study within the Basilicata region: the town of Stigliano, located in the province of Matera, which was selected as a test case. The main objective was to analyze slow ground movements, which are not always immediately detectable, but may act as precursors of paroxysmal events, such as those that occurred in the southern outskirts of the town during January–February 2014.

The gravitational deformation phenomena affecting Stigliano area are partly known, although never specifically investigated, mainly because their slow kinematics made monitoring difficult before the advent of interferometric satellite-based techniques. The present study was developed using Advanced Differential Interferometric Synthetic Aperture Radar (A-DInSAR) data, available through the European Ground Motion Service (EGMS) portal (<https://egms.land.copernicus.eu>).

The analyses carried out so far have highlighted and quantified significant deformations affecting the northeastern side of the town, showing a continuously evolving dynamic. Satellite data indicate for this area a subsidence rate of approximately 4 mm/year and a horizontal displacement toward the west of about 2.4 mm/year. Overall, the entire side exhibits comparable movements, with subsidence rates of 3–3.5 mm/year and horizontal displacements toward the northeast, consistent with the mechanics of lateral spreading phenomena.

Using explainable AI and GNSS integration to investigate rainfall-driven landslide processes

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Abstract. Landslides are a widespread hazard in Italy, but Landslide Early Warning Systems (LEWS) can help reduce and mitigate this risk through non-structural measures. Research on LEWS has advanced considerably over the past decade, owing to improvements in monitoring technologies and data analysis. However, identifying landslide-triggering factors remains challenging, as these vary across time and space. A comprehensive understanding of these factors is essential for effective natural hazard assessment. Combining recent low-cost GNSS instruments with existing precipitation monitoring networks can significantly enhance the performance of a LEWS. In this study, a continuous early warning system designed to investigate the role of rainfall as a triggering factor was applied to a complex deep-seated landslide in the Carnic Alps, north-eastern Italy. The Cazzaso landslide monitoring system, installed in 2016 by the CRS (OGS) in collaboration with the Regional Civil Protection, continuously records displacement data from 12 GPS and 2 GNSS stations. Displacement time series from the geodetic network and precipitation data from two rain gauges were analyzed and compared. By applying a velocity threshold to the geodetic data, an inventory of landslide reactivation events was developed—a novel step that provides valuable insights for further analyses and for enhancing or updating LEWS performance. The Cazzaso landslide was found to be primarily triggered by rainfall, prompting the use of empirical rainfall thresholds (Intensity–Duration, or I–D thresholds) to define early warning levels. However, validation of these thresholds showed limited reliability, likely due to the complexity and depth of the landslide, which cannot be fully captured by simple statistical approaches. To address this limitation, a more advanced methodology combining a Random Forest (RF) model with Explainable AI (XAI) techniques was adopted. Specifically, the Out-of-Bag Error (OOBE) was used to assess the importance of different variables, while Partial Dependence Plots (PDPs) were employed to visualize their influence. The machine learning analysis identified 8-day cumulative rainfall as the most effective predictor of landslide reactivation, allowing for the definition of reliable thresholds to support the GNSS-based warning system. This integrated approach not only enhances the operational effectiveness of the early warning system but can also be adapted to assess the impact of short- and long-term rainfall in diverse geological and climatic contexts. Although the system is site-specific, its structure provides a useful framework for similar cases and offers potential applicability to broader settings.

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Interrelations Between Hydro-Geomorphological Disasters and Urbanization in Italy

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Abstract. Hydrogeological risk represents a persistent and complex challenge worldwide, and particularly in Italy, where hydro-geomorphological disasters (floods and landslides) have caused severe damage to the urban environment, infrastructure and, in severe cases, even loss of human life. While climate change is widely acknowledged as a key driver shaping the frequency, intensity, and duration of such events, their impacts are strongly influenced by a combination of environmental and anthropic factors. This study aims to investigate the underlying drivers that shape the spatial distribution, temporal persistence, and societal consequences of these disasters. The analysis draws upon the Italian Civil Protection database of national emergency declarations, reprocessed to derive two key indicators for each province over a twelve-year period (2013–2024): the cumulative count of declared emergencies and their total duration (in months). These two indicators were used to assess the recurrence and persistence of hydro-geomorphological impacts across the national territory. Spatial analysis revealed that the distribution of both indicators, particularly the duration, is non-random and exhibits well-defined spatial patterns. To identify potential explanatory factors, these variables were integrated into a model designed to explore correlations with a comprehensive set of environmental and anthropic indicators. Approximately sixty variables were selected and filtered from two publicly available databases. For each model iteration, four statistical parameters were computed to evaluate the strength and significance of correlations. Results indicate a strong positive correlation between soil sealing in areas classified as intermediate hydrogeological risk and the temporal persistence of disaster impacts. A temporal trend analysis further revealed that soil sealing in these areas continues to increase at a rate of approximately 1% per year. This finding highlights the critical role of consumed land and urbanization processes in amplifying hydrogeological disaster impacts and underscores the urgent need for more effective urban planning and land management strategies to mitigate future risks.

Advanced Data-Driven Mapping of Soil Water Content and Pore Water Pressure for Operational Landslide Prediction

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Abstract. Shallow landslides induced by heavy rainfall represent a significant geohazard globally, causing severe damage to infrastructure and posing risks to human life. Current regional early warning systems primarily rely on rainfall intensity and duration thresholds, which often provide limited prediction accuracy due to their failure to account for subsurface conditions.

It is well established that the actual triggering mechanism for most rainfall-induced landslides is the change in the subsurface hydrological state, specifically the increase in Soil Water Content (SWC) and Pore Water Pressure (PWP). Therefore, the development of robust and accurate methods for spatio-temporal mapping of these hydrological fields is critical for enhancing predictive capabilities. While the importance of SWC and PWP is widely recognized, a major challenge lies in developing methodologies that are both highly accurate and easily reproducible for the reconstruction of maps of these parameters at large scale.

Current methods are often constrained by the complexity of physically-based models or the limited depth of sensing data, as remote sensing and sensors in the earth only captures very shallow (3–10cm) SWC. This work addresses this gap by proposing a novel, data-driven framework designed for operational simplicity and ease of application. We leverage long-term, multi-depth monitoring data from the Oltrepò Pavese area to develop a robust spatio-temporal prediction methodology.

The study area is the Oltrepò Pavese, an area in north of Italy (Lombardy region) at the northern termination of the Apennines. This area was chosen for its high susceptibility to rainfall induced shallow landslides. In fact, more than 2000 shallow landslides were triggered last 15 years.

Our approach focuses on using machine learning to accurately reconstruct deep-layer SWC and PWP profiles also from easily measurable, shallow-layer soil moisture, meteorological variables, and geomorphological attributes. The resulting high-resolution hydrological maps could be integrated into stability models, offering a tangible improvement in the reliability and operability of landslide early warning systems.

Enhanced mapping and modeling of multiple debris flow by LiDAR-based fixed wing UAV surveying

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Abstract. Debris flows are a major geo-hydrological hazard in areas with steep slopes and unconsolidated deposits. Accurate characterization of source areas and flow paths is essential for hazard assessment and for planning mitigation measures. In contexts where initiation zones are distributed across multiple slopes or small catchments, traditional terrestrial surveys or multicopter UAV techniques are limited in spatial coverage and continuity.

To overcome these limitations, this study proposes a methodological approach based on fixed-wing UAVs equipped with LiDAR and high-resolution cameras, aimed at the synoptic mapping of multiple debris flow channels and the quantitative assessment of morphological changes.

Survey campaigns enabled the generation of high-resolution Digital Terrain Models (DTMs) and the derivation of elevation difference models using GIS-based techniques, allowing the estimation of eroded and deposited volumes, the delineation of source areas, and the identification of main flow paths through flow accumulation and watershed analysis algorithms.

Analysis of multitemporal surveys, conducted a few months apart, revealed that the most significant erosional processes are concentrated in the upper portions of slopes, with average erosion depths of several tens of centimeters and localized incisions exceeding 5–10 meters. Delineating of flow lines and drainage basins also allowed mobilized volumes to be correlated with specific channels, identifying basins with the highest reactivation potential.

The use of fixed-wing UAVs proved particularly effective for covering large areas within short operational times, ensuring centimeter-scale spatial resolution even at poorly accessible sites. Integration with LiDAR technology allowed for the accurate reconstruction of ground morphology in densely vegetated areas, providing a solid basis for subsequent numerical simulations of debris flow propagation. These simulations enabled the estimation of potential inundation scenarios and supported the design of structural mitigation measures.

The results show that the integrated UAV–LiDAR and numerical modeling approach constitutes an effective tool for the geomorphological characterization of multiple basins affected by debris flows, providing quantitative support for hazard assessment and mitigation planning.

Integrating ambient vibration and numerical modal analysis to invert subsurface geometries of fracture-controlled slope instabilities

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Abstract. Detailed engineering-geological modeling of rock slope instabilities is essential for assessing landslide hazards and developing targeted risk mitigation strategies. These models distill information on complex geometries, boundary conditions, and material properties into schematic representations of geostructural settings by combining data from geotechnical and geophysical investigations. However, when discrete fracture networks control geometries and failure mechanisms, these methods have shown inherent limitations, and defining the internal structure and subsurface conditions of unstable rock slopes remains an overarching challenge. As a result, structural models often rely on oversimplified assumptions about fracture extents and rock mass continuity, introducing substantial uncertainty, especially when performing slope stability analyses.

We address this challenge by integrating ambient vibration modal analysis with eigenfrequency numerical modeling to invert for the subsurface geometry of fracture-controlled rock slope instabilities. To this end, we selected two slope instabilities featuring similar failure mechanisms but with different geological settings. The first site is the Courthouse Mesa slope instability (Moab, UT, USA), a 100 m high toppling rock slab partially isolated by a 500 m long and up to 70 m deep rear open fracture. The second site, located in the Paradise Bay promontory (Malta), features a 70 m long and 30 m high rock slab that, despite the smaller scale, exhibits an analogous rigid-block toppling failure mechanism. At each site, we deployed linear seismic arrays to record ambient vibrations and characterize the site’s dynamic response. Field data were analyzed using the Frequency Domain Decomposition (FDD) technique to characterize resonance frequencies and corresponding three-dimensional mode shapes.

We then constructed 3D finite-element models for each site, including only the unstable volume, with the fracture defining the rear model boundary. Hence, we designed a stochastic, rule-based algorithm implemented through a MATLAB–COMSOL Multiphysics pipeline to generate thousands of unique fracture geometry scenarios (i.e., distinct combinations of fixed and open boundary elements) and to test a broad spectrum of subsurface geometries. Each scenario was tested by performing an eigenfrequency numerical analysis to extract the resonance frequencies and mode shapes for every simulated configuration. Numerical results were compared with field-derived modal parameters using a multi-metric similarity ranking score to quantify the consistency between simulated and observed dynamic behavior.

Our results indicate that top-performing models can reproduce observed dynamic behaviors and converge toward fracture configurations consistent with field measurements of fracture depths. The analysis also shows that inversion stability improves with the number of identified resonance modes. By quantitatively linking dynamic behaviors to subsurface structural conditions, this analytical framework has the potential to pave the way to improved structural characterization and monitoring of fracture-controlled slope instabilities.

Underground cavities and their aggravation effects on the local seismic response: a parametric analysis

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Abstract. The main source of cavity-related risk is due to two different phenomena: i) stress induced by seismic shaking can exceed the rock strength of around the caves, causing a vault collapse; ii) seismic waves propagating inside the caves can be modified in frequency, amplitude and duration, influencing the local seismic response with respect to a free field bedrock (Fabozzi et al., 2024). Nowadays, the impact of underground caves and the prediction of their related effect on seismic motion are not properly considered for Seismic Microzonation (SM) studies, either in urban areas or in free field conditions.

In the literature, a 2D model has been proposed to study the propagation of shear seismic waves caused by a single arch-shaped cave in homogeneous rock, considering size and depth (Lancioni et al., 2016). Faraone et al. (2023) performed a local seismic response study using 2D linear numerical analysis on urban cavities, considering different soil shear wave velocities (V_s), sizes, depths, and lining conditions.

This study, based on PhD research, proposes an improvement in understanding the mechanisms of interaction between surface seismic waves and natural caves under free-field conditions, starting from a statistical analysis of a dataset of sinkholes in the Maltese Archipelago. This analysis identified the main morphometric parameters: predominant geometries, size classes, depths and lithologies. Five distinct scenarios were defined, each analyzed considering four cavity geometries (circular, elliptical, sub-elliptical, and elongated) and three size classes (small, medium, large), for a total of 60 model combinations.

We carried out a two-dimensional numerical modeling (2D) under Linear Elastic conditions through the finite difference code FLAC2D (Itasca Consulting Group). The soil density (ρ), Shear Wave Velocity (V_s), Poisson Ratio (ν), Shear Modulus (G) and Bulk Modulus (K) are applied to each layer. To avoid spurious waves, absorbing layers are placed at the lateral boundaries (quiet boundaries). At the base of the model, a seismic input is applied, in terms of upward-traveling SV shear, represented by a Gabor Function with a not negligible frequency content up to 20 Hz.

Wave propagation has been monitored through control points: on the cavity, along both the vertical and horizontal axes of the cavity, on a vertical line on the right side of the model, and on the surface.

At the surface control points, surface waves (Rayleigh) are first identified through the generation of seismic wave propagation maps and then extracted using a time-frequency method "Normalized Inner Product" (NIP), after resolving each component of the seismogram into time-frequency domain by using the Stockwell Transform. With the isolation of the Rayleigh phases, it is possible to quantify the amount of surface wave energy present in the seismograms and to determine their dominant frequencies (Meza-Fajardo et al, 2019).

The challenge is to derive a severity index to standardize the seismic response of natural cavities under free-field conditions by proposing an abacus of parameter combinations which will consider shape, depths, and size classes.

To check the reliability of the parametric modelling some demonstrative cases from Maltese Archipelago and Italy will be studied and modelled with site-specific properties.

Integrated Geophysical Analysis of Active Paleo-Landslides in the Pays de Herve, Belgium

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Abstract. The Pays de Herve region, located in eastern Belgium, is characterised by widespread slope instability, including numerous Quaternary paleo-landslides, some of which remain active. These movements are primarily controlled by weak surface layers composed of clayey deposits, locally overlain by altered gypsum, resting on discontinuous sand and silt layers. This stratigraphic setting, combined with climatic and anthropogenic factors, promotes landslide occurrence that can damage infrastructure and buildings.

This study presents an integrated geophysical investigation of three representative landslides in the area: Sérezé, Thimister, and Manaihan, with special focus on the Manaihan site, which is the most active and impactful. The survey combined electrical resistivity tomography (ERT), seismic P-wave refraction (SRT), multi-channel analysis of surface waves (MASW), and environmental seismic noise measurements analysed using the horizontal-to-vertical spectral ratio (H/V) technique. While ERT, SRT, and MASW provided high-resolution data along specific survey lines, H/V measurements enabled comprehensive spatial coverage across the landslide areas.

Integrating these complementary datasets allowed for the identification of key lithological boundaries and potential slip surfaces, particularly at the interface between sandy clays and underlying shales, at depths ranging from approximately 10 to 30 m. These results were used to develop a detailed 3D geological model of the Manaihan landslide, offering insights into its subsurface structure and slope movement mechanisms.

The study demonstrates that multimodal geophysical approaches provide a cost-effective and non-invasive method for characterising landslides in soft sedimentary terrains. By combining active and passive techniques, it is possible to overcome the limitations of individual methods, enhance the interpretation of subsurface geometry, and support risk assessment. This integrated methodology can be applied to other landslide-prone regions worldwide, providing a robust framework for mapping slip surfaces, understanding triggering mechanisms, and guiding mitigation strategies.

Geo-structural and Karst Controls on the Evolution of Mt. Prato DSGSD (Central Apennines)

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Abstract. Ongoing Deep-Seated Gravitational Slope Deformation (DSGSD) processes may compromise the long-term stability of slopes, posing both direct and indirect risks to communities and the environment. Roads, bridges, dams, and other infrastructures built on DSGSD-affected slopes are subject to slow, persistent deformations, subsidence, or structural damage. Moreover, DSGSD-affected slopes may evolve into catastrophic landslides, mobilizing large rock volumes. In addition to landslide hazards, in tectonically active regions DSGSDs can amplify earthquake effects. Therefore, the analysis of DSGSDs and related geological processes is essential for effective risk management and mitigation in mountainous environments.

Mt. Prato, located along the Olevano–Antrodoco thrust (central Apennines), represents a significant example of DSGSD in a complex carbonate environment. The ridge consists of Lower Cretaceous limestones overthrusting Neogene sequences of marls, clays, and biotrititic limestones, resulting from multiple thrust-related tectonic structures. The structural setting is further complicated by the presence of N–S-oriented normal faults and shear surfaces, which fractured the ridge and define a half-graben depression in its central sector.

Gravity induced deformation occurs at multiple scales. Within the terrigenous sequences, rotational slides have produced wide counter-slope terraces and uphill-facing scarps, with a thickness of deformed deposits estimated at approximately 500 m. The inferred geometric connection between the basal shear zone and the main longitudinal trenches at the ridge crest suggests the presence of a large compound sagging. Along the margins of the klippe, peripheral spreading phenomena are also observed, where limestone blocks overlying more ductile marls have been dismembered as testified by metric-scale trenches and scarps.

The entire deformation system extends over an area of approximately 7 km², characterized by a semicircular summit depression and minor secondary trenches. The structural setting characterized by brittle limestone rock masses overlying more ductile marly calcareous layers, the presence of major faults and bedding planes, and extensive fault-related damage zones together with the local relief, can be regarded as key predisposing factors for the activation of the DSGSD. Comparable conditions are known to control other DSGSDs in the central Apennines. A distinctive aspect of this case study is the potential influence of karst processes, which may act as preparatory or even triggering factors in the deformation. Karst activity is concentrated within the carbonate sequence forming the hanging wall of the klippe. The dissolution of Lower Cretaceous limestones has resulted in the formation of a large sinkhole (~550 m in diameter and ~50 m deep), around which the carbonate walls display clear evidence of progressive stress release. This process could have promoted the development of a medium-scale sackung on the southwestern flank of the karst depression.

Further investigation of this case study could provide valuable insights into a subset of Apennine DSGSDs in which karst circulation and related dissolution are significant controlling factors.

A European Subsidence Database: Integrating EGMS Level-3 Ground Motion Data with Systematic Review Insights (1981–2025)

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Abstract. Land subsidence is the progressive settling or lowering of the Earth's surface and is recognized as one of the most significant geohazards affecting infrastructure stability, water resources, and sustainable urban development. In Europe, particularly in its densely populated coastal and low-lying areas with key industrial, agricultural, and cultural assets, understanding subsidence processes is important for long-term socio-economic resilience and spatial planning. Therefore, this study integrates EGMS (Level-3) data and a systematic literature review from 1981 to 2025 to develop a unified Subsidence Database for European Regions. By analyzing more than 442 Scopus-indexed publications and InSAR-derived LOS velocity maps, we investigated subsidence dynamics in nine major European countries. The analysis was performed using VOSviewer and Bibliometrix in accordance with PRISMA guidelines for further refinement and screening, with the integration of EGMS Level-3 ground motion data (2019-2023) to establish scientific correlations between current deformation trends, research patterns, and the primary contributing factors of subsidence across Europe. The outcome reveals that Italy, Netherlands, and Spain are the most active subsidence hotspots, driven by groundwater withdrawal and coastal sediment compaction, whereas moderate to low trends are observed in Greece, Poland, Germany, France, Belgium, and the United Kingdom. Our findings reveal new potential hotspots of land subsidence and provide valuable information to support planning and policy actions aimed at reducing this growing problem across Europe.

Three decades of InSAR observations for the analysis of landslide evolution: the Santo Stefano d'Aveto case study

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Abstract. Landslides are one of the most common geohazards in Italy, with rainfall as the main trigger. This study explores the long-term changes and rainfall responses of the Santo Stefano d'Aveto landslide (Northern Apennines, Italy) by combining satellite Interferometric Synthetic Aperture Radar (InSAR) data acquired by different sensors, ground-based data, and historical rainfall records. The Santo Stefano d'Aveto landslide is a historical complex landslide, defined as a slow-moving earth rotational slide evolving into a flow. It has been selected as a representative case study due to the favourable east-west orientation of its movement, which aligns well with the viewing geometry of both ascending and descending satellite orbits. Furthermore, the landslide exhibits a slow-moving behaviour, making it well-suited for monitoring and long-term deformation analysis using InSAR. Space-borne InSAR represents a powerful tool to detect and quantify ground displacements over large areas with millimetric precision, enabling the long-term analysis of landslide dynamics and their response to extreme climatic events.

The research aims to reconstruct a 30-year displacement timeline (from 1992 to 2024) at Santo Stefano D'Aveto site by integrating data from C-band radar missions (ERS-1/2, Envisat, and Sentinel-1) with high-resolution X-band imagery from COSMO-SkyMed (2011 - 2014), which has been processed using the PSI (Persistent Scatterers Interferometry) approach. These datasets provide a temporally continuous screening of slope deformation over three decades. X-band data enables more accurate and widespread monitoring of inhabited areas at the expense of vegetated areas. Although there are some gaps in the satellite mission data, time-series integration and cross-sensor harmonisation allow for the reconstruction of a long-term displacement scenario spanning the entire monitoring period. The precipitation records are provided by the Santo Stefano rain gauge, which is operated by ARPAL Liguria. This ensures coverage from 1990 to the present day.

Preliminary results show that, while no clear or direct correlation has yet been identified between rainfall and ground displacement data, the reconstruction of the 30-year deformation history provides valuable insight into the long-term kinematics of the landslide. The study critically compared satellite and in-situ data (e.g. inclinometers and piezometers) to enhance the understanding of landslide behaviour.

This work highlights the value of long-term Earth observation data for understanding the evolution of the landslide behaviour. The Santo Stefano d'Aveto case study demonstrates the potential of combining multi-sensor InSAR data with rainfall records and in-situ measurements to support regional hazard assessment and guide the integration of satellite and ground-based monitoring systems.

Capturing the formation of a landslide-dam by time-lapsed UAV LiDAR: the Boccassuolo earthslide-earthflow (Northern Apennines, Italy)

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Abstract. The formation and stability of landslide dams have been widely studied (Costa & Schuster, 1988) in the last decades. Nowadays, versatile tools such as UAV LiDAR enable time-lapsed surveys that show how, in earthslides–earthflows, stream blockage can result from the combined effects of riverbed uplift and debris accumulation.

This contribution deals with the Boccassuolo earthslide-earthflow (Modena Province, Northern Apennines, Italy), reactivated in late March 2025. During April, the landslide progressively travelled from the source to the track and finally to the toe zone, mobilizing more than 5×10^6 m³ over a length of 3 km and an area of 60 hectares. By the end of April, the landslide partially blocked the Dragone Torrent, creating a dam lake extending over 6,000 m², impounding roughly 20,000 m³ of water. The event received considerable attention from local and national media for both its geomorphological relevance and its impact on local communities. Road interruptions, temporary isolation of rural settlements and the collapse of previously evacuated buildings led to the declaration of a regional and later national state of emergency. This also allowed the activation of emergency response actions, which were capable of preventing the complete blockage of the Dragone torrent, thanks to the use of heavy excavators.

Starting from April 2025, a UAV-LiDAR monitoring campaign was activated, with a time-lapse ranging from 3 to 4 days. The combination of LiDAR and RGB acquisitions resulted in digital elevation models (DEM) with a 25 cm resolution and orthophotos with 10 cm resolution. This high-resolution and high-frequency time-lapsed dataset, allows the reconstruction of the progressive development of the landslide along the slope and to capture and constrain the multi-stage formation of the landslide-dam. Specifically, it clearly evidences the downslope propagation of movements and the progressive reactivation of portions of the slope due to undrained loading and dragging processes. It also proves that the blockage of the Dragone torrent was initially caused by riverbed uplift related to rotational sliding, and only several days later the stable dam started developing because of debris accumulation, which buried pre-existing check-dams as well as rock outcrops. In its final stage of evolution, the dam reached a volume of approximately 144,000 m³, which by considering a drainage basin of 51 km² results in a Blockage Index (Canuti et al., 1998) of 2.55 and a Dimensionless Blockage Index (Ermini & Casagli, 2002) of 3.63. These values indicate potential instability of the dam or uncertainty regarding its stability. Nonetheless, as of today (October 2025), the landslide dam is still stable, but the lake has reduced its extension to less than 3,800 m².

Results from the Boccassuolo landslide highlight the effectiveness of time-lapsed UAV-LiDAR surveys from multiple perspectives. On one hand, it proved capable of providing near-real-time, high-resolution data essential for monitoring the evolution of complex mass movements. At the same time, it provides scientific added value by allowing the capture of the multi-stage formation of the landslide-dam lake which was one of the most relevant direct impacts of this large landslide.

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A simple approach for landslide dam susceptibility mapping at the river basin scale

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Abstract. A landslide dam is the blockage of a river valley caused by a slope mass movement. The formation and failure of landslide dams are controlled by the dynamic interaction between slope instability and river processes, and may cause a series of hydraulic hazards, mostly related to the flooding of upstream areas (backwater formation) and downstream areas (dam breaching). Landslide dams are more frequent in hilly and mountainous regions, where assessing the likelihood of river damming becomes fundamental for managing the associated risks. Several studies have focused on this topic, highlighting the complexity of the analysis, which is mainly due to the large number of parameters involved, data and analytical uncertainty, and the lack of standardized criteria. This project developed a novel methodology for landslide-dam susceptibility assessment, combining morphometric analysis of the landslide–river system with a heuristic approach. Starting from an inventory of active and dormant landslides, the morphometric analysis aims to identify slope movements with higher occlusion potential, which depends on landslide length, river valley width, and drainage area. A semi-automated GIS-based procedure is presented to calculate the morphometric characteristics of the landslide–river system. A new classification scheme is proposed to characterize landslide dams, identifying 515 typological configurations. An interactive tool was developed to guide the users through the classification procedure. Compared with previous geomorphic-based classifications, the proposed scheme gives greater importance to stream type, and to landslide material and dynamics. For each landslide dam class, a list of ten critical risk parameters was derived, including the probability of dam lake formation. Finally, a susceptibility matrix was designed to associate the likelihood of river damming with three main parameters: the probability of lake formation, landslide velocity class, and landslide volume. Criteria for assessing landslide dam susceptibility are still debated, and no standardized framework currently exists in the literature. The heuristic approach provided a practical solution to this complex problem. It overcomes some limitations of existing statistically-based methods, which often have low predictive power and may be influenced by landslide type and regional conditions. The procedure was tested in two watersheds located in northern Italy (Rio Frejus) and the southern Apennines (S. Spirito Torrent). The method proved effective in distinguishing hazardous slope instabilities, offering valuable support for prioritizing monitoring strategies and guiding subsequent slope-instability and hydraulic modeling.

Integrated Monitoring for the conservation of the cultural and architectural heritage of small towns: the Civitacampomariano case study (southern Apennine)

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Abstract. Satellite-based remote sensing provides ground-motion time series for many urban areas worldwide. These data are widely used in both research and practical applications because they enable detailed analyses of slope-instability processes, including their spatial distribution, temporal evolution, and deformation rates. In recent years, numerous studies have focused on slope instabilities affecting historically significant sites. In these areas, continuous in-situ monitoring is typically lacking, and information on slope instability is often limited to sparse historical records or interpretations of satellite and aerial imagery. In this context, ground-motion remote sensing has proved essential, as it now provides long-lasting and continuous deformation time series. When combined with geological and hydrological data, these time series support the identification of the predisposing and triggering factors of landslides.

This study investigated the slope instability processes affecting the historical town of Civitacampomariano (Molise) through satellite ground movement and hydrological time series. The town is located on an arenaceous ridge whose instability is causing severe damage to buildings and the architectural heritage. In March 2017, a landslide struck the historical center, and many houses were evacuated. The event was recorded by InSAR (Interferometric Synthetic Aperture Radar) time series of ground displacements, which revealed complex temporal patterns of the slope deformation. This condition limits the application of classical approaches to InSAR time series analysis, thus alternative solutions were tested. The data revealed an abrupt change in ground movement rates since January 2017, that is, two months before the first occurrence of failure and damage. Satellite-based measurements were integrated with in-situ monitoring data of precipitation, groundwater levels, and deformation of buildings. The analysis allowed the recognition that the landslide instability was likely triggered by the high precipitation occurred in January 2017, while predisposed by several natural factors. Although the specific landslide mechanism remains still uncertain, hydrological and anthropogenic factors help explaining the triggering of the March 2017 landslide. In the detachment zone, the water table time series showed wide and rapid oscillations in response to rainfall, probably due to poor management of the sewage system crossing the unstable sector of the ridge. This factor, joined with the incorrect management of the running water collected by roof gutters draining at the base of buildings and at the upper limit of the rocky slope, favored the direct infiltration of water into the subsurface through discontinuity networks existing in the rock mass.

This research activity was carried out within the framework of the LIVES Project (LIVING in unstable historical towns: landslide hazard Evaluation Strategies for safety improvement and conservation), whose objective is to develop strategies for landslide hazard monitoring and mitigation in unstable towns.

Integrated monitoring and interpretation of coastal landslide processes under extreme rainfall forcing: the Sirolo case (central Italy)

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Abstract. In the context of increasingly pronounced climate change, the risks associated with landslide hazard are continually rising, particularly in areas with high geomorphological susceptibility, such as coastal slopes. In these settings, complex landslides may develop as deep-seated translational movements that can evolve into sudden debris collapses at the slope toe, generating high-risk conditions for beach areas highly frequented by tourists, especially during the summer season.

This study presents an integrated and multidisciplinary approach for the analysis of the instability mechanism of an Adriatic coastal slope located in the Ancona area (Marche region, central Italy). The analysis integrates geotechnical monitoring instruments (inclinometers and piezometers) with D-InSAR satellite techniques based on time series from Sentinel-1 and COSMO-SkyMed satellites: the InSAR data were primarily employed to characterize the spatial distribution of surface movements across the slope and to provide a qualitative comparison with the inclinometric records. These results were integrated with geological and geomorphological field surveys. In parallel, a detailed pluviometric analysis was carried out, to characterize extreme precipitation events through the application of a novel climatic index, called ERPI (Extreme Rainfall Periodic Index), developed to quantify the contribution of extreme rainfall to total annual precipitation. The integration of these various methodologies allowed for the reconstruction and interpretation of the slope's kinematics, thus outlining a consistent conceptual model of its landslide mechanism and the role that extreme hydrological conditions exert in its dynamic evolution.

Monitoraggio di grandi frane con l'utilizzo dell'*Automated Inclinometer System* (AIS)

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Abstract. Il monitoraggio inclinometrico è riconosciuto come la tecnica standard per il controllo dei versanti in frana, permettendo di misurare e tracciare con precisione gli spostamenti orizzontali lungo la verticale per identificare la profondità delle eventuali superfici di scorrimento. Tradizionalmente, le misurazioni sono eseguite con una sonda dotata di sensori (servo-accelerometrici o MEMS) calata manualmente nel tubo dall'operatore secondo campagne di misura periodiche. Questa procedura manuale, tuttavia, è intrinsecamente soggetta a errori che originano da diverse fonti, tra cui l'operatore, il riposizionamento della sonda e la tubazione stessa. L'esigenza di comprendere la cinematica dei movimenti franosi con maggiore dettaglio ha guidato una transizione verso sistemi automatici. Sebbene l'adozione di trasduttori inclinometrici fissi in configurazione multipla abbia consentito un'acquisizione continua e una mitigazione degli errori casuali, tale approccio fornisce un dato che rappresenta solo lo spostamento locale nel punto o nella zona di installazione, non offrendo una visione completa del profilo di deformazione lungo l'intera verticale.

La soluzione più avanzata ad oggi è il Sistema Inclinometrico Automatizzato (IRPI-CNR), che combina l'affidabilità delle misure convenzionali con l'efficienza dell'automazione. Il cuore del sistema rimane la sonda inclinometrica, collegata a una *Inclinometer Control Unit* che elimina le tradizionali connessioni cablate. I vantaggi di un sistema robotizzato sono molteplici: consente di campionare l'intera lunghezza del foro (anche oltre 250 m) con una singola sonda; l'uso dell'encoder e la calibrazione robotica eliminano l'errore umano di riposizionamento; permette un'alta frequenza di misura al giorno), abilitando un monitoraggio quasi in tempo reale. Questa capacità di acquisizione continua è

fondamentale per il monitoraggio e per la tempestiva attivazione di sistemi di allerta precoce, specialmente in frane con cinematica veloce o in fase di pre-collasso.

Il sistema robotizzato ha fornito ottimi risultati nel monitoraggio, sia per le frane in terra che per quelle da crollo. Nel contesto delle frane da crollo, un esempio è il dissesto che affligge il Comune di Borrello (CH). Qui, la situazione litologica vede la presenza di arenarie fortemente fratturate poggiate su di un basamento argilloso, con strati a inclinazione variabile da circa 10° a 45°, che formano una scarpata strutturale di oltre 140 m di altezza. Il fenomeno è un lateral spread lento e profondo che evolve attivamente in crolli e ribaltamenti. Nel caso delle frane in terra, invece, le analisi si sono concentrate sull'area nord del Comune di Chieti, storicamente interessata da intensi fenomeni di scivolamenti roto-traslativo. L'area è caratterizzata dalla sovrapposizione di un intervallo Arenaceo-Sabbioso, con spessori di oltre 30 m, sulla formazione Argilloso-Sabbiosa. All'interno della zona superiore, caratterizzata da consistenze non uniformi, si localizzano le superfici di scorrimento responsabili dell'innescò e della propagazione del dissesto. In entrambi i contesti, la capacità del sistema automatizzato di fornire dati precisi e ad alta frequenza sulla deformazione profonda è risultata essenziale per comprendere l'evoluzione e gestire il rischio idrogeologico presente.

Integrative passive seismic monitoring and remote sensing as a tool for detecting landslide instabilities from preparedness-to-trigger

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Abstract. Landslides are among the natural processes with the highest socio-economic impact; these phenomena are constantly evolving and require specific quantitative analysis approaches, often involving complex numerical modeling. This follows the identification of predisposing conditions (e.g., geostructural setting), preparatory factors (e.g., meteorological forcing), and triggering actions (e.g., impulsive transient stresses) responsible for their (re)activation (Martino, 2023).

Noninvasive geophysical methods are valuable tools for investigating the internal structure, dynamics, and mechanical properties of hydraulically active systems such as earth-slides. They provide essential insights into the spatiotemporal variations of physical parameters that are crucial for geological and geotechnical interpretation (Guedes et al., 2023).

This study integrates active and passive geophysics with satellite interferometry (InSAR) to enable continuous remote monitoring of landslide displacement, providing valuable insights into how external factors, progressively change the slope conditions and prepare it for potential instability induced by triggers.

The selected test site is the San Vito Romano landslide (RM), ~50 km east of Rome. The newest part of the village lies on an active roto-translational landslide characterized by slow but continuous movement. The landslide body consists of siliciclastic deposits of the Laga Flysch Formation (Upper Tortonian), composed of alternating clayey marls and marly sandstones, which make the slope particularly prone to instability. The last major reactivation occurred in 2011, triggered by intense rainfall, causing structural damage and the evacuation of a residential building.

For the continuous monitoring of ambient seismic noise at the study site, four triaxial seismometers (SARA electronic instruments, eigenfrequency 2.5 Hz) were installed and have been continuously operating since February 2024 at 250 Hz sampling. The data are processed to estimate temporal variations in seismic velocity (dV/V) and resonance frequency (dT/T), which describe the slope's mechanical evolution and serve as indicators of landslide mobility, reflecting deformation, stiffness, and water-saturation changes. Furthermore, Standard Spectral Ratios (SSR) are derived from the ambient noise to assess the dynamic response of the slope to both local and distant seismic events, even of low magnitude.

The main indicators of landslide mobility (dV/V and dT/T) will be analyzed synoptically together with rainfall time series, local seismicity, and, critically, surface displacements derived from satellite interferometry (InSAR). All these parameters will be integrated into an artificial neural network (ANN), casting the task as a multivariate regression in which past external forcings (rainfall and local seismicity) and seismic indicators from ambient-noise processing (dV/V , dT/T) are used to estimate displacement change (Δs) or velocity from satellite-derived surface motion. Model performance will be assessed with blocked time-series validation and compared against simple baseline models.

Once trained, the network will reconstruct the dynamic behavior of the slope and predict its displacement evolution under meteorological forecast or seismic hazard scenarios, providing a practical tool to support risk management and resilience-building strategies.

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A scalable Artificial Neural Network approach for forecasting rock mass plasticity based on monitoring data and weather predictions

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Abstract. Understanding how environmental stressors can influence rock mass deformation and its preparation, and, over the long term, lead to slopes failing, remains a key challenge in engineering geology. Rock mass progressive damage driven by cyclic or episodic environmental conditions is controlled by subtle plastic deformation that is frequently elusive to monitoring. In this context, data-informed approaches based on Artificial Neural Networks (ANNs) have emerged as powerful tools for exploring large datasets, investigating and forecasting rock mass responses, and ultimately improving predictive models for instability mitigation.

In this study, two distinct ANNs were developed and trained using multi-parametric datasets that combine long-term in situ monitoring records of rock strain with meteorological forecasts. The first ANN relies on historical monitoring data from the Acuto Field Laboratory (Central Italy) to evaluate correlations between observed deformation patterns and environmental stressors, identifying the meteoroclimatic factors that act as preparatory conditions for instability. The second ANN, based on the geomechanical response monitored at the site, exclusively adopt daily weather forecasts to assess the probability of anomalous rock mass deformation and anticipate related failure events. The model distinguishes between days characterised by elastic or plastic deformation behaviour, enabling a refined understanding of how environmental forcing influences progressive damage. Feature importance analysis highlights the dominant role of temperature-related variables, specifically peak temperatures and thermal excursions over multi-day windows, as the main predictors of anomalous strain responses.

The weather-based ANN was subsequently exported to an independent test site characterised by similar climatic and geomorphological conditions, to assess its spatial transferability and temporal reliability. The model successfully predicted a rockfall event one day in advance during the testing phase, thereby demonstrating its robustness and transferability across different contexts. This cross-site validation underscores the feasibility of ANNs as a promising framework for near-real-time indexing of the potential instability of rock slopes.

By coupling long-term monitoring data with predictive weather datasets, the proposed approach enhances the understanding of the meteorological and thermomechanical controls on rock mass behaviour.

Leveraging timely, accurate, and spatially distributed forecasts across the Italian territory, this strategy, trained on high-resolution datasets, would enable flexible nowcasting and near-term forecasting over broader areas, representing a significant step toward scalable, affordable, and transferable rockfall hazard assessment. Moreover, from a future perspective, hybrid data- and IT-informed ANNs could help bridge the gap related to the limited understanding of climate-dependent parameters and their expected trends of variation.

Scienza partecipativa per il monitoraggio di Crolli Diffusi attraverso Tecnologie Mobili

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Abstract. Le infrastrutture viarie presenti sul territorio nazionale rappresentano asset critici per la mobilità territoriale, ma risultano spesso particolarmente vulnerabili ai fenomeni di instabilità geologica, con eventi di crollo diffuso che comportano significativi impatti socioeconomici e rischi per la sicurezza. I metodi tradizionali di monitoraggio presentano limitazioni strutturali legate agli elevati costi operativi, alla necessità di personale altamente specializzato e all'impossibilità di garantire copertura spazio-temporale continua su reti estese, risultando spesso in interventi tardivi e reattivi piuttosto che preventivi.

La ricerca propone l'evoluzione verso approcci partecipativi integrati che valorizzino il contributo dei cittadini come risorsa strategica per i tecnici specialisti, trasformando le comunità locali in osservatori attivi del territorio per garantire monitoraggio capillare e continuità temporale sui fenomeni di crollo diffuso. Il sistema tecnologico sviluppato implementa un'architettura ibrida che combina algoritmi avanzati di *Digital Image Correlation* (DIC) e *change detection* multi-temporale su dispositivi mobili consumer con tecniche di monitoraggio convenzionali, creando una piattaforma integrata per il riconoscimento automatico di pattern di instabilità e precursori di movimento, anche con finalità di *early warning*.

L'innovazione metodologica sviluppa una piattaforma tecnologica integrata basata su due componenti chiave: un'applicazione mobile che implementa protocolli scientificamente validati per guidare i cittadini nell'acquisizione di fotografie professionali utilizzando i sensori GNSS integrati negli smartphone per un posizionamento metrico di precisione e un motore di intelligenza artificiale che combina algoritmi avanzati di DIC con tecniche di *change detection* multi-temporale per l'analisi automatica sub-pixel delle variazioni strutturali, consentendo una visualizzazione dinamica dei risultati. Il sistema implementa algoritmi avanzati di intelligenza artificiale, specificamente addestrati, integrando correzioni geometriche prospettiche e calibrazione radiometrica per compensare variazioni prospettiche e di illuminazione. L'architettura combina l'acquisizione distribuita tramite l'applicazione dedicata con totem fotografici fissi che forniscono punti di riferimento controllati per la calibrazione continua degli algoritmi e la validazione dell'accuratezza del sistema di rilevamento.

I risultati sperimentali su casi studio di strade regionali documentano capacità di rilevamento precoce di instabilità, dimostrando accuratezza diagnostica comparabile agli standard professionali con riduzione sostanziale dei costi operativi e incremento della frequenza di acquisizione dati rispetto alle metodologie convenzionali. La validazione tecnica conferma l'efficacia del sistema integrato nel superare le limitazioni delle tecniche singole attraverso ridondanza informativa e validazione incrociata multi-sensore.

L'approccio rappresenta un contributo significativo al campo dell'ingegneria geotecnica introducendo un paradigma di monitoraggio scalabile che democratizza l'accesso a tecnologie avanzate, aprendo prospettive concrete per l'implementazione sistematica di *early warning* su reti infrastrutturali estese e promuovendo la transizione da strategie reattive a preventive nella gestione del rischio geologico.

A near real-time forecasting system for shallow landslides at regional scale based on distributed modelling and weather predictions

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Abstract. This work presents the development of a forecasting system for shallow rainfall-induced landslides, designed to provide daily near-real-time outputs at a regional scale. The system integrates hydrological and slope stability distributed modelling with daily rainfall forecasts from a weather prediction model to generate daily shallow landslides initiation forecasts for an area of hundreds of square kilometers.

Research activities focused on: i) the optimization of the HIRESSS model to enhance computational efficiency and physical consistency for real-time forecasting; (ii) the calibration of hydrological and geotechnical parameters based on the local characteristics of the Aosta Valley, including soil properties, land cover, and precipitation regimes; and (iii) developing algorithms enabling the continuous use of meteorological forecasts and the production of both distributed (grid-based) and aggregated (sub-basin) outputs.

The operational system based on the HIRESSS model has been active since June 2024 for the Alert Zone B of the Aosta Valley Region. It uses precipitation forecasts from the ICON-CH2 weather prediction model as dynamic input. The system generates landslide initiation susceptibility maps in terms of failure probability, with a 10 m spatial and 3-hour temporal resolution, producing forecasts for the current and following day. Additionally, it provides aggregated probabilities at sub-basin level through a calibrated threshold system, supporting early warning activities.

Recent developments have focused on optimizing the real-time dissemination of model outputs through an open-data platform ensuring transparency, accessibility, and operational usability for regional authorities and decision-makers. The developed system represents a significant step toward a fully operational landslide early warning system at the regional scale based on physically based distributed modelling and meteorological forecasting.

Dall'EGMS alla valutazione dei *geohazards*: applicazione degli ADATools nella Regione Lazio

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Abstract. L'analisi delle deformazioni del terreno tramite tecniche di interferometria radar satellitare rappresenta oggi uno strumento consolidato per la mappatura e la caratterizzazione dei *geohazards*. Il recente sviluppo del servizio *European Ground Motion Service (EGMS)*, nell'ambito del *Copernicus Land Monitoring Service*, ha reso disponibili dati InSAR Sentinel-1 ad alta risoluzione, liberamente fruibili e aggiornati annualmente sull'intero territorio europeo. Tuttavia, l'enorme volume e la complessità di tali dati richiedono strumenti capaci di facilitarne l'interpretazione e di renderli operativi per la gestione del territorio.

Per rispondere a questa esigenza, il progetto europeo *EGMS RASTOOL (European Ground Motion Risk ASsessment TOOL)* finanziato dall'UCPM dell'Unione Europea ha sviluppato gli *ADATools*, un set di *tools open-source* per la semplificazione della lettura di milioni di punti di misura dai dati radar interferometrici satellitari *EGMS* e per l'identificazione e classificazione semiautomatica di Aree a Deformazione Attiva (ADA). Tali tools consentono di passare rapidamente dai dati *EGMS* alla mappatura dei fenomeni deformativi, integrando informazioni morfometriche, tematiche e temporali in un flusso di lavoro *user-friendly*.

Lo studio presentato riguarda l'applicazione degli *ADATools* nella Regione Lazio, area caratterizzata da una complessità di fenomeni di deformazione del terreno, che risultano in diversi tipi di instabilità, tra cui frane, *sinkholes*, subsidenza e cedimenti strutturali. L'analisi ha utilizzato i dati *EGMS* (2018-2022) in geometria ascendente e discendente, scaricati e convertiti tramite la *webapp EGMSStream*. L'individuazione delle ADA è stata eseguita con il tool *ADAFinder*, mentre la classificazione dei fenomeni è stata ottenuta attraverso il tool *ADACategorizer*, che integra parametri morfometrici, carte tematiche e inventari regionali. Il tool *LOS2HV* ha permesso di derivare le componenti di velocità orizzontale e verticale, mentre l'andamento temporale delle deformazioni del terreno è stato analizzato con il tool *TSClassifier*.

L'applicazione regionale ha permesso di individuare oltre 750 ADA. Sono state inoltre svolte analisi di dettaglio che hanno evidenziato la coerenza dei risultati con le conoscenze pregresse sulle aree di studio e la capacità del metodo di individuare nuove aree potenzialmente instabili.

L'esperienza condotta nella regione Lazio dimostra l'efficacia e la flessibilità degli *ADATools* per l'analisi e la gestione dei dati *EGMS*, offrendo un approccio replicabile e operativo per la valutazione dei *geohazards* a diverse scale territoriali. Questi strumenti e relativi risultati possono essere utili per gestori territoriali e Autorità di Protezione Civile e pertanto rappresentano un passo concreto verso un utilizzo sistematico e integrato delle informazioni satellitari nei processi di pianificazione e mitigazione del rischio.

Investigating Coastal Cliff Dynamics through Integrated Geostructural and Photogrammetric Methods

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Abstract. The retreat of coastal cliffs represents a geomorphological process of primary importance for understanding the evolution of coastal systems and for assessing the associated risk, particularly in urbanized areas. In the south-eastern sector of Sicily, along the coast of Syracuse, the limestone and calcarenite cliffs of the Hyblean Foreland are characterized by widespread fracturing and active karst phenomena, which reduce their mechanical strength. This area represents an ideal study context, not only from the geomorphological point of view, but also because of its historical-environmental relevance. Here, in fact, the presence of quarries used since the times of ancient Greece (Latomiae) represents a widespread feature that modified the local landscape. For these reasons, this area was chosen as a test site to carry out a study on the instability dynamics affecting rocky coasts, linked also to the interaction between geostructural, lithological, and marine weather factors. The increase in the frequency of extreme events, along with variations in climatic conditions, is accelerating coastline retreat, with direct repercussions on safety and land management. For this study, an integrated modelling approach, based on rock mass surveys and airborne photogrammetry applications, is presented with the aim of characterizing the main forms of instability and the evolution of the cliff. The three-dimensional models obtained from the surveys allowed for the identification of the coastal sector mostly affected by collapses and the recognition of the different failure patterns. These patterns were found to be linked to the regional tectonic setting. In particular, discontinuities oriented along NE-SW and WNW-ESE directions resulted consistent with the main faults in the area. The proposed approach, which integrates field observations and digital modelling, proved effective in representing the complexity of the cliff evolution processes. Beyond its scientific value, the results obtained could provide a useful contribution to coastal planning, offering supporting tools for risk management in a coastal context affected by rapid transformations.

Advanced numerical modelling of earthflow dynamics: application of the Material Point Method (MPM) to the Montaguto case study

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Abstract. Earthflows are highly diffuse throughout the Apennines and frequently generate huge damages to the transport infrastructures located at the foot of the slopes. From the kinematic point of view, such landslide processes are characterized by the alternation of stages with relatively fast-moving activity, sometimes evolving into rapid accelerations, and slow-moving or dormant stages. In the available literature, earthflow kinematics has frequently been explained through simplified approaches that simulate the soil behaviour as one-phase soil material characterized by a significantly increased water content. However, modelling properly the complex kinematics of these phenomena remains a challenge for geoscientists. Traditional numerical methods, as the Finite Element Method (FEM), often encounter severe limitations when attempting to capture the exceptionally large strains, complex hydro-mechanical behaviour, and impulsive nature inherent in earthflow movement.

This study presents an advanced numerical investigation of a large-scale earthflow by employing the Material Point Method (MPM), which is a hybrid Eulerian-Lagrangian technique capable to simulate large deformation problems by discretizing the continuum into a set of material points that move through a fixed computational grid. Such a technique has been applied to the Montaguto earthflow (Southern Apennines, Italy), one of the largest and most extensively monitored complex landslides in Europe, characterized by a fast-moving reactivation between 2006 and 2010, followed by a slow but continuous deceleration in recent years. In 2014, 2016 and 2020, Lollino and co-authors have investigated through analytical and numerical techniques the role of excess pore pressures generated by undrained loading processes active in the Montaguto earthflow mass in the activation of the landslide movements.

In order to investigate more properly the Montaguto earthflow kinematics taking into account the two-phase soil behaviour, a 2D MPM model was developed based on the available geological and geotechnical characterization. In particular, the numerical analyses are aimed at simulating the mechanisms that gave rise to the reactivation phase and the following evolution, both in the source and in the channel areas.

The numerical results successfully reproduce the key kinematic features of the Montaguto earthflow. This includes the realistic simulation of the velocity and displacement distribution of the channelized flow, as well as the role of pore water pressures, in agreement with the observed monitoring data. Sensitivity analyses were carried out to evaluate the influence of specific mechanical and hydraulic soil parameters on the generation of the excess pore pressures within the landslide mass and on the mobility of the flow.

The findings demonstrate the high potential and robustness of MPM as a tool for simulating the full life cycle of complex earthflows, from the rapid acceleration, to the propagation and deceleration. Such a modelling approach provides a significant advancement over traditional methods, offering a powerful tool for enhanced hazard assessment, scenario-based forecasting, and the design of effective mitigation strategies for critical infrastructure protection in earthflow-prone areas.

"Digital twin" approach to rockfall hazard assessment: remote analysis of the cliff overlooking the Santa Maria dei Rotoli monumental cemetery, Palermo

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Abstract. Rockfall phenomena influence human activities in areas where urban expansion reaches the slopes of the reliefs. Rockfall hazard assessment is particularly required when exposed elements exist in the area, thereby creating the conditions for a risk scenario.

Since direct data acquisition for rockfall hazard characterization is not always feasible due to logistical constraints and exposure to the factors generating the hazard, indirect approaches have emerged over the past decades as a reliable solution. The main goal of these approaches is to generate a three-dimensional model of the analyzed rock mass, making it possible to extract parameters for the characterization of discontinuity systems and to perform stability analyses remotely.

The proposed case study concerns a portion of the eastern sector of Mount Pellegrino (Sicily), overlooking the monumental cemetery of Santa Maria dei Rotoli. The mount, a carbonate relief that rises 606 m a.s.l. within the city of Palermo, is constantly affected by rockfall phenomena. The cemetery represents a vulnerable element that needs to be preserved, both as an artistic and historical heritage site and as a place where human lives are exposed due to tourism and religious activities. In this context, a Terrestrial Laser Scanning (TLS) survey was carried out, allowing the acquisition of a high-resolution 3D point cloud model of the rock face. Once processed and filtered, the point cloud can be assimilated to a digital twin of the studied rock front, serving as the raw dataset from which to extract useful information for the geomechanical characterization.

In particular, the application of rock mass classification systems allowed for the identification of high-priority sectors where specific analyses were performed to determine quantitative parameters for hazard analysis.

Valutazione del rischio multi-hazard per la salvaguardia delle Mura Aureliane di Roma

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Abstract. Il presente lavoro illustra i risultati di un'analisi di rischio multi-hazard condotta sulle Mura Aureliane di Roma nell'ambito dell'Accordo con il Ministero della Cultura per il Piano Straordinario di Monitoraggio dei beni culturali immobili. Le infrastrutture storico-monumentali in ambito urbano sono esposte a molteplici fenomeni di pericolosità geologica che ne minacciano l'integrità. L'obiettivo dello studio è stato sviluppare una metodologia sistematica per la valutazione integrata del rischio associato a frane, subsidenza e *sinkhole* di origine antropica, fornendo uno strumento operativo per la prioritizzazione degli interventi di salvaguardia. La metodologia implementata si basa su un modello di rischio semplificato che integra tre componenti fondamentali: pericolosità, attività ed esposizione. La pericolosità è stata derivata da carte di suscettibilità geologica disponibili per ciascun fenomeno. L'attività dei processi è stata quantificata mediante elaborazione di dati interferometrici satellitari InSAR (*Cosmo SkyMed* 2010-2022), che consentono di misurare con precisione millimetrica gli spostamenti della superficie terrestre. L'esposizione è stata valutata in funzione dell'importanza storico-culturale e dell'accessibilità dei segmenti murari.

Il tracciato è stato discretizzato in segmenti uniformi di 15 metri, costituenti le unità elementari di analisi. Per ciascun segmento sono stati estratti, mediante tecniche di statistica zonale, i valori di suscettibilità e i parametri cinematici specifici per ogni tipologia di fenomeno. Questi parametri sono stati classificati su scale ordinali e integrati per calcolare indicatori di rischio mono-hazard. L'integrazione in un indicatore sintetico è stata realizzata mediante somma pesata che riflette la diversa natura dinamica dei fenomeni. Ai processi a manifestazione rapida e potenzialmente catastrofica (frane e *sinkhole* - di origine antropica -) è stato assegnato peso unitario, mentre alla subsidenza, caratterizzata da evoluzione lenta e progressiva, è stato attribuito peso ridotto. Oltre al rischio integrato, per ciascun segmento è stato identificato il fenomeno dominante.

I risultati forniscono una caratterizzazione quantitativa e spazialmente esplicita delle condizioni di rischio per l'intero circuito murario. L'analisi evidenzia una distribuzione differenziata delle criticità: i fenomeni franosi predominano nelle porzioni su versanti acclivi, la subsidenza nelle aree pianeggianti con depositi compressibili, i *sinkhole* in zone con peculiari caratteristiche geologiche. La classificazione finale ha permesso di identificare i segmenti caratterizzati da condizioni di rischio elevato e molto elevato, prioritari per approfondimenti diagnostici e interventi di mitigazione. La metodologia costituisce un approccio scalabile e replicabile per la gestione del patrimonio storico-architettonico in contesti urbani, integrando telerilevamento, analisi geospaziale e modellazione del rischio.

Modelling long-term coastal slope deformation process in the archaeological site of Aegina Kolona (Greece)

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Abstract. Coastal slopes are sensitive to meteorological and marine forcings and, over the long term, exposed to the effects of climatic stressors that cause their retreat, threatening socioeconomic and cultural heritage assets.

This study explores the stability of the sea cliff at the archaeological site of Kolona on the island of Aegina (Greece), which is one of eight pilot sites of the H2020 European project TRIQUETRA (<https://triquetra-project.eu/>). This culturally valued archaeological site is threatened by several environmental and geological factors, including ongoing coastal erosion, intense local seismicity, and diffuse coastal cliff collapses which border the promontory. The progressive sea cliff retreat has already caused the irreversible loss of part of the not yet excavated archaeological remains. Archaeological data, collected so far both on the emerged promontory and in the submerged near shore, allow to determine the position of the coastline at about 2ka ago. As part of the TRIQUETRA project activities, an engineering-geological model of the promontory was conceptualised thanks to detailed engineering-geological and geophysical surveys. Photogrammetric surveying also allowed to process a high-resolution DEM of the relief.

The local geological setting, characterized by Quaternary calcarenites overlying Pliocene clays, predisposes the area to a continuous coastal retreat due to lateral spreading processes responsible for the instability of the sea cliffs. In this context, we utilized a 3D photogrammetric model to identify the primary overhangs along the sea cliff, enabling the implementation of a preliminary slope stability analysis. We also performed numerical slope stability analysis using a time-dependent visco-plastic rheology for Pliocene clays, considering the specific stratigraphic setting of the promontory. The primary objective of numerical modelling was to understand how the promontory evolved over the last two millennia by back-analysing the lateral spreading and constraining model results with archaeological and bathymetric field evidence.

Numerical modelling results highlight the destabilizing role played by the geostructural setting of the promontory, which will continue to shape the exposed sea cliff over the next millennia. Using a hybrid Finite–Discrete Element Method (FDEM) integrated with Computational Fluid Dynamics (CFD) analysis, we simulated sea wave impacts and the resulting mechanical response of the cliff, including the effects of notch excavation on its overall stability. The findings drive an interpretation of the mechanisms driving the coastal slope instability in the Kolona promontory, underscoring the role of local geostructural settings, sea level rising and sea wave action in predisposing, preparing and triggering, respectively, the sea cliff instabilities.

Urban sinkholes and implications in coastal cliff retreat

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Abstract. Coastal instability is the result of a combination of natural factors, including marine erosion, sea level variation, and meteorological action. Cliffs undergoing retreat show a complex geomorphological evolution, often governed by the interaction between local geological–structural settings and exogenous processes. Although cliff recession represents a natural component of coastal morphodynamical evolution, its occurrence within urbanized areas poses a significant hazard to infrastructure, settlements, and human activities located along the cliff edge. Moreover, coastal retreat may be associated with, or exacerbated by, the development of sinkholes if peculiar structural and lithological features predispose the rock mass. These are localized ground collapses related to processes of dissolution, void formation, or the collapse of subterranean cavities, with critical implications for land stability and territorial safety.

This study aims to analyze two sinkholes along the eastern coast of Sicily (southern Italy) occurred at the main towns where, despite the different geological setting, this morphological feature characterizes the coastline evolution. The integration of field surveys, geomechanical data, and rock mass digital models is presented. Dense point clouds were generated from aerial photogrammetry imagery, allowing for a quantitative characterization of fracture surfaces and discontinuity systems, key elements for assessing the stability of coastal cliffs and the evolution of sinkholes.

Results show that the genesis of sinkholes in the volcanic rock coast of Catania is mainly related to the presence of cooling joints and lava tunnels. On the contrary, in the carbonate rock masses of Syracuse, their origin is mainly linked to karst dissolution processes and tectonics. The achieved interpretative models allowed the definition of predictive scenarios of morphological evolution, useful for planning strategies and risk management plans in urban areas.

First insights on the potential of a “new” geomorphic parameter to strengthen landslide susceptibility assessment

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Abstract. Landslides are a significant natural hazard causing severe societal and environmental impacts. Mapping areas prone to landslides is a key step in mitigating such consequences. Several authors have proposed methodologies for landslide susceptibility mapping (LSM), broadly classified into qualitative and quantitative methods [1]. The choice of methodology depends on factors such as the scale of analysis, mapping unit, data resolution, and the availability and accuracy of information [1]. It is well established that the selection of factors and the choice of methods should be closely related to the type of landslide under investigation [1]. Another key consideration in LSM is the multicollinearity among environmental factors, which must be assessed. From this premise, this study proposes a new covariate for LSM, aimed at identifying areas prone to different types of landslides (e.g. shallow landslides, rockfalls, slow-moving slides and rapid debris flows). A central element of the approach is the widely used slope–area (S–A) function [2]. Accordingly, the present study introduces a customized version of the S–A function, called the Slope–Weighted Area–Curvature function (SwAC), for producing a synthetic covariate for LSM. This function integrates slope, hydrological data (runoff values derived from the BIGBANG model [3]), and curvature parameters, enabling a more accurate differentiation of geomorphological domains (hillslope, unchanneled, debris-flow channeled, and fluvial). Curvature enhances the recognition of morphological variations (convergence and divergence), while runoff values allow for a realistic extraction of the stream network. In this way, the territory can be zoned according to its natural predisposition to landslides and floods, providing a robust basis for further analysis. To evaluate the effectiveness of the covariate defined Weighted Geomorphic Domain (GD_w) in LSM, it was tested using the statistical data-driven method Weight of Evidence. This approach made it possible to estimate the spatial association between landslides and the different covariate classes (hillslope domain – rockslides; unchanneled domain – slow earth flows and shallow landslides; debris-flow channeled domain – debris flows), and to assess the extent to which each domain contributes to increase or decrease the probability of landslide occurrence.

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Flood and landslide resilience mapping: an index-based methodology applied to the Emilia Romagna case study

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Abstract. In recent years, the concept of resilience has gained significant prominence and recognition, particularly within the Disaster Risk Reduction (DRR) concept. Resilience has become a key paradigm for understanding how societies, infrastructures, and environments can anticipate, absorb, adapt to, and recover from adverse events. However, resilience cannot be fully understood without addressing its complementary concepts — vulnerability and risk perception. Vulnerability represents the susceptibility of a system or community to suffer damage when exposed to hazards, reflecting weaknesses in physical, social, economic, or environmental conditions. At the same time, risk perception shapes how individuals and institutions understand, interpret and respond to potential threats, influencing preparedness, adaptive behaviour, and decision-making. Together, these aspects define the overall capacity of a system to deal with disturbances and determine the degree of resilience.

Landslides and floods are among the most impactful natural hazards worldwide, generating severe damage, losses, and long-lasting impacts on communities and ecosystems. From 1900 to 2024, landslides have caused approximately \$11.5 billion in damages and more than 70,000 fatalities globally, while floods have resulted in over seven million deaths and nearly \$100 billion in economic losses. The frequency and magnitude of these hazards are expected to rise due to a combination of environmental changes, land-use transformations, population growth, and socio-economic inequalities, as well as political and economic instability in several regions. Understanding these hazards and their potential effects represents an important aspect for saving lives, reducing losses, and fostering sustainable development.

This study focuses on the Emilia-Romagna region in northern Italy, which has recently experienced significant impacts from multiple hydrogeological events. In May 2023, an exceptional storm triggered widespread flooding and landslides, causing severe damage to infrastructure, housing, and productive activities. The aim of this work is to quantify and map the resilience of Emilia-Romagna in relation to these hazards, providing insights to support Civil Protection and regional authorities in disaster preparedness and recovery planning.

An index-based methodology was developed to assess resilience across multiple dimensions — social, economic, infrastructural, and environmental — integrating the quantitative indicators into four main dimensions that characterise resilience itself: resistance, adaptation, response, and recovery. These components were analysed through a combination of geospatial data, statistical methods, and normalisation procedures to produce resilience maps for both floods and landslides. The proposed framework offers an innovative and complementary approach to traditional vulnerability and risk maps, delivering new and original information on the dynamic capacities of communities and systems.

A data-driven model for investigating slow-moving landslides from a hydrogeological perspective: the role of mountain springs

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Abstract. Slow-moving landslides are large-scale gravitational phenomena affected by complex hydro-mechanical dynamics due to the interaction of multiple involved factors.

Their long-term evolution could pose a significant geohazard to nearby buildings and infrastructure. Understanding the processes that cause these deformations is crucial for the development of effective monitoring and mitigation strategies.

Lithology, geological settings and tectonic stresses are the main predisposing factors that strongly control the ground instability over time. In mountain regions, deglaciation is also one of the most impactful processes on landslide deformations, as it causes a stress redistribution on slopes, thereby contributing to rock damage. This phenomenon is frequently observed in the European Alps, particularly in glacial valleys such as the Susa Valley (Italian Western Alps) with a high density of Deep-Seated Gravitational Slope Deformation (DSGSD).

Furthermore, extreme hydroclimatic events, such as heavy and prolonged rainfall or snowmelt, can accelerate transitions from slow creep to significant landslide reactivations, as substantial infiltration changes pore water pressures, reduces effective stress on shear zones, and increase movement rates. These dynamics may develop gradually across seasons or episodically during anomalously wet years. In this framework, a detail investigation of the relationship between groundwater regimes and landslide behaviour is needed. Several authors have proposed different approaches to address this challenging topic.

Given the amount of weather data, groundwater level measurements and continuous time series of monitored displacements, the definition of a data-driven model capable of statistically estimating the deformation response to changes in the main triggering factors may be useful.

The research aims to demonstrate that spring water levels, an important indicator of aquifer dynamics, can be used as a powerful tool for detecting slow-moving landslide displacements and for establishing thresholds for early warning and risk mitigation in mountainous or hilly environments. The analysis, which was carried out at two landslide sites in the Susa Valley, improved understanding of the hydrogeological aspects influencing slow-kinematics phenomena.

Spring data, in terms of groundwater levels, were compared with displacements from automatic inclinometer probes. Leveraging relevant monitoring data, the proposed methodology combines statistical tools such as cross-correlation function and Fourier spectral analysis to investigate time series characteristics. Results showed that when springs and inclinometers are in proximity and belong to the same landslide dynamics, the spring trend can effectively predict conditions triggering movement. However, the limited spatial distribution of springs over large areas, as well as their location with respect to other instruments, can affect the reliability of the findings.

While this research supports the forecasting of landslide accelerations, a more robust monitoring network is essential to detect deformation phases. Nevertheless, this study lays the foundation for an alternative use of deep displacement monitoring and for identifying of threshold values resulting from the combined effects of snowmelt and precipitation.

A prototype national Landslide Early Warning System for Italy integrating rainfall thresholds and spatial risk indicators

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Abstract. Conventional TLEWSs (Territorial Landslide Early Warning Systems) rely solely on rainfall thresholds applied over large alert zones, which, while easy to use, lack spatial precision and may issue warnings over excessively broad areas. The proposed system integrates rainfall thresholds (temporal component) with spatial landslide risk indicators, resulting in a dynamic matrix-based framework that enhances both spatial resolution and operational reliability.

The methodology was implemented across Italy (approximately 300,000 km²), focusing on 150 mountainous or hilly alert zones prone to landslides. Hourly rainfall data from over 3,000 rain gauges (2010–2019) were combined with a landslide inventory generated of about 10,500 events derived from online news sources. For each alert zone, rainfall thresholds were defined following a power-law relationship between rainfall intensity and duration. To limit false alarms, multi-level thresholds were calibrated: the moderate criticality level allows a maximum of 1 false alarm per year, while the high criticality level allows a maximum of 0.1 false alarms per year.

To represent spatial variability, the Landslide Risk Index (LRI) was used, combining landslide susceptibility maps with land consumption data to account for both the predisposition to landslides and the exposure of anthropogenic elements. Then the Average Landslide Risk (ALR) was calculated for each municipality to quantify how hazardous the anthropized areas are on average. Municipalities were classified into three spatial risk levels (S0, S1, S2), which were combined with three rainfall hazard levels (T0, T1, T2) through a 3×3 dynamic matrix, generating five risk classes (R0–R4). Matrices calibration ensured that no landslides occurred in class R0, while at least 90% of recorded landslides occurred in classes R2–R4.

Validation used a dataset of 96 hydrogeological events that caused declarations of national emergencies between 2013 and 2019. Results showed strong agreement between predicted high-risk municipalities and observed impacts: 97% of the affected municipalities corresponded to R2–R4 levels, confirming the model's predictive capability. In terms of reliability, 98.4% of matrices met the calibration criteria, with 74.8% showing reliability above 95%.

By refining the spatial unit from large alert zones (≈1,770 km²) to municipalities (≈38 km²), the system provides more detailed and actionable information to civil protection authorities. The integration of rainfall thresholds and spatial risk indicators enables a more realistic and operational representation of landslide risk, directly linking hazard with the presence of exposed elements.

In conclusion, the proposed prototype TLEWS represents a significant advancement toward dynamic, high-resolution early warning systems, capable of merging temporal and spatial forecasting into a single framework, enhancing warning accuracy and reducing false alarms.



Advancing rail network resilience through integrated InSAR and geotechnical monitoring data analysis

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Abstract. The increasing frequency and impact of ground instabilities on railway infrastructures demand the adoption of advanced and integrated monitoring strategies to enhance resilience and ensure operational safety. This research explores the synergistic use of satellite-based Interferometric Synthetic Aperture Radar (InSAR) and conventional ground-based monitoring systems, such as inclinometers, to develop a comprehensive framework for slope instability assessment. The methodology is specifically designed to address the challenges posed by structurally complex geological settings, including areas with heterogeneous lithologies, where slow-moving landslides are particularly common.

The core of this study lies in the quantitative correlation between time-series displacement data derived from remote sensing and detailed subsurface measurements from inclinometric profiles. This integrated approach enables for: (1) a robust cross-validation of satellite data in localized geological contexts, thereby increasing the reliability of displacement interpretations; (2) the generation of high-resolution spatiotemporal maps of deformation patterns, allowing the identification of slope kinematics; and (3) the precise delineation of critical sectors requiring priority intervention along both active and planned railway alignments.

Applications of this methodology during feasibility studies for new rail routes have demonstrated a strong correlation between surface displacement trends detected via InSAR and deep-seated movements recorded by inclinometers. This consistency underscores the capability of the integrated analysis to resolve complex ground displacement phenomena affecting infrastructure stability.

The proposed framework promotes a proactive approach to hazard management through multiparametric data fusion, offering a scalable solution for optimizing infrastructure design in unstable terrains. Future developments will focus on streamlining data harmonization processes to enable more dynamic visualization and interpretation of monitoring parameters, thereby improving decision-making efficiency. This work highlights the pivotal role of interdisciplinary monitoring strategies in building resilient transportation networks, providing valuable and transferable insights for infrastructure projects in geodynamically active regions worldwide.

Monitoring soil movements with EGMS data: an integrated approach for geological hazard

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Abstract. Monitoring and analysis of ground motions are indispensable steps for hazard assessment, geological risk management and land planning. Among the available resources, the European Ground Motion Service (EGMS), developed under the Copernicus programme, offers data with systematic and high-precision coverage of European ground deformations, at local and regional scales, thanks to satellite radar interferometry (InSAR) techniques applied to Sentinel-1 data. However, for the correct and effective use of this information, it is necessary to define shared operational procedures and interpretation criteria that allow interferometric data to be integrated into land planning and management activities.

The present study focuses on the elaboration of a methodological approach based on the integration of EGMS data with geological, geomorphological and territorial information from different sources, especially the Regional Geoportals, in order to support the zoning of landslide hazard at basin scale. Such an approach aims to explore in a systematic and analytical way the potential and critical issues related to the use of EGMS data for spatial planning and the prevention of geological risks.

Areas considered in this study include the Upper Reno Basin, in Tuscany, and the Provinces of Belluno and Vicenza, in Veneto. The heterogeneity of the territorial contexts analyzed allows us to observe how the instability phenomena vary in relation to the different geological conditions and how the different land use can influence the distribution and quality of the EGMS points.

The adopted approach consists of several phases, starting with the initial selection and processing of satellite data. In the areas of interest, the interferometric data (Permanent Scatterers, PS) present are classified on the basis of the deformation rates that have been evaluated with respect to reference thresholds, allowing the distinction between negligible movements and significant movements. Through a test phase on a sample area, a data selection and cross-referencing process has been developed that allows us to identify areas characterized by soil instability, associating them with known geological and environmental contexts or possible new areas of attention.

The results obtained demonstrate the effectiveness of the proposed method and the capacity of EGMS data to support spatial planning and risk mitigation, as long as they are inserted within an interpretative framework consistent with local geological knowledge. These results also allow us to identify possible technical and operational solutions useful to support a more conscious use of EGMS data in the context of land management and risk mitigation. Finally, the work highlights the need to define shared operational procedures, capable of promoting a more standardized use of EGMS data in the management of geological and environmental risks.

Visibility of sinkhole and subsidence processes in the Lazio Region through combined spatio-temporal PS Interferometric Analysis and ancillary data integration

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Abstract. The availability of periodic scans of the entire Lazio Region through EGMS provides administrations responsible for land management and risk mitigation with the opportunity to monitor large areas, inventory and characterize active ground deformation processes, and rank and prioritize Areas of Interest (AOIs).

Following the experience gained in detecting AOI candidates hosting landslides across the Lazio Region (Marmoni et al., 2025), and within the framework of the Cooperation Agreement between the regional administration and the CERI–Sapienza University of Rome, the analysis has been extended to include slow subsidence processes and potential sudden sinkholes. This was achieved by integrating Sentinel-1 and COSMO-SkyMed Persistent Scatterers (PS) interferometric data with ancillary geological and hydrogeological information.

The most recent EGMS releases, covering the period 2019–2023, led to the identification and classification of more than 1,800 AOIs characterized by a consistent negative displacement along the Line of Sight in both orbital geometries, indicating ground lowering. These AOI clusters are spatially related to the main alluvial and intermontane plains of the region, where compressible deposits crop out or coincide with the main outlets of the hydrogeological units of the central Apennines. Approximately 5% of them are located within 500 m of mapped sinkholes.

A subset of AOIs can be considered newly developed when compared to those detected during the previous monitoring interval (2015–2021). Among them, 78 new AOIs show an absolute velocity greater than 6 mm/yr and an area smaller than 5 km², with about one-third located in areas classified as having high to very high sinkhole susceptibility (Ciotoli et al., 2016). In these areas, which are potential candidates for ground deformation processes related to underground compaction or cavity formation, subsequent analyses focused on the displacement time series. The objective was to identify the occurrence of so-called Turning Points (TPs – Ghaderpour et al., 2024), defined as long-term variations in displacement rates, and Jumps (Js), characterized by abrupt and localized shifts observed across multiple Persistent Scatterer (PS) time series within the susceptible Areas of Interest (AOIs). These parameters proved particularly effective in detecting anomalous subsidence patterns, making them valuable for further investigation as potential proxies for sinkhole occurrence and as early indicators of incipient instability.

Ongoing activities include extending the analysis through dual-geometry COSMO-SkyMed processing and integrating the results with geophysical surveys and remote sensing data. The workflow proposed here represents a step forward in the development of an integrated regional system for monitoring slow ground deformation processes and rapid sinkhole phenomena.

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Three decades of Ground Deformation in Lettomanoppello Landslide (Central Italy) revealed by InSAR Observations

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Abstract. Lettomanoppello, a historic town on the northwestern slopes of the Maiella Massif (Central Italy), is affected by a slow-moving, deep-seated gravitational landslide that has long been known to impact its western portion. However, until recently, the full extent of instability remained uncertain. Previous investigations focused on localised damage and assumed partial involvement of the town.

In this study, we provide the first long-term satellite-based reconstruction of ground deformation over the past 40 years (1992–2023) using Interferometric Synthetic Aperture Radar (InSAR) monitoring. By integrating multi-sensor SAR datasets from the ERS, ENVISAT, and Sentinel-1 missions and applying advanced multi-temporal InSAR techniques on both ascending and descending orbits, we estimate the vertical and east-west components of displacement at high spatial resolution.

Our analysis reveals that the entire urban area of Lettomanoppello is affected by measurable ground deformation. This represents a significant advancement in understanding the landslide's real extent. Displacement rates exceed 1.5 cm/yr in some sectors and show consistent seasonal and long-term trends, reflecting both hydrological forcing and deep-seated gravitational creep. Importantly, ground motion is not confined to peripheral areas but extends across the historic centre, affecting residential buildings, critical infrastructure, and public spaces.

This finding significantly changes the risk scenario for the town. A phenomenon previously regarded as a partially localised landslide is now recognised, through satellite monitoring, as a widespread, ongoing process affecting the entire urban area. Our results highlight the urgent updates to hazard assessments, protection planning, and mitigation priorities.

The InSAR-based displacement data are being integrated with in situ geotechnical investigations and numerical modelling to support a new interpretation of the landslide process. This combined approach enhances understanding of landslide susceptibility and contributes to a more accurate assessment of landslide hazard, as well as the associated risk when vulnerability and exposure are known.

Implementation of Innovative Low-Cost Techniques for Data Collection and Mudflow Monitoring

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Abstract. The present study arises from the need to collect a comprehensive dataset of laboratory-scale mudflow experiments to validate a mathematical model, currently under development, designed to describe the evolution of these phenomena.

The first part of the work involved designing the experimental setup. A removable module, specifically designed for this experimental campaign, was integrated into an existing landslide simulator in the Gap2Lab (Laboratorio di Geologia e Geofisica Applicata) at the Lecco Campus of Politecnico di Milano to carry out the experiments. The landslide simulator consists of a tiltable plane with an adjustable inclination using a motorised system. The removable module, placed on the simulator, consists of a channel divided into two parts by a gate, which separates the source area from the transition area.

A non-uniform material, chosen for its suitability for this purpose in terms of granulometry, was used to reproduce the mudflow with varying water content, resulting in different material densities. For validation, the following parameters were analysed: mudflow flux height, velocity, accumulation area, and volume. The analysis of the last two parameters is of particular interest in risk management, as they are typically correlated with the greatest impact on human infrastructures. Since these phenomena are characterised by very high speeds (on the order of tens of km/h), the monitoring setup must be designed accordingly to effectively track them. Photo acquisition has proven particularly useful in monitoring mudflow. By processing photo frames to automatically detect and scale the mudflow level, it is possible to track the evolution of the height and, consequently, gather information about the flux velocity. A similar procedure has been employed to investigate the dynamics of the accumulation zone. In addition, low-cost coherent optical fibres were positioned for the measurement of the average velocity in the transition area. When the flux stops its macroscopic movement, LIDAR scans are performed, allowing for the collection of detailed information about the geometry of the accumulation zone.

The work has enabled the collection of a rich and diverse dataset, covering various conditions, which is being used for the validation of the mathematical model under development. Furthermore, it has highlighted how these low-cost techniques, when properly implemented, can be effectively used to monitor these phenomena, potentially even at a real-scale level.

Unstable historical towns: a multi-disciplinary approach for landslide analysis and mitigation strategies

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Abstract. The Apennine Mountains of southern Italy host numerous historical small towns that constitute a unique cultural heritage of global relevance. Many of these settlements are experiencing rapid depopulation and progressive structural degradation, largely due to landslide processes affecting historical buildings and infrastructures. The preservation of their cultural, social, and economic value requires a multi-disciplinary approach based on a comprehensive understanding of landslide predisposing and triggering factors, including their temporal evolution. This study, developed within the framework of the PRIN LIVES project (LIVing in unstable historical towns: landslide hazard Evaluation Strategies for safety improvement and conservation), addresses these challenges through: i) identification of representative unstable historical towns in Southern Italy; ii) monitoring and mapping of damage to historical buildings; iii) landslide hazard analysis through the reconstruction of engineering-geological slope models; iv) identification of triggering factors and displacement trends; v) definition of mitigation strategy. The selection of the most representative unstable historical towns was carried out by integrating regional landslides inventory maps, A-DInSAR displacement time series, and detailed field surveys. These investigations were complemented by the assessment of damage intensity and its spatial distribution on historical buildings and infrastructures, as well as interviews with local inhabitants to evaluate risk perception. The research focused on three representative towns of the southern Apennines - Civitacampomariano (Molise region), Lauria (Basilicata region) and San Lorenzo Bellizzi (Calabria region) – each located in complex geological and geomorphological settings historically affected by different types of landslides that have caused severe damages.

For these case studies, engineering-geological models and landslide mechanisms were reconstructed by combining field surveys, aerial photogrammetry, InSAR data and pre-existing geological and landslide maps. The results provide insights into landslide dynamics, forming the basis for the planning of monitoring systems, stabilization measures, and conservation strategies for the architectural heritage. Based on the specific engineering geological, landslide and ancient buildings features the design of mitigation strategies including the improvement of surface and underground drainage systems, installation and/or integration of monitoring systems and structural interventions on historic buildings as well as the enhancement of the preparedness of population in facing landslide movements is under evaluation. Given that the proposed methodological framework was tested across different geological and geomorphological frameworks, it can serve as a reference model for the analysis and management of similar historical towns throughout the southern Apennines of Italy.

Prima applicazione sistematica del fotomonitoraggio per la sorveglianza di frane in Italia: risultati del progetto Geosciences IR

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Abstract. Il fotomonitoraggio rappresenta una tecnica innovativa di remote sensing basata sull'applicazione di algoritmi di image analysis 2D (change detection e digital image correlation) su immagini acquisite da camere ottiche. Nonostante il potenziale per il monitoraggio di frane a costi contenuti, l'assenza di validazioni sistematiche su larga scala ne aveva finora limitato l'adozione operativa.

Questo studio presenta i risultati della prima applicazione sistematica del fotomonitoraggio su scala nazionale, condotta nell'ambito del progetto PNRR "Geosciences IR". Tra gennaio 2024 e giugno 2025, sono stati monitorati 13 siti franosi distribuiti lungo tutta la penisola italiana, rappresentativi di diverse tipologie di dissesto: deformazioni gravitative profonde di versante (DGSD), colate in terra, rock avalanche, crolli e ribaltamenti. La rete di monitoraggio ha impiegato 17 camere fisse e un sistema UAV, con strategie differenziate: 8 siti con acquisizione continua (frequenza oraria), 5 con monitoraggi periodici, e 2 con analisi di archivi storici. Le immagini acquisite sono state processate mediante il software IRIS (NHAZCA s.r.l.), applicando algoritmi di change detection per fenomeni rapidi e digital image correlation (DIC) per deformazioni lente.

Il dataset generato comprende oltre 150.000 immagini (390 GB) acquisite lungo un gradiente di distanze sensore-target da 50 m a oltre 1100 m. L'analisi mediante change detection ha identificato e catalogato 1235 cluster legati a fenomeni gravitativi, con dimensioni multi-scala. La DIC ha quantificato tassi di spostamento variabili da cm/anno (DGSD di Cercevesa) fino a m/giorno (colata di Baldiola).

La validazione quantitativa condotta presso il sito di Baldiola, confrontando le serie temporali di spostamento ottenute dal fotomonitoraggio con misure geodetiche da stazione totale robotizzata, ha prodotto coefficienti di correlazione eccezionali (r -Pearson: 0,831-0,999; media 0,966; $p < 0,001$), dimostrando accuratezza comparabile alle tecniche geodetiche convenzionali. A Poggio Baldi, l'acquisizione oraria ha permesso di documentare eventi precursori: micro-crolli localizzati in prossimità spaziale e temporale (ore-giorni) rispetto a collassi maggiori, aprendo prospettive per sistemi di early warning. L'analisi delle correlazioni con variabili meteorologiche ha confermato trigger specifici: precipitazioni per Baldiola ($r > 0,973$; soglia di attivazione 31,3-46,8 mm/giorno per 91 eventi di accelerazione) e scioglimento nivale per La Saxe.

L'analisi comparativa delle performance ha evidenziato la superiorità dei sistemi fissi rispetto ai monitoraggi periodici in termini di risoluzione temporale, complessità analitica e qualità dei risultati. Configurazioni ottimali prevedono camere con risoluzione minima di 8 MP e alimentazione elettrica continua.

Questo studio dimostra che il fotomonitoraggio è una tecnica matura e affidabile per applicazioni operative di sorveglianza franosa, fornendo dati quantitativi con accuratezza confrontabile alle tecniche tradizionali a frazione del costo. La scalabilità dimostrata in termini di distanza sensore-target (50-1100 m) e la capacità di rilevamento multi-scala rendono il fotomonitoraggio uno strumento strategico per ampliare le reti di monitoraggio sul territorio nazionale, dove attualmente solo 1250 delle 636.000 frane censite IFFI sono monitorate.

Valutazione delle aree a potenziale rischio di frana nei Monti Lessini orientali (Veneto, Italia)

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Abstract. L'individuazione e monitoraggio di aree instabili rappresenta un passaggio fondamentale per la gestione del rischio geomorfologico e una pianificazione territoriale sostenibile. Il presente studio si concentra sull'analisi delle aree potenzialmente soggette a frane nei Monti Lessini orientali (Regione Veneto, Italia), attraverso l'integrazione di dati geologici, geomorfologici e interferometrici in ambiente GIS.

L'approccio metodologico adottato si basa sulla combinazione di dati spaziali e temporali applicata ad un insieme di unità di versante (Slope Units). La componente spaziale consiste nella stima della suscettibilità di frana definita sulla base di alcuni dei principali fattori condizionanti: morfometrici (pendenza, esposizione, curvatura), litologici, idrologici e legati all'uso del suolo. La mappa di suscettibilità è stata integrata con la componente temporale derivata dai dati EGMS (European Ground Motion Service); l'integrazione di questi dati ha permesso di individuare variazioni di velocità significative nel tempo e distinguere le aree con potenziali movimenti del suolo attivi da quelle stabili.

I risultati evidenziano che la presenza di depositi sciolti o debolmente coesivi, derivati dall'alterazione delle rocce vulcaniche, costituisce il principale fattore di instabilità dei versanti, mentre le informazioni interferometriche si sono rivelate utili per la validazione del modello e per l'individuazione di zone di attenzione non ancora censite.

La combinazione tra l'analisi spaziale e quella temporale ha consentito di ottenere una valutazione più completa della pericolosità da frana, dimostrando l'efficacia dell'integrazione tra strumenti GIS e dati InSAR per il monitoraggio e la gestione del territorio. Il metodo proposto in questo studio si è dimostrato semplice, affidabile e replicabile, in grado di supportare le autorità nelle attività di prevenzione e mitigazione del rischio geologico a scale di bacino o superiori.

Response to meteo-climatic forcing of an alpine deep-seated rockslide (Trafoi, South Tyrol)

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Abstract. The Trafoi landslide, located in the Province of Bolzano near the Stelvio Pass (South Tyrol, Italy), is a deep-seated rockslide affecting metamorphic rocks (paragneiss and orthogneiss) and covering an area of approximately 1.2 km² directly above the village of Trafoi. The landslide develops within a broader deep-seated gravitational slope deformation that has been active for decades, representing both a potential hazard for the Trafoi valley and a key natural laboratory for long-term monitoring and analysis.

Over the years, several monitoring techniques have been implemented to investigate its dynamics, ranging from field-based instruments—such as inclinometers and periodic GNSS measurements—to space-borne SAR interferometry and multi-temporal LiDAR surveys from helicopter platforms. More recently, within the framework of the SoLoMon project, the monitoring system has been significantly enhanced through the installation of a continuous GNSS station and a Robotic Total Station (RTS) equipped with a network of 12 monitoring prisms.

More than 15 years of periodic GNSS data reveal that annual average displacement rates vary locally between 1–2 cm/year and 6–7 cm/year, in agreement with the results provided by the newly installed continuous systems. These data confirm that the Trafoi rockslide does not behave as a single coherent mass but rather as a complex system composed of multiple sub-units moving at different velocities. The landslide has previously been subdivided into two main sub-units (Iannacone et al., 2013), with Unit A, located in the central part of the slope, representing the active deep-seated rockslide that is the focus of this work.

In this study, newly acquired datasets from continuous GNSS and RTS were processed to remove noise and fill temporal gaps, yielding a clearer and more continuous depiction of the landslide's kinematics. Based on this refined dataset, the relationship between slope velocity and climatic forcing—specifically precipitation and snow accumulation and melting—was analysed across distinct kinematic sectors.

This integrated approach revealed recurrent seasonal accelerations during spring (April to June), primarily driven by snowmelt. However, these displacement modulations are differentiated within the Unit A, suggesting further internal complexity of the sub-unit.

The results underscore the importance of combining continuous ground-based monitoring and meteo-climatic data to better understand the behaviour of deep-seated landslides. The Trafoi case study highlights that such large, slowly evolving systems—though apparently stable or characterised by semi-constant displacement rates—can actually experience localized acceleration phases in response to seasonal or climatic conditions. Therefore, the continuous and integrated monitoring of this phenomenon represents not only a valuable scientific opportunity but also a strategic component for risk mitigation and the development of early-warning systems in alpine environments.

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Landslide monitoring using satellite-based Offset Tracking: the ASI-Paracelso project

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Abstract. Satellite remote sensing techniques have become essential tools for monitoring and analysing Earth's surface, providing valuable insights into natural hazards and supporting effective decision-making. Within this context, the Paracelso project, funded by the Italian Space Agency (ASI), aims to enhance the mapping and monitoring capabilities of the Po River Basin Authority (ADBPO) by integrating satellite observations and advanced data analysis methods for studying the dynamics of rivers, landslides, and rock glaciers.

Focusing on landslides, a python package (named Sensetrack) has been developed to support the Po River Basin Authority in mapping and surveillance practices. The package implements well-known offset tracking (OT) techniques for detecting and characterizing large-scale slope movements, particularly those exhibiting displacement rates too high for conventional multi-interferometric approaches.

This study specifically investigates the application of OT algorithms, including Phase Correlation (PC) and Optical Flow (OF), to satellite imagery acquired from the Sentinel-2 mission.

Two case studies were selected and used as tests to assess the performance of the Sensetrack package with the aim of reconstructing the evolution of these phenomena in recent years. The two sites are the Ca' Lita and Valoria earthslides-earthflows, located in the Reggio Emilia and Modena province (Northern Apennines).

Preliminary results, that cover the period from 2019 to 2025, validated through ground-based monitoring and field evidence, demonstrate that offset tracking can effectively retrieve displacement patterns and motion distributions at the slope scale for active earthslides and earthflows. These findings highlight the potential of OT-based approaches to provide consistent and spatially detailed information on landslide dynamics over both short and extended time periods.

However, the analyses also reveal several limitations related to data pre-processing—particularly image co-registration and terrain correction—as well as to algorithmic optimization, which currently impact computational efficiency and accuracy. Addressing these challenges is essential to fully exploit the potential of OT techniques for operational applications.

Overall, the study confirms that offset tracking, represents a powerful approach for leveraging multi-source satellite data to improve landslide monitoring and mapping, enhancing the effectiveness of hazard assessment and risk management strategies for both researchers and decision-makers.

An operational framework for Landslide Early Warning System in Campania region (southern Italy) considering variable antecedent soil hydrological status

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Abstract. The assessment of hazard related to rainfall-triggered shallow landslides commonly relies on the recognition of threshold values of rainfall, considered to cause slope instability with a significant probability. Usually, rainfall thresholds are a main part of Landslide Early Warning Systems (LEWSs), coupled with methods for rainfall forecasting. Among the most relevant uncertainties affecting the reliability of rainfall thresholds, the evaluation of antecedent soil moisture conditions remains the most critical issue. The definition of an effective LEWS which consider antecedent soil hydrological status in the estimation of rainfall conditions triggering shallow landslides involving ash-fall pyroclastic soil-mantled slopes of the peri-volcanic mountainous area of the Campania region (Italy) is particularly required to improve the risk management of these catastrophic landslides. Indeed, these landslides are probably the most frequent type of mass movement in the Campania region, as well as the most dangerous. Many events tragically confirmed this statement, from at least 1954 landslides and floods at Salerno and surrounding municipalities to the latest episode occurred at Gragnano (province of Naples) in September 2024. Many studies have investigated the triggering role of rainfall events, while the preparatory effect of antecedent soil moisture conditions is still poorly addressed.

Starting from these considerations, this study aims to develop an empirical model to estimate antecedent hydrological status, expressed as initial soil water pressure head (Ph), starting from physics-based rainfall thresholds known in literature. The forecasting of initial Ph was carried out by empirical time-decay relationships, controlled by gravity drainage and evapotranspiration processes, occurring in the soil system during dry and wet seasons. Modeled Ph was introduced in the classical I-D rainfall threshold allowing better reproducing cause-effect relationships between triggering rainfall events and shallow landslide occurrence. Therefore, results were incorporated into a procedure to obtain a forecasting tool for which rainfall threshold values change depending on selected antecedent hydrological status, which could be modeled or measured.

Besides the specific case study, the proposed approach can be considered generally applicable in all cases in which the lack of past landslide inventories and/or the unreliability of corresponding rainfall records as well as different antecedent soil hydrological conditions prevent the setting of effective empirical rainfall thresholds.

Inclinometer time series for automated detection of landslide displacement

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Abstract. The monitoring of landslides represents a complex and multidisciplinary challenge that requires the integration of various sensors, techniques, and analytical approaches. The monitoring network for the presented case study is based on the systematic collection of data from inclinometers, piezometers, and GNSS sensors. Moreover, the intensification of meteorological events, linked to the climate change, improves the complexity of landslides investigation through the triggering of episodic displacement accelerations.

In this work we present a new approach to detect acceleration in landslide displacement. The case study selected is a landslide in the northeastern Alps affecting the San Lorenzo Road tunnel along the SS 52 route between Forni di Sotto and Ampezzo (Friuli Venezia Giulia region). The landslide body has an estimated volume of approximately 24 million cubic meters and covers an area of about 4.13 square kilometers.

The initial phase of the study involved a manual analysis of the inclinometer data to identify deformation patterns and characterize movement in relation to precipitation events.

In the second phase, an automated method was developed to analyze the inclinometer time series using an hourly moving window. This approach enabled the detection of displacement accelerations and the calibration of regression coefficients across multiple time intervals. Significant displacement peaks were identified through a quantile-based thresholding technique, ensuring robust detection of deformation events correlated with precipitation. Additionally, data normalization and standard deviation adjustments were applied to enhance the visibility of primary peaks while reducing the influence of secondary fluctuations.

In the third phase, the results were used to automatically detect anomalous displacement rates and generate preliminary warning signals.

The proposed approach enhances the interpretative capacity of long-term monitoring data and contributes to the development of early warning systems for landslide risk mitigation.

Hydrogeological Interaction Between Ephemeral Lake and Karst aquifer behavior in Dragone Plain Polje (Southern Apennines, Italy)

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Abstract. Under a period characterized by increasing temperatures and decreasing precipitation, effective water resource management and groundwater recharge assessment have become critical issues. In karst systems, the interaction between surface flows, temporary surface water bodies and spring discharge provide a clear illustration of the links between groundwater and surface water. The ephemeral lake systems in the area act as temporary storage components of the karst aquifer, store part of the flow during high rainfall seasons and subsequently recharge the groundwater aquifer, positively influencing spring discharge and, especially in mountainous regions such as southern Italy (southern Apennines), play a critical role in controlling aquifer dynamics and spring discharge. However, many of these systems are temporarily or seasonally active and may dry up or reach a more stable function depending on recharge and rainfall conditions. Especially in areas with reduced precipitation or limited recharge, these lakes can become important indicators for monitoring groundwater storage changes.

In this context, the present study examines a temporary and seasonal lake in the vicinity of the Volturara Valley (Terminio Mountains), which directly influences the output of the Cassano spring. The Dragone Plain of the Terminio-Tuoro carbonate massif is one of the largest existing endoreic runoff areas in the Southern Apennines, an important water supply resource for southern Italy.

The lake was mostly dry and low in water during the period 2021 to 2025. Considering the fact that the output of the Cassano spring is a function of the aquifer conditions and its surface recharge, this highlights the need for a detailed assessment of the relationship between precipitation and the state of the lake, groundwater level and spring output and for this purpose, initially, continuous monitoring of groundwater was carried out in the Dragon Plain using deep wells.

Without performing such an analysis, a complete picture of the impact of the lake's dryness on the hydrological performance of the spring will not be provided. Therefore, the aim of this study is to evaluate and quantify the relationship between precipitation and the presence or absence of lakes, changes in their volume and area using Sentinel-2 Satellite Images, digital elevation models (DEM), and GIS-based processing (QGIS) and the outflow of the Cassano spring.

Thus, the present study not only contributes to a better understanding of the dynamics of groundwater-dependent lake systems in karst areas, but also can contribute to the sustainable management of water resources in conditions of reduced recharge in mountainous areas. The findings of this study can be applied to planning the protection of karst watersheds, designing monitoring systems, and assessing the impacts of climate change on the performance of springs and groundwater storage.

Assessing specific groundwater vulnerability to agrochemicals at the farm scale

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Abstract. Effective and sustainable groundwater management relies on a thorough characterization of aquifer systems, particularly in alluvial environments where intense agricultural and industrial activities pose a significant risk of contamination. Therefore, assessing the specific groundwater vulnerability to agrochemicals used in farming practices represents a key challenge toward the achievement of zero-pollution targets and sustainable agriculture aimed at Agenda 2030 goals.

In the framework of the PNRR AGRITECH project, a multiscale and multidisciplinary approach has been implemented at the Torre Lama experimental site (55 ha), located in Bellizzi (Campania, southern Italy). The test site, representative of alluvial hydrogeological framework, is situated within the Sele River plain, an area characterized by a complex stratigraphic setting and a multilayered aquifer system. The research focused on the hydrogeological characterization of the test area by applying integrated methodologies across different spatial scales and the monitoring and modeling of agrochemical transport through the unsaturated zone to the water table.

At the farm scale, the hydrogeological setting was investigated by collecting borehole data, measurement of piezometric levels in existing wells and execution of 18 Vertical Electrical Soundings (VES). Moreover, to investigate transport processes of agrochemicals, an experimental plot was set by carrying out site characterizations based on 4 boreholes, 3 dynamic penetrometer tests, 12 piezometers, 7 infiltration tests, soil sampling and laboratory analyses.

Results allowed the recognition of alternating horizons of clayey-silt and silty-sands with contrasting hydrogeological properties. This information supported the design of a monitoring station equipped with suction lysimeters, aimed at collecting capillary water samples and tracking the migration of selected agrochemical (three herbicides) through the unsaturated zone, as well as a multi-level probe for monitoring soil water content, temperature, and salinity. In addition, several groundwater samples were collected from 13 multi-level piezometers to obtain an hydrogeochemical characterization of saturated zone and to monitor the fate of herbicides. Based on soil hydrological and meteorological time series, a 1D hydrostratigraphic model was implemented in HYDRUS numerical code to simulate agrochemical transport to the water table by estimating the travel time and concentration across the unsaturated zone. The numerical modeling was calibrated using a 1-year (December 1, 2023–December 1, 2024) dataset of rainfall and evapotranspiration, together with typical local agricultural practices regarding herbicide application and then applied to a period of 10 years.

The modeling results indicated a downward movement of the pollutant through the unsaturated zone, characterized by concentration fluctuations that attenuate in amplitude and become more prolonged with increasing depth. The extremely high travel time values obtained highlight how the unsaturated hydraulic conductivity, and its variability depending on soil properties and soil water pressure head, controls the velocity of pollutant transport within the unsaturated zone, varying from 0.22 to 0.26 cm/day. Furthermore, the hydrogeochemical characterization of water samples revealed a herbicides concentration lower than 0.05 ug/L, confirming the modeling outcomes. The results obtained at the plot scale were considered extendible to the whole farm area according to the homogeneous hydrostratigraphic setting, as derived by the VES survey.

Preliminary assessment of thermo-hydro-mechanical interactions in the mountain karst aquifer of the Bossea Cave

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Abstract. The Bossea Cave system represents a mountain karst aquifer located within the Ligurian Alps (Piedmont, Northwestern Italy). The system is structurally controlled by the lithological contact between a low-permeability Permian metavolcanic basement and an overlying Triassic metacarbonate sequence, which serves as the primary conduit for groundwater drainage. Recharge occurs predominantly through meteoric inputs, including rainfall and snowmelt within the aquifer's recharge area.

Water levels in both the main drain (Torrente Mora) and the secondary inflows have been monitored for decades, while sub-hourly, in-depth rock temperature measurements have been conducted since 2021. The initial results demonstrate different interaction mechanisms: the rock mass affected by a reduced overburden thickness (i.e., near the entrance) is significantly influenced by external meteorological factors, exhibiting both daily and long-term thermal effects. Conversely, thermal variations in the innermost rock are mainly influenced by the hydrodynamic behaviour of the main drain and the external wave is detectable only with a seasonal delay in limited sites within the cave.

In parallel, passive seismic monitoring has been implemented to investigate the role of both thermal fluctuations and variable water inflows on rock mass fracturing processes. Frequency domain analysis of the seismograph signal has revealed a continuous hydrodynamic signature in the 30-35 Hz band, with spectral content increases during Torrente Mora flood events. However, microseismic events sampling through the STA/LTA algorithm has demonstrated a stronger correlation between incipient fracturing events and daily temperature variations in both the atmosphere and shallow rock.

These results suggest the need for further seismic monitoring to investigate the potential role of water in inducing deformation within the rock mass. It is recommended that a high-frequency seismograph be installed in a deeper area of the cave to detect these potential effects. Furthermore, a preliminary manual displacement monitoring system for the cave roof has recently been implemented and is expected to achieve a precision of approximately 2 mm in detecting displacements following significant water infiltration events.

Seawater intrusion in a coastal aquifer: three decades of change simulated using SEAWAT

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Abstract. Industrial activities in coastal areas often lead to overexploitation of groundwater resources, resulting in negative impacts such as seawater intrusion, with consequent degradation of water quality. This is the case of the industrial area of Catania, located on the eastern coast of Sicily (Italy), where intense groundwater pumping over past decades contributed to increased aquifer salinization. This study aims to evaluate the evolution of seawater intrusion over a thirty-year period by means of a density-dependent groundwater flow model developed with the FREEWAT-Q3 platform and the SEAWAT code. The model simulates seawater intrusion under state conditions for the years 1995, 2003, and 2025 and allows the estimation of seawater flow entering the aquifer system. A further goal, being the year 2003 a turning point as several wells within the industrial area were decommissioned, is to determine whether the reduction in pumping led to either stabilization or regression of the seawater intrusion wedge. The model is built using fourteen model layers, each 5 meters thick, representing recent alluvial deposits with varying permeability values and deeper units composed of sandstone and gravel. The hydrogeological conceptual model was defined based on geological and hydrogeological data, which allowed us to determine that groundwater direction is west to east. Aquifer recharge is provided by rainfall and inflows from the Simeto River and the surrounding hills, while discharge occurs towards the Ionian Sea, along with intrusion. These boundary conditions were implemented in the numerical simulation and historical pumping data as well as meteoric recharge were integrated in the model as source/sink terms. Model calibration was performed using groundwater head data and field measurements of groundwater electrical conductivities arising from monitoring campaigns conducted in 1995, 2003 and 2025. The latter were converted to chloride concentrations to represent salinity concentration. The implemented model underscores the importance of sustainable groundwater management in coastal zones, especially in industrialized areas. The modeling approach adopted in this study provides a valuable tool for assessing the effects of human activities on aquifer salinization and supports the development of informed strategies for groundwater protection and remediation.

GIS-Based Assessment of Groundwater Recharge in a Mediterranean Karst System Using CHELSA and MODIS Data

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Abstract. Assessing groundwater recharge (GR) in karst aquifers is a challenging task due to their complex and heterogeneous hydrogeological characteristics. Moreover, the spatial and temporal variability of precipitation and air temperature data adds further uncertainty to recharge estimation, especially in mountainous karst areas.

This study presents an integrated GIS-based approach for determining and mapping groundwater recharge in a Mediterranean karst aquifer in southern Italy during the period 2000–2018. The methodology combines climatological datasets and satellite products to overcome the scarcity of continuous ground observations. Annual precipitation (P) data were obtained from the CHELSA v2.1 dataset (Climatologies at High Resolution for the Earth's Land Surface Areas; Karger et al., 2017), which provides 30 arcsec (~1 km) resolution climatological variables derived from the statistical downscaling of global reanalysis data (ERA5) and ground-based observations. This dataset offers a realistic representation of spatial precipitation patterns, particularly in areas with limited meteorological coverage. Actual Evapotranspiration (AET) data were retrieved from the MODIS MOD16A3GF product (Running et al., 2021), which provides annual AET values (500 m resolution, HDF format, $\text{kg}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ units) computed through an algorithm based on the Penman–Monteith equation.

Groundwater recharge was estimated by applying groundwater recharge coefficients (GRCs) according to a dual criterion. The first approach calculated the percentage of precipitation that potentially infiltrates using the APLIS method (Andreo et al., 2008), an empirical GIS-based model specifically developed for karst aquifers. It computes spatially distributed GRCs as a linear function of altitude, slope, lithology, preferential infiltration, and soil type. The second approach used the effective precipitation ($P - \text{AET}$) and applied literature-based GRC values depending on aquifer lithology (i.e., 0.95 for karst aquifers; Celico, 1988).

The first analysis compared CHELSA-derived precipitation data with six rain gauge stations characterized by discontinuous records, mostly located in surrounding plain areas. A good correspondence was found for both long-term and interannual trends, confirming the reliability of CHELSA in compensating for missing ground-based data. At the basin and mean annual scale, precipitation ranged from 1120 to 1497 $\text{mm}\cdot\text{yr}^{-1}$, while AET varied between 551 and 1013 $\text{mm}\cdot\text{yr}^{-1}$. Regarding groundwater recharge, both methods produced comparable average values and discharge rate estimates (~1.3–1.4 $\text{m}^3\cdot\text{s}^{-1}$). GR estimated through the APLIS method ranged from 247 to 1056 $\text{mm}\cdot\text{yr}^{-1}$ (mean 563 $\text{mm}\cdot\text{yr}^{-1}$), whereas the approach based on effective precipitation and lithological GRCs yielded similar results (250–848 $\text{mm}\cdot\text{yr}^{-1}$; mean 569 $\text{mm}\cdot\text{yr}^{-1}$). However, some spatial discrepancies were observed due to methodological differences between the two approaches.

Overall, the adopted GIS-based framework proved effective for estimating groundwater recharge in data-scarce karst environments by integrating climatological and remote sensing datasets. The consistent results from both methods confirm the robustness of the approach and highlight its potential applicability to other Mediterranean karst systems.

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From geological complexity to applied models: integrating structural geology and hydrogeology for groundwater management in Mediterranean settings

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Abstract. Groundwater systems in Mediterranean regions are commonly characterized by geological complexity, spatial heterogeneity, and temporal variability driven by both natural processes and human pressures. In such contexts, applied hydrogeological analyses often rely on simplified conceptual and numerical models that inadequately represent the geological controls governing groundwater flow, storage, and vulnerability, often underestimating the uncertainty inherent to geological systems. This contribution argues that geological interpretation, particularly structural and stratigraphic analysis, should be regarded as a central component of groundwater assessment, and that its effectiveness is significantly enhanced when coupled with geochemical and multi-isotopic investigations explicitly aimed at reducing model uncertainty.

We present an integrated methodological framework developed through several research projects and case studies in Sardinia (Italy), a region representative of many Mediterranean environments affected by water scarcity, groundwater salinization, and diffuse contamination. The proposed approach combines detailed geological reconstruction, structural analysis, long-term monitoring data, hydrogeological modeling, and targeted geochemical and isotopic analyses to address geological complexity and to constrain conceptual and numerical models while acknowledging data limitations and scale-dependent uncertainty.

The selected case studies include (i) coastal alluvial aquifers affected by salinization processes, where sedimentary architecture and structural features exert a primary control on seawater intrusion pathways; (ii) intensively cultivated plains impacted by nitrate contamination, where the interaction between shallow aquifers, unsaturated zone processes, and geological heterogeneity controls contaminant transport and attenuation; and (iii) volcanic aquifers, characterized by permeability contrasts and recharge mechanisms linked to lithological variability and fracture networks. In all cases, stable water isotopes ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) are used to identify recharge sources, seasonal signals, evaporation effects, and mixing between different groundwater bodies, providing constraints that help discriminate among alternative conceptual models. Tritium measurements offer additional insight into groundwater residence times and the contribution of recent recharge, while nitrate isotopes ($\delta^{15}\text{N}-\text{NO}_3^-$, $\delta^{18}\text{O}-\text{NO}_3^-$) support the interpretation of contamination sources and transformation processes under uncertain boundary conditions.

The results highlight how structural elements influence preferential flow paths depending on their internal architecture and spatial arrangement, while stratigraphic heterogeneities and depositional geometries strongly affect groundwater flow patterns and system responses to stresses such as pumping or prolonged droughts. Geochemical and isotopic data act as independent, process-based constraints that reduce non-uniqueness in model calibration and improve the robustness of scenario analysis, particularly where monitoring networks are sparse or unevenly distributed. A key aspect of the proposed framework is the explicit recognition that geological and hydrogeological models are inherently based on incomplete and scale-dependent data and should therefore be considered as working hypotheses rather than definitive representations. By integrating geological interpretation, monitoring data, and isotopic tracers within a multi-evidence framework, uncertainty is not eliminated but managed transparently, supporting risk-informed and adaptive groundwater management strategies. This study emphasizes that the effectiveness of groundwater management in complex Mediterranean environments depends on both the quality of geological understanding embedded within applied models and the explicit treatment of uncertainty. Strengthening the dialogue between structural geology, hydrogeology, geochemistry, and monitoring practices is crucial for moving from reactive approaches toward more proactive and sustainable groundwater governance.

Unravelling anomalies in aquifer recharge dynamics using transient time-series analysis: the case of the Shenzhen megacity, China

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Abstract. Urban aquifers are highly complex systems influenced by both natural processes and interactions with the overlying anthropogenic environment. These effects are often spatially clustered, making them difficult to identify at the catchment scale. Groundwater pumping and drainage can induce drawdowns, while leakages from water supply or sewage networks, and irrigation of gardens or small agricultural areas can generate localized, unconventional recharge. Such recharge sources are frequently associated with contaminated waters, posing potential risks to groundwater quality.

Shenzhen (Guangdong, China) is a megacity that has expanded rapidly since the 1980s and now hosts about 16 million inhabitants over ~2,000 km². Early urbanization consisted of densely built low-rise clusters forming extensive impervious surfaces. During this initial phase, the first subsurface infrastructures were designed. Later urban plans introduced taller buildings with great attention to the creation of advanced subsurface networks and the widespread presence of small community parks, as well as several large urban parks and preserved rural zones. The Shenzhen aquifer is a phreatic system hosted in thick weathered laterites originated from igneous and metamorphic bedrock, locally mixed with fine-grained alluvial deposits. The water table generally lies 1-2 m below the surface, and aquifer productivity is low.

A monitoring network of 27 disused hand-dug wells and new drilled piezometers (5-63 m deep) provides daily groundwater level data. The Meteorological Bureau of Shenzhen Municipality manage a network of 27 meteorological stations that uniformly cover the entire municipal area.

We applied the Sliding-Window Cross-Correlation Function (SW-CCF) to rainfall and groundwater level time series to identify anomalies in aquifer recharge dynamics, due to unconventional sources. SW-CCF analyzes the relationship between the input (i.e., rainfall) and output (i.e., groundwater levels) time series in portions of the whole monitoring period (i.e., time windows) by performing a window-by-window calculation of response times and correlations. Consequently, it was possible to investigate how the groundwater recharge varies over the monitoring period due to rainfall infiltration and to identify potential secondary natural/anthropogenic contributions to the aquifer water budget. Because of temporary instrument malfunction during the data collection, groundwater level time series were sometimes affected by the presence of missing values. To address this issue and be able to perform time-series analyses, we first used the Multivariate Imputation by Chained Equations method. This machine learning method leverages measured data from the other groundwater level time series to estimate missing values in a reliable way.

The SW-CCF results showed that correlation between rainfall and hydraulic heads are maximum during wet seasons (i.e., April to October), with response times in the order of 1 to 3 days. In some cases, this response time decreases when groundwater is shallower due to more consistent aquifer recharge. During dry periods, in some monitored points, groundwater levels seemed to decorrelate from rainfall temporal patterns. These anomalies could be ascribed to the connection with wetlands or streams. A few wells located in urbanized areas showed similar anomalies that could not be attributed to surface water, suggesting possible local anthropogenic recharge (e.g., leaks from the sewage systems, or subirrigation systems).

Multidisciplinary insights on PFAS contamination: the case of a deep multilayered aquifer, Parma, northern Italy

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Abstract. PerFluorinated Alkylated Substances (PFAs) are considered ubiquitous substances since they were detected in surface-, drinking-, waste-, rain-water, landfill leachate, soil and sediments and once released into the environment they are particularly persistent. However, fewer hydrogeological studies have focused on possible PFAs contamination in groundwater with an emphasis on the role of hydraulic interconnections between surface- and groundwater and both shallow and deep layers in heterogeneous complex aquifer systems. Therefore, the research was conducted by analysing both surface waters and groundwater, sampled at different depths. A multidisciplinary investigation has been carried out in the context of the multilayer alluvial aquifer of the Parma plain, integrating: (i) hydrogeological investigations; (ii) tritium (³H) analysis; (iii) chemical analysis of both short-chain and long-chain PFAS; (iv) characterization of the microbial community, in order to verify potential natural attenuation phenomena. Furthermore, a spatial map was reconstructed through GIS software by applying the cross-checking methodology to illustrate the spatial distribution of industrial activities potentially using PFAs within the study area. Chemical results showed the presence of PFAs in both surface and groundwater, however, not all groundwater monitoring points exhibited instrumentally detectable PFAs concentrations, suggesting a heterogeneous distribution of the chemical compounds within the complex aquifer system. The observed temporal and compositional variations between the two campaigns suggest the occurrence of complex contaminant migration and transformation dynamics in both space and time. The conceptual hydrogeological model was therefore reconstructed in detail, as to identify the hydraulic interconnections between the more permeable horizons coexisting within the heterogeneous system, and between these horizons, the streams and the ground surface. Supporting this hydrogeological interpretation, tritium (³H) analysis provided insight into dynamic flow regime characterized by relatively short transit times and the characterization of the native microbial community revealed the presence of bacterial genera known for their involvement in the biotransformation of organic contaminants, including PFAS. The analysis of the possible PFAs migration pathways, as well as the potential industrial activities that can release PFAS, at the basin scale opened some questions about the influence of wells characteristics and management practices on PFAs distribution in shallow and deep groundwater.

Geo-hydrological features contributed to the choice and configuration of the ancient Roman aqueducts Aqua Augusta and Sannitico from Serino springs

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Abstract. In Campania Region, the Romans built two important aqueducts: Augustan (1 st Century B.D.), also known as Aqua Augusta, and Sannitico (1 st Century A.D.). The first, built between 33 and 12 B.D., provided drinking water to the Puteoli area and the imperial fleet stationed at Capo Miseno, and extends over 100 kilometers.

The Sannitico aqueduct fed Benevento, for a total length about 33 km, and it is believed to have been built in the first century A.D. Both aqueducts were fed by Serino springs, located along the Sabato river, near Avellino and connected with the wide aquifer of the Terminio-Tuoro karst massifs.

Literature mainly focuses on archeological, architectural and engineering aspects of these aqueducts, less about the hydrogeological aspects. Hydrogeological and hydrological features have been analyzed to reconstruct the rationale behind the selection of the aqueduct's water sources: flow rate, ground level, and quality of the karst waters of the Serino springs best met the supply requirements. These characteristics, and other of historical and archeological nature, suggest that Augustan Aqueduct had hydraulic connection with Sannitico aqueduct, also fed by the Serino spring group. In this research, we retained that both aqueduct systems could be part of a unique and great hydraulic system, built in the 1st century B.D. to supply areas of great residential importance (cities and patrician villas) or military importance (Miseno harbor and Benevento). This hypothesis is further supported by analyses of supply flows that account for the civil, military, and productive needs of Regio I, Latium et Campania. From this perspective, the Aqua Augusta and Sannitico aqueduct emerge not only as a complex water infrastructure, born from careful hydrogeological and engineering considerations, but also as a vital tool for territorial planning and political-military control, aligning with the strategies of Emperor Augustus.

These aqueducts were then abandoned at some point, though exactly when is unknown, most likely due to the destruction during barbarian invasions, the floodings of Sabato River, or landslides and seismically events affecting their layout. In current era, to supply the area of Naples, Urciuoli (1885-1888) and Acquaro-Pelosi springs (1934) were re-tapped by the "Serino Aqueduct" through a gravity channel, followed by a system of pressure conduits.

Towards Quantitative DNA Tracing of Groundwater Flowpaths and Hydrodynamic Processes

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Abstract. Ensuring sustainable water management and safeguarding water resources require precise tools to trace groundwater flowpaths and contaminant transport. Conventional hydrological tracers often lack the sensitivity, specificity, and scalability needed to characterize complex or large-scale aquifer systems, limiting their usefulness for water quality monitoring and pollution control. This study presents an innovative passive device designed to selectively capture biotinylated synthetic DNA tracers, a new generation of environmentally safe, highly specific, and quantitative markers for tracking water movement and pollutant dispersion.

The device integrates streptavidin-functionalized superparamagnetic beads (1.0 μm diameter; binding capacity ~ 500 pmol mg^{-1}) within a 0.6% agarose hydrogel matrix, housed in a sealed hybridization chamber. This configuration enables both semi-quantitative and quantitative assessments of groundwater flow and contaminant migration through qPCR analysis. Laboratory column tests (flow rate = 1.65×10^{-4} L s^{-1} ; hydraulic gradient = 1.4%) and field-scale experiments in a natural stream (~ 6 L s^{-1} ; 200 m reach) benchmarked DNA tracer performance against conventional tracers (KCl, NaCl, and Fluorescein). Quantification achieved by qPCR (100.2% amplification efficiency; $R^2 = 0.997$; detection limit < 10 DNA molecules per reaction) demonstrated high analytical precision and sensitivity. Breakthrough curves (BTCs) derived from both manual sampling and the passive capture device closely matched conservative tracer responses, with peaks at ~ 3 pore volumes in column tests and ~ 15 min in field trials. The device produced slightly broader BTCs, reflecting its ability to perform time-integrated sampling and capture delayed or retained fractions ($\sim 2.1 \times 10^6$ molecules trap^{-1}).

This approach provides a low-impact, reproducible, and highly sensitive method for monitoring hydrodynamic processes, identifying contamination sources, and assessing risks to water safety. The developed system advances molecular-based diagnostics for sustainable groundwater management and improved protection of vital water resources.

Interaction between Surface Water and Groundwater in an area with a Managed Aquifer Recharge (MAR) system: The Case Study of Val di Cornia (Tuscany)

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Abstract. Interactions between surface water and groundwater play a key role in water resources management, especially in overexploited systems.

This study analyzes these dynamics in Val di Cornia, in an area located within the system consisting of the lower course of the Cornia River and the alluvial plain aquifer, historically affected by irrigation, industrial, and municipal withdrawals that caused significant groundwater level declines, with serious consequences for both the quantitative and qualitative protection of the groundwater resource.

The study area hosts a Managed Aquifer Recharge (MAR) system, implemented as part of the LIFE REWAT project, representing an almost unique case in Italy, especially due to its instrumented monitoring network. This network allows continuous (every 15 minutes) collection and storage of various physico-chemical parameters, creating a high-frequency dataset that enables tracking the quantitative and qualitative evolution of surface water and groundwater at the site since the MAR became operational in 2018.

The analysis of the data aims to develop a model of interpretation and simulation of surface water–groundwater interactions, with potential applications for integrated water resource management.

With the aim of further investigating the river–aquifer transfer dynamics, two transects were identified as potential candidates for instrumentation, including some of the existing monitoring piezometers.

In order to analyze the relationship between surface water and groundwater by considering only the input from the river, periods when the MAR was inactive (to avoid interference with the signal from the Cornia River) were selected, focusing on the most significant flood events and comparing river and groundwater signals. Since no river level measurements were available directly at the study site, data from the Regional Hydrological Service (SIR) station upstream of the area were used. To estimate the travel time of the perturbation to the study area, hydrographs from the two upstream and downstream SIR stations were analyzed for the most significant floods to calculate the average transfer velocity along the river. This preliminary estimate is currently being refined through numerical modeling, which will provide water level values over time at the study site.

Groundwater recharge evaluation of Morcone karst massif (Southern Italy)

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Abstract. Karst aquifers represent the most important resources of fresh water and with good chemico-physical features. The actual recharge is the portion of infiltrated water that reaches the aquifer, and it is confirmed based on groundwater studies. In karst aquifers this process is dual distinguishing a diffuse recharge and focused recharge. The former is derived from the infiltration of precipitation through fractures and fissures in karst rocks; the second one is that happen in endorheic areas through a ponor. Thus, the detecting and mapping of endorheic areas is an important task in recharge evaluation studies. Several methods for recharge evaluation have been developed (Chloride Balance method, SWB Method and so on); some of them were developed especially for recharge evaluation of karst aquifer (APLIS and Groundwater Recharge Model). The modified APLIS method is developed for the average annual recharge estimation in GIS environment for karst aquifers considering some variables such as Altitude (A), Slope (P), Lithology (L), Infiltration landforms (I) and Soil type (S), adding a correction factor accounting for the hydrogeological features of the study area (Fh). In this research the preliminary detecting and mapping of dolines and related endorheic areas affecting Morcone karst massif (Southern Italy) was carried out. The connection of the areas with the main basal spring discharges was highlighted. Then, a recharge evaluation using APLIS and SWB methods was performed. The mapping procedure shows that endorheic areas are widespread in the central part of the massif and cover the almost the 12% of the whole area. The recharge evaluation carried out with APLIS and SWB model shows an average infiltration rate of about 50 million of meter cubic per years, for both methods. The high deviation rate between input and output, represented by spring discharges, is justified by the diffuse flow path affecting the massif. The water that infiltrates inside the karst massif feed several groundwater transfers between the carbonate aquifer and the near aquifer of the alluvial plain of Calore River and forms part of the supply of Grassano spring group located in Teleso plain.

Distinguishing the roles of land use change and climate change in groundwater resource decline: a case study from Sibillini Mountains (Central Italy)

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Abstract. In recent decades, the assessment of groundwater resources has gained increasing importance due to population growth and rising per capita water demand. Rainfall trends in the Mediterranean region are highly heterogeneous: some sub-regions have experienced a decline in annual precipitation, while others show an increase in the frequency of extreme events, such as intense rainfall and droughts. At the same time, average temperatures exhibit a widespread positive trend, leading to higher evapotranspiration. Sudden winter temperature spikes also play a critical role by causing rapid snowpack melting. All these factors negatively affect groundwater recharge. Additionally, as highlighted by several studies, changes in land use can significantly alter the water budget, with impacts dependent on local vegetation and climatic conditions.

The study area, the Sibillini Mountains National Park in the northern Apennines (central Italy), features suspended aquifers of varying size as well as a deep basal aquifer hosted in fractured and karstified micritic limestones. Spring water quality is excellent, which has led to long-term exploitation for drinking water and continuous monitoring over decades. Observed trends in spring discharge, together with river flow measurements representative of linear springs, indicate a consistent and progressive decline in stored groundwater resources since the mid-20th century. In parallel, the central-northern Apennines have experienced significant forest expansion, associated with the gradual abandonment of mountain areas by local populations who previously relied on wood for heating and housing, and used high-altitude areas for pasture.

In this study, the authors: (i) analyze forest growth across the study area considering different land use categories; (ii) perform an in-depth analysis of crop coefficients, a key parameter for calculating crop evapotranspiration; and (iii) quantify the impacts of both land use change and climate change on spring discharge in the Pescara d'Arquata spring catchment (Arquata del Tronto) using a dual complementary approach, based on water budget calculations and a lumped-parameter model. Finally, the lumped-parameter model is used also to assess the influence of snowpack variations on the spring hydrograph.

Long- And Short-Term Trends In Karst Groundwater Resources Using Standardized Spring Discharge And Piezometric Time Series

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Abstract. Karst aquifers host significant groundwater volumes and represent a primary source of potable water in Europe and the Mediterranean region. These systems are particularly sensitive to changes in environmental conditions driven by natural factors and by anthropogenic pressures. Monitoring hydraulic head and spring discharge is essential to assess the impacts of these forcings on groundwater resources. Statistical analysis of monitoring time series is widely used for this purpose, but it requires long historical datasets which are rare in karst areas. Consequently, the impacts of historical climate change on karst aquifers remain still poorly understood. Using hydraulic head and spring discharge data from a typical Mediterranean karst system (the Terminio–Tuoro massif, southern Italy), we investigated long- and short-term trends in groundwater resources and their relationships with climate drivers. Ten observation piezometers located in the Serino discharge area at different depths have provided hydraulic head data since 1963. The study emphasizes several practical and formal aspects of statistical analysis of real hydrological time series. To facilitate comparison among different datasets, values were standardized using the z-score transformation. Standardization is recommended for these analyses, where the relative amplitude of trends and cycles is more relevant than absolute physical values. By standardizing, variables (and their time components) become directly comparable regardless of measurement units. This approach also allowed us to obtain a single hydrological signal from the ten hydraulic head time series by stacking them. This combined signal reflects the same hydrological phenomenon across all monitoring locations, namely ascending groundwater flow affecting the Serino Plain. Results show that the karst groundwater resource has undergone long-term depletion, inducing a persistent negative trend in both hydraulic head and spring discharge since the early 1960s. Rainfall explains most of the annual variability and cyclical behavior of hydrological variables; however, it exhibits no long-term trend, indicating that precipitation alone cannot account for the observed groundwater decline. Between 1960 and 1989, groundwater availability decreased significantly, and this critical condition persisted until 2008. The year 1986 represents a changepoint: from then onward, the aquifer shows a weakened response to rainfall, and the frequency of below-normal hydrological years increases compared to the preceding period. The availability of multiple hydrological time series proved essential in this study. In particular, spring discharge data required pre-whitening, which “altered” their original structure, whereas pre-whitening could be avoided for hydraulic head data. From this perspective, the stacked hydraulic head time series represents a “stronger” hydrological signal, even because it integrates observations from multiple measurement points. The presented analysis provides an overview of the impacts of historical climate change on groundwater resources in a relatively undisturbed karst catchment. The results are consistent with findings from other areas of the Mediterranean basin. In the studied region, rainfall shows no long-term trend, but the late 1980s mark a clear changepoint. Since then, groundwater resources have experienced significant depletion that cannot be explained solely by rainfall cycles and aquifer inertia. Atmospheric warming may be a contributing factor, although further investigation is required.

Hydrostratigraphic mapping and 3D modelling of gravel bodies at the southern margin of the Po Plain, for MAR planning

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Abstract. Managed Aquifer Recharge (MAR) refers to the controlled infiltration of water into aquifers, either for recovery purposes or to achieve environmental benefits. It represents a promising strategy for climate change adaptation, as it supports the replenishment of depleted aquifers and mitigates the effects of drought and groundwater overexploitation.

A key aspect of identifying suitable MAR sites lies in the hydrostratigraphic characterization of buried deposits. Particularly in alluvial settings, where gravel bodies serve as efficient groundwater reservoirs, identifying areas with a high degree of gravel-body connectivity is essential for the effective implementation of fully functional MAR systems.

We present a series of hydrostratigraphic maps and a 3D geological model that highlights features relevant to MAR implementation, such as the geometry, volume and degree of interconnection of aquifer bodies, and the areal extent of potential recharge zones.

The study area, located at the southern margin of the Po Plain, corresponds to the outlet of one of the major rivers draining the Northern Apennines: the Secchia River. The geological mapping and sedimentological characterization of Secchia alluvial deposits relied upon two new cores: i) outcrops along fluvial scarps and ii) extensive stratigraphic dataset provided by the Geological Service of the Emilia-Romagna Region, composed of well and core logs.

Subsurface stratigraphy was reconstructed through the correlation of these data along seven cross-sections reaching depths of ca. 350 meters. Correlations were based on the relative age of deposits and on the lateral tracking of laterally continuous paleosols and mud horizons. This process allows for the definition of the volume, the geometry and the degree of interconnection of gravel bodies. Stratigraphic data were subsequently analyzed using 3D geological modeling software (Leapfrog Geo) to construct an hydrostratigraphic model of the Secchia alluvial deposits.

This approach, which can be extended to similar geological contexts, provides a valuable framework for identifying the most suitable sites for MAR implementation and for supporting the design of fully functional MAR systems.

Assessment of groundwater resource evolution over thirty years in the Mount Etna aquifer

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Abstract. Over the past three decades, the hydrogeological system of Mount Etna (eastern Sicily, Italy) has undergone substantial quantitative changes due to both the climate variability and the intensive exploitation of groundwater resources. This study investigates the evolution of the water balance and potentiometric surface of the Etnean volcanic aquifer by comparing data from the years 1994 and 2023. The objective is to assess the main variations in groundwater storage in relation to changes in precipitation, evapotranspiration, runoff, and recharge regimes within a highly heterogeneous volcanic aquifer. The aquifer of Mount Etna, one of the largest and most productive in Sicily, consists of alternating lava flows, pyroclastics, and volcanoclastic deposits overlying a Meso-Cenozoic sedimentary basement. This complex lithological architecture influences the path of groundwater, altering its direction according to the hydrogeological characteristics of the formations. For this study, carried out in the frame of an agreement between the University of Catania and the Sicilian regional Autorità di Bacino, well data were used to develop geological and hydrogeological conceptual models. The morphology of the impermeable sedimentary basement was reconstructed, allowing the identification of different hydrogeological sub-basins within the volcanic edifice. The analysis of the water table levels revealed significant variation in the piezometric surface between 1994 and 2023, caused by a decrease in effective recharge, which in turn is linked to the regional climatic trend, namely, a reduction in precipitation and an increase in potential evapotranspiration. Moreover, the effects of growing anthropogenic pressures, especially groundwater abstraction for domestic and agricultural uses, further intensify these variations, causing piezometric level declines in certain areas and altering the main groundwater flow drainage patterns. Achieved results indicate a variation in the quantitative status of groundwater related to climatic variability over the reference period (1994–2023) and to a general increase in anthropogenic pressures (well withdrawals for domestic and agricultural uses). The study emphasizes the need for an integrated assessment of the water balance and piezometric dynamics as a key tool to support the management and sustainable development of groundwater resources in peculiar geological contexts that are increasingly subject to evolving climatic conditions.

Hydrogeological conceptual model and tetrachloroethylene contamination pattern in a complex karst aquifer

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Abstract. Karst aquifers are a vital global resource for drinking water. However, their unique hydrogeological features, such as high permeability and rapid flow paths, make them susceptible to contamination from persistent groundwater pollutants. Chlorinated solvents such as perchloroethylene (PCE), a dense non-aqueous phase liquid, pose a significant environmental risk due to their density, low solubility, toxicity, and carcinogenicity (EPA, 1988). In Italy, PCE concentrations in the groundwater exceeding the 1.1 µg/L threshold value (D.L.vo 152/2006) trigger a mandatory detailed site characterisation plan.

This study presents a hydrogeological conceptual model and a spatial analysis of PCE distribution in the Solofra Mts. karst aquifer, Campania region, affected by an industrial-made organic contamination detected in some public and private wells since 2014.

The hydrogeological conceptual model and pattern of PCE in groundwater were constructed by the implementation in Rockworks and QGIS environment of a multiparametric geodatabase, including geological and structural data, stratigraphic logs, piezometric and hydraulic measurements, hydrological data, and groundwater sampling on 86 wells in the years 2014, 2015 and 2023.

The hydrogeological conceptual model identified five hydrostratigraphic units, vertically divided into three aquifers (a basal karst aquifer and two shallow pyroclastic-alluvial aquifers), one aquitard (tuff) and an aquiclude (flysch). The basal karst aquifer has a hydraulic head ranging from 293 to 126 m a.s.l., and an average piezometric gradient of 0.02. The hydraulic conductivity of karst aquifer locally estimated by 6 pumping tests steady-state varies in the order of magnitude 10^{-7} ÷ 10^{-5} m/s.

By using the Inverse Distance Weighting method, the PCE pattern of distribution for the basal aquifer was reconstructed. Maximum concentrations, up to 1200 µg/L, were recorded in deep wells located within the Solofra industrial area, along the preferential drainage axis of the basal aquifer.

Finally, using precipitation data from 13 rain gauges and MODIS-derived evapotranspiration rates, groundwater recharge of the karst aquifer in the period 2000-2024 was estimated, indicating a mean annual value of 627.1 mm/y. Data integration allowed to reconstruct a robust hydrogeological conceptual model for understanding the groundwater circulation and contamination mechanisms within a complex karst aquifer. These results are a key step in the development of a numerical flow and transport model of the organic contaminant as a support tool for decision makers in the strategies for protecting of the groundwater.

Groundwater flow and microbial contaminant dynamics in low-permeability heterogeneous aquifers: a multidisciplinary study from the Northern Apennines, Italy

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Abstract. Low-permeability aquifers hosted in marls, sandstones, and pelites represent strategic but often complex water storage bodies in regions where extensive and highly productive groundwater reservoirs are absent. Understanding the hydrogeological functioning of these systems and their vulnerability to microbial contamination is a key scientific challenge, relevant to many areas worldwide where similar lithological and structural settings occur. In this framework, the area of Varano de' Melegari (Northern Apennines, Italy) was selected as a representative test site to investigate groundwater flow and fecal contamination dynamics within low-permeability aquifers. The study area, covering approximately 15 km², includes two formations of the sedimentary Epiligure Succession, the Monte Piano and Ranzano Formations, and hosts numerous wells and springs used for irrigation, domestic supply, and livestock farming. The main objective of this work was to identify the processes governing the occurrence and spatial distribution of fecal indicators in such aquifer systems, and to develop a conceptual framework applicable to comparable hydrogeological contexts. A multidisciplinary approach was employed, combining (i) detailed geological surveys, (ii) long-term monitoring of discharge, hydraulic head, and physico-chemical parameters, and (iii) sampling for chemical (major ions), bacteriological (fecal indicators), and isotopic ($\delta^{18}\text{O}$, δD , Tritium) analyses. The integration of the results allowed the development of a strong hydrogeological conceptual model capable of explaining the mechanisms that control microbial contaminant transport in low-permeability medium. The results emphasize that heterogeneity within these rocks can exert a fundamental hydraulic control on the distribution and persistence of fecal contaminants, through the interplay between structural discontinuities and stratigraphic features.

Behavioural analysis of nitrate and bicarbonate ions as a tool for identifying groundwater-recharge zones

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Abstract. The identification of aquifer recharge zones becomes a priority for the protection of underground resources. The present research introduces a novel methodological approach that considers the behavior over time of the concentration of the nitrate (NO_3^-) and bicarbonate (HCO_3^-) parameter pair. In particular, by analyzing time series of NO_3^- and HCO_3^- concentrations in the Po Plain (northern Italy) for the period 2012–2023, and applying criteria of an $\text{HCO}_3^-/\text{NO}_3^-$ ratio < 10 and $\text{NO}_3^- > 30$ mg/L, it was possible to identify areas where aquifer recharge processes are clearly evident. This unconventional method could be particularly useful for quick recognition of recharge areas and hence the assessment of the vulnerability of the aquifers. This method can be additionally applied as a tool complementary to traditional conventional approaches, contributing to enhancing their accuracy and robustness in identifying aquifer recharge.

Assessment of Groundwater Recharge in the Province of Lecco (Northern Italy) using the APLIS Method

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Abstract. Groundwater recharge is a key component in understanding and managing water resources, particularly in regions characterized by heterogeneous hydrogeological conditions. In this study, the APLIS method (Altitude, Slope, Lithology, Infiltration, and Soil) was applied to the Province of Lecco (Northern Italy) to estimate the spatial distribution of groundwater recharge, expressed as a percentage of mean annual precipitation. The main objective was to identify areas with different recharge potential in order to support sustainable groundwater management and improve the understanding of local hydrogeological dynamics. The APLIS approach integrates several physiographic and lithological parameters derived from GIS-based spatial analysis. Digital Elevation Models (DEMs), geological and pedological maps, and land cover datasets were used to compute the five main factors influencing infiltration and recharge. Each factor was assigned a weight based on established literature and regional calibration, and combined using the APLIS empirical equation to obtain a continuous map of recharge percentages across the study area. The results highlight a clear spatial differentiation of recharge potential across the Province of Lecco. High recharge values (>50%) were primarily observed in the central area of the Province, where permeable lithologies (mainly limestones and dolomites), and high precipitation rates promote infiltration. Conversely, low recharge values (<20%) were identified in the southern plain, dominated by low-permeability deposits and anthropogenic land uses that reduce infiltration capacity. Intermediate recharge values (20–50%) characterize transition areas with mixed lithologies and moderate slopes. These findings provide valuable insights into the hydrogeological functioning of the area and contribute to a better understanding of the spatial variability of groundwater recharge under different geological and morphological conditions. The resulting recharge map can serve as a useful tool for local water authorities and decision-makers to guide groundwater protection, land-use planning, and climate adaptation strategies. Furthermore, the application of the APLIS method at a provincial scale demonstrates its effectiveness as a cost-efficient and flexible approach for preliminary recharge assessment in data-scarce regions. Future developments will focus on integrating the APLIS derived recharge estimates with hydrological features (spring discharge, total volume) to improve the accuracy and reliability of recharge quantification and on the impact that climate change will have on the recharge of groundwater recharge. Overall, this study underlines the importance of spatially distributed recharge assessment for sustainable groundwater management and provides a methodological framework applicable to other regions with similar hydrogeological settings.

Stochastic simulations for mapping groundwater contamination risk

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Abstract. The protection of groundwater resources in inhabited, industrialized areas characterized by the presence of important transport infrastructures is of critical importance, especially in valley floor regions where aquifers are exploited for drinking water purposes. Infiltration of pollutants resulting from anthropogenic processes represents the main threat to resource quality. Using the case study of the Val Lapisina (TV) unconfined aquifer, numerical simulations of flow and advective transport with a stochastic approach were used to integrate the traditional pollution risk assessment with a probabilistic factor for the propagation of contaminants over time. This methodology allowed to produce four contamination risk maps for the aquifer, assessed at 5, 10, 20, and 50 years from the moment a hypothetical contaminant reaches the saturated zone, providing a more dynamic and effective decision-making tool for resource management.

Initially, the pollution risk (R) was assessed according to an established methodology that considers three factors (Civita & Sappa, 2005): the Territorial Hazard (Ht), calculated using the Hazard Index (IP) of the Centers/Sources of Hazard (CDP/FDP), mapped in a GIS environment from available data; the Intrinsic Vulnerability (VuSAR), determined by applying the parametric SINTACS R5 method (Civita & De Maio, 2000); and the Value of the Subject at Risk (VaSAR). This first assessment resulted in a map of the study area classified into four different risk classes.

The second phase introduced the Probabilistic Contaminant Propagation Factor (Pcp(t)), which represents the innovative contribution. A stochastic approach was adopted to manage the uncertainty inherent in the estimation of hydrogeological parameters. Advective transport simulations were implemented using MODFLOW-2005 and MODPATH codes via the GMS 10.5 interface. The Latin Hypercube method combined with a normal probability distribution was used to maximize the representativeness of possible parameters, yielding a set of 237 solutions considered equiprobable. The locations of the CDP/FDP were used to associate advective transport particles. For each stochastic solution, the particle migration paths were calculated for time intervals of 5, 10, 20 and 50 years. Through GIS analysis, the probability that each cell would be reached by potential contamination was determined, which corresponds to the factor Pcp(t).

Finally, the initial risk values (R) were reclassified as probabilistic values and multiplied by the propagation factor, obtaining the final contamination risk value ($R_c = Pcp(t) \times R$). This produced four risk maps at 5, 10, 20 and 50 years, with a final classification into ten risk classes. These results, which include a conservative assumption (absence of attenuation), provide an easy-to-interpret decision-making tool, useful for land-use planning and the dynamic safeguarding of the water resource in the event of contamination.

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Coupled hydrogeochemical-isotopic approach for characterizing groundwater of Somma-Vesuvius volcanic aquifer, Italy

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Abstract. Groundwater monitoring in active volcanic areas is an important tool to management and protection of groundwater resources and improve the understanding of hydrothermal systems and forecasting of volcanic dynamics.

In this study, the hydrochemical and isotopic composition of groundwater in the Somma-Vesuvius volcanic aquifer system (southern Italy) was investigated by coupling historical hydrogeological, hydrochemical, and isotopic data available in the literature (1978-2010) and new field data collected between 2021 and 2025 from 83 wells and thermal-mineral springs. The dataset allowed the identification of main hydrogeological processes governing the hydrochemical and isotopic composition of volcanic groundwater and interactions with of deep magmatic and hydrothermal fluids.

The Somma basin is characterized by a prevalent Ca-Mg-HCO₃ water type, whereas the Vesuvius basin is mainly marked by Na-HCO₃ water type in southern and northwestern sectors. In the eastern sector of Somma basin, sulfate-chloride-alkaline waters with high temperatures (up to 24 °C) and abundant dissolved gases has been detected for the first time, near Apennines fault systems.

The average groundwater temperature is equal to 15.9 °C for the Somma basin, and 18.2 °C in the Vesuvius basin, with peaks up to 24.7 °C in wells located near to structural lineaments. The average electrical conductivity values are equal to 2,045 and 3,250 μS/cm for the Somma and Vesuvius aquifer, respectively, with maximum values up to 16,930 μS/cm measured in the southern Vesuvian sector.

These hydrochemical anomalies highlight the mixing between volcanic groundwater, mineralized and CO₂-rich fluids rising along faults of the deep carbonate substrate belonging to the Lattari Mountains and Monti di Sarno, as well as possible and localized seawater intrusion near the coast.

Long-term monitoring suggests relatively stable mean values of temperature and EC, although localized increases were observed in 2022. Chloride and bicarbonate concentrations confirm interactions with deep magmatic fluids, reaching up to 2078 mg/L and 4227 mg/L, respectively, in the southern sector of Vesuvius basin. Fluoride concentrations range from 4 to 5.2 mg/L, with picks up to 12.4 mg/L in wells aligned with major faults. Dissolved CO₂ shows average values between 5 and 13 mmol/L, with picks of 65.6 mmol/L in the southern sector of Vesuvius basin. Nitrate concentrations are higher in the Somma basin (median 69 mg/L) than in the Vesuvius basin (median 52 mg/L), mainly due to anthropogenic inputs from agriculture and urban areas, with an increasing trend over the last decades. Also, isotopic analyses of δ¹⁸O, δD and δ¹³C suggest a mixing process between shallow groundwater circulating in volcanic aquifer and deeper hydrothermal fluids rising from the carbonate basement. The presence of noble gases (He, Ar) and N₂ further supports this mixing model. The results provide new insights into the hydrogeochemical and isotopic evolution of the Somma-Vesuvius volcanic aquifer, highlighting the role of structural lineaments in controlling fluid ascent. The continuous hydrogeological monitoring network represents a valuable tool for integrating the existing volcanic, seismic, and hydrogeological surveillance systems of this highly hazardous volcanic area.

Comparison of the application of the hybrid and EPM approaches in mining environment.

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Abstract. To date, there is no standardized approach to numerical groundwater flow modelling in the mining environment. Generally, three approaches are used: i) the equivalent porous media (EPM), which considers the rock mass and its discontinuities as a continuum; ii) the discrete fracture network (DFN), where the hydraulic characteristics are related to natural and/or anthropic discontinuities of the rock mass; iii) the hybrid, a combination of the two approaches. To identify the pro and cons of these different approaches, a selected mine located in the Metalliferous Hills (Colline Metallifere; GR), in the Tuscany Region, Italy, is used as a case study. The mine is part of a complex of five, joined by a level at -200 m asl, that was active for pyrite extraction until 1981, and was selected among others as case study because data covering a time span of almost 100 years, from around 1920 to 2024, are available. Currently, the mine is simulated with two three-dimensional transient state numerical models, developed with FEFLOW 10 following the hybrid and EPM approaches. Both numerical models simulate the three managed flooding events that occurred in the period 1997-2014, during which groundwater levels in the mine rose from -200 m asl to the current -95 m asl, by decreasing the pumping rates of the well systems active 24/7. In the hybrid approach simulation, the rock mass and its minor discontinuities are represented as EPM, while all the 1-D anthropic discontinuities (mining infrastructures like tunnels, shafts, and wells) and all the 2-D natural discontinuities (major faults) are represented as discrete features. At this stage of the research project, the main goal is to evaluate which model is better at simulating the hydrogeological conditions observed during managed flooding events. The selected model will be used as a reference to perform predictive simulations that will reproduce the planned shutdown of the pumping well systems, which will bring groundwater levels in the mine from the current -95 m asl to 70 m asl, where a drainage tunnel is located. In the next stage of the research project, these two approaches will also be compared with the numerical model performed following the DFN approach.

Earthquake-related hydrogeological changes in carbonate aquifers: insights from transient groundwater flow modelling

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Abstract. Earthquakes produce co-seismic static and dynamic strain within the Earth's crust. In the uppermost ~2 km, seismic deformation induces perturbations in hydrogeological systems by modifying the hydro-mechanical properties of aquifers and, consequently, groundwater flow dynamics. These perturbations commonly manifest as variations in spring discharge, river stage, and groundwater levels, as well as changes in hydrochemical and isotopic signatures. Such responses may be short-lived or persist for months to years. The most pronounced hydrogeological variations have been documented worldwide, especially following large-magnitude earthquakes associated with co-seismic surface faulting.

In this work, we present a conceptual and numerical modelling approach to semi-quantitatively assess spring discharge and groundwater level variations in carbonate aquifer systems induced by strong earthquakes. The methodology is tested on the 30 October 2016 Mw 6.5 Norcia earthquake, which profoundly altered the hydrodynamic equilibrium of the Sibillini Mts carbonate hydrostructure and triggered strong anomalies in spring regimes. Transient groundwater flow hindcasting simulations were carried out to evaluate the critical role of seismogenic faults in controlling subsurface hydrodynamics. The modelling results support our conceptual hypotheses, demonstrating that seismogenic faults exert a first-order control on groundwater storage and flow dynamics prior to co-seismic rupture.

Analysis of open-loop and closed-loop low-enthalpy geothermal potential in a representative alluvial aquifer of the Campanian Plain (southern Italy)

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Abstract. Low-enthalpy geothermal energy is a renewable and sustainable form of energy that employs heat exchange from shallow depths, primarily using groundwater. This resource is highly beneficial, with excellent reliability, stable operation conditions, and an environmental footprint much lower than conventional fossil fuels. The use of ground source heat pumps for thermal transfer allows significant energy savings for the climatization of buildings (heating and cooling). The studies addressed to low-enthalpy geothermal energy have as objective to achieve Goal 7 ("Affordable and Clean Energy") and Goal 11 ("Sustainable Cities and Communities") of the UN 2030 Agenda. Therefore, a widespread application of low-enthalpy geothermal energy can be considered an effective tool for mitigating the impact on the climate change.

In such a scientific framework, this research is carried out in the Campania region (southern Italy), where the growth of this important resource of energy is still underdeveloped. The study is aimed at the assessment of low-enthalpy geothermal potential of the pyroclastic-alluvial aquifer of Phlegraean Fields and Campanian Plain. These aquifers provide an ideal case study for three reasons: (i) the shallow depth of the water table, which favours the construction of wells for accessing groundwater; (ii) the high degree of urbanization of the area, namely the potentially high demand for energy saving for heating and cooling; (iii) a spatial variability of the groundwater temperatures (ranging from approximately 16°C to over 80°C) that is controlled by the caldera structure of the Phlegraean Fields and represents a natural gradient for investigating the geothermal potential.

This study analysed the low-enthalpy geothermal potential related to two principal methods of exploitation: open-loop systems (GWHP), which use groundwater directly, and closed-loop systems (GCHP), which use vertical ground heat exchangers. Using the Banks' approach (2012), the open-loop geothermal potential was assessed based on the aquifer's sustainable yield, groundwater temperature, and the seasonal thermal difference with ambient air, with two distinct seasonal scenarios being implemented. For the closed-loop potential, the analytical G.POT. model (Casasso and Sethi, 2015) was applied. This method employs subsurface thermal properties such as thermal conductivity, diffusivity, and undisturbed temperature and borehole geometry.

The results show a general relevant low-enthalpy geothermal potential. Depending on local hydrogeological features, the most profitable zones are in the Phlegraean Fields and the southwestern area, with a high low-enthalpy geothermal potential for open and closed loop systems which can be suitable for sustaining large industrial plants. Instead, the central and northern parts of the study area are characterized by moderate low-enthalpy geothermal potential, but appropriate for medium-scale commercial and residential buildings.

These findings demonstrate that exploiting this resource could significantly reduce fossil fuel consumption and lead to a transition toward a low-carbon economy in alluvial aquifers of the Campania region where hydrogeological conditions are generally very favourable to the exploitation of low-enthalpy geothermal energy.

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Geothermal co-production of critical raw materials: a data-driven screening from global patterns to European basins

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Abstract. Meeting the rising demand for critical raw materials (CRMs) requires extraction routes that align with the principles of the energy transition. Geothermal systems offer a unique dual opportunity: renewable heat and power generation combined with mineral-rich brines that could enable co-production.

This study presents an evidence-based screening approach that integrates plant infrastructure, fluid characteristics, and mineralization context to identify promising sites and near-term pilot opportunities. A GIS workflow was developed by combining the JRC Geothermal Power Plant inventory (including location and turbine technology) with geochemical data from REFLECT (temperature, TDS, pH, and major ions). Entity resolution was achieved through name matching and a nearest-neighbor join. As a contextual layer, occurrence points from the EGDI CRM database were spatially linked to the nearest features and used solely as indicators of proximity to hard-rock mineralization (and potential scaling risk), not as evidence of dissolved species.

Global geothermal capacity remains unevenly distributed, with North America and Europe accounting for most of the installed base, while other regions contribute smaller shares. The global turbine fleet is dominated by ORC/binary units, alongside substantial flash systems and a smaller proportion of dry-steam plants. Since turbine configuration governs phase partitioning and the temperature/availability of residual brines, this technological mix defines the practical envelope for mineral co-production.

Applying this workflow to the Upper Rhine Graben (URG, France–Germany) yielded approximately 50 linked records that combined attributes from JRC, REFLECT, and EGDI. Most plants are binary/ORC systems, yet their fluids show moderate to high temperatures and saline Na–Cl compositions consistent with published Li-bearing signatures. This combination is technically compatible with modern direct lithium extraction (DLE) and ion-exchange systems. Collectively, the URG stands out as a strong near-term European testbed for lithium-focused co-production.

Focusing on Italy, the JRC dataset confirms Tuscany (Larderello–Travale/Radicondoli and Monte Amiata) as the country's geothermal core, dominated by dry-steam plants with smaller contributions from single-flash and ORC units (mainly at Amiata). In the current dataset, REFLECT provides no site-level Italian records; thus, the assessment is infrastructure-led, with EGDI CRM data used solely as a mineralization context. Given the plant configurations and likely brine availability, Monte Amiata emerges as the most promising candidate for REFLECT-compatible sampling, whereas dry-steam districts are better suited for silica management and potential valorisation.

Next steps include targeted REFLECT-style sampling (to close Italian data gaps), 2D/3D geological modelling and transport simulations of lithium dynamics, and pilot-scale reporting with closed mass/energy balances and transparent LCA/LCC to evaluate project bankability.

The TREASURE Project: Monitoring the Euganean Geothermal Fields (EuGFs) for a Sustainable Use of Geothermal Resources

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Abstract. The Euganean Geothermal System (EuGS), located in the Veneto Region (northeastern Italy), represents one of the most significant low-enthalpy geothermal systems in Italy. It is characterized by a water-dominated geothermal resource, with temperatures reaching up to 87 °C. The geothermal system is controlled by a complex structural framework associated with the Schio–Vicenza Fault System and a regional relay ramp, which enhance deep fluid circulation and facilitate the ascent of thermal waters. These waters are hosted in a deeply fractured carbonate reservoir overlain by 100–200 m of Quaternary alluvial deposits.

Since the early 20th century, the thermal resource has been intensively exploited for both recreational and therapeutic purposes. This long-term overexploitation led to the progressive drying of most of the natural springs and a marked decline in potentiometric levels across the Euganean Geothermal Fields (EuGFs). To preserve the resource, a monitoring network was established in the 1970s, enabling the continuous observation of potentiometric fluctuations. Historical data revealed a strong dependency of the potentiometric levels on the tourism seasonality. The lowest values recorded in spring and autumn usually match the water extraction peaks, whereas higher levels have been observed during winter and summer, when pumping activities decreased. These instruments, during the closure for the COVID-19 pandemic recorded a sharp and rapid recovery of the potentiometric levels. This event provided evidence that groundwater pressures in the EuGFs are almost entirely controlled by anthropogenic extraction, confirming the system's high responsiveness to changes in exploitation rates.

In 2025, within the framework of the TRASURE Project (funded by the Veneto Region), a new monitoring network was implemented to restore continuous observation of the geothermal system. The current network consists of 14 monitoring stations installed in inactive wells across the geothermal area, recording hourly measurements of groundwater levels and temperature. Unlike the previous monitoring system, the new temperature sensors are positioned hundreds of meters deep, where measurements are expected to be more representative of the reservoir temperature.

This contribution presents the first results obtained from the newly established monitoring network, and preliminary analyses highlight a marked spatial variability in the hydraulic response across the Euganean Geothermal Fields (EuGFs). These data represent a fundamental step toward a better understanding of the current state of the resource, improving its sustainable management, and supporting the development of predictive models for geothermal system behavior under different exploitation scenarios.

Borehole heat exchanger spacing design optimization for ground source heat pump system energy performance enhancement

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Abstract. The exploitation of shallow geothermal energy for building air-climatization has significantly increased in recent years, driven by the global decarbonization process and continuous technological advancements. However, Ground Source Heat Pump (GSHP) systems must be carefully designed to prevent efficiency losses. The thermal perturbation (both in extent and shape) generated by vertical Borehole Heat Exchangers (BHEs) is strongly influenced by the hydrogeological conditions of the surrounding subsurface. In the literature, no specific guidelines exist for determining the optimal lateral spacing between BHEs in a borefield, and in practical applications, arbitrary values are often adopted.

This study proposes a method to define the optimal spacing between vertical BHEs with the aim to minimize the energy inefficiency caused by overlapping thermal plumes. The analysis was performed through numerical simulations using MODFLOW-USG, a numerical code for coupled flow and heat transport, implementing BHEs with Connected Linear Network (CLN) package validated by (Antelmi et al., 2021). Lithologies with different thermal conductivity and hydraulic conductivity values were implemented into the model to simulate a wide range of groundwater flow velocities (between 0 and 0,86 m/d). Assuming a heating operation of the GSHP system, a fixed inlet fluid temperature of 1°C in the U-shaped pipe and an undisturbed aquifer temperature of 14.5°C were set. The outputs of the simulations allowed to evaluate the spatial extent of thermal perturbations around BHEs for two borehole depths and three operating timeframes. Single-BHE simulations were first performed to assess undisturbed thermal behavior. Results showed that high groundwater flow (0,86 m/d) enhances heat exchange by up to 150% compared to zero flow conditions. Moreover, while the shape of the thermal plume varies with groundwater velocity (from radial-shape to elongated shape according to the direction of groundwater flow), it remains vertically uniform along the BHE length.

Subsequent multi-BHE simulations (from 3 to 5) investigated the influence of borehole proximity, modeling BHEs arranged linearly and perpendicular to the flow direction, with spacing ranging from a minimum of 1 to a maximum of 8 meters. For instance, in a configuration with three BHEs spaced 2 meters apart and groundwater velocity equal to 0,043 m/d, the total exchanged energy decreased by 11.4% due to thermal interference. By defining an acceptable energy loss threshold of 2%, optimal spacing values were identified for each operational condition. Assuming highest Darcy flow velocities, no significant interference was detected even at a 1-meter spacing, whereas for zero flow conditions, a spacing of up to 7 meters is recommended, along with a balanced thermal load between the summer and winter operating periods to avoid thermal drifts. Finally, the optimal BHE spacings were synthesized into an abacus as a function of the system's operating duration and the hydrogeological context. This tool provides practical support for designers and researchers in selecting appropriate spacing between BHEs in linear borefield, reducing thermal interference and enhancing GSHP performance.

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The Critical Influence of the underground on shallow geothermal system design

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Abstract. Shallow geothermal energy offers a low-carbon solution for heating and cooling buildings, supporting the energy transition. However, designing and optimizing geothermal exchange systems requires a comprehensive, interdisciplinary approach that accounts for building energy demands alongside complex subsurface characteristics, including hydrogeology, geochemistry, thermophysical properties, and both regulatory and environmental constraints.

A pilot study was conducted in the alluvial plain of the Po River (northern Italy) to characterize the shallow subsurface for geothermal applications. Sedimentological and grain-size analyses through continuous core drilling reconstructed local sedimentary sequences and identified aquifer systems, providing a geological framework for understanding groundwater flow and thermal transport. Hydrogeological investigations, including pumping tests and hydrodynamic monitoring, informed a conceptual model of subsurface flow dynamics, hydraulic connectivity, and interactions with natural thermal gradients, crucial for sustainable geothermal use.

Hydrochemical and isotopic analyses of groundwater ($\delta^{18}\text{O}$, $\delta^2\text{H}$, $^{87}\text{Sr}/^{86}\text{Sr}$) revealed recharge processes, water–rock interactions, and mixing between different water sources, offering insights into aquifer behavior under varying hydrological conditions. Thermo-physical properties were assessed, and thermal response tests were conducted using Distributed Fibre-Optic Temperature Sensing (DTS) and laboratory measurements, providing essential data for the design and sizing of geothermal heat exchangers.

The integrated analysis enabled a robust characterization of the subsurface and informed the selection of a sustainable low-enthalpy geothermal system. Predictive numerical models calibrated with these data simulate thermal responses under operational loads, supporting system optimization and risk mitigation. This study highlights the value of a multidisciplinary approach to achieve efficient, environmentally compatible integration of shallow geothermal energy in the built environment.

TEMATICHE DI GEOLOGIA APPLICATA E CARATTERIZZAZIONE DI GEOMATERIALI

Preferential Flow Dynamics in Calcarenite: Experimental and Numerical Investigation of Capillary–Gravity Transition During Infiltration

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Abstract. Understanding preferential flow dynamics during infiltration in geological porous media is an important challenge in engineering geology.

Infiltration mechanisms play a central role in controlling contaminant transport within the vadose zone, Infiltration dynamics govern contaminant transport in the vadose zone, regulate the balance between runoff and infiltration, and critically affect slope stability.

In this context, some soft and porous rocks are characterised by a dual-porosity system, where the coexistence of macro- and microporosity gives rise to a rather complex flow behaviour. In particular, preferential pathways for rapid, gravity-driven flow tend to develop through the macropore network, whereas capillary forces acting within the micropores govern water retention and slower drainage.

On this basis, the research investigates the transition from capillarity-driven flow within the micropores to gravity-dominated preferential transport.

The analysis is performed on calcarenite materials, namely medium-grained grainstones of the Calcarenite di Gravina Formation (Lower Pleistocene), quarried from the “Tufarelle” site (Canosa di Puglia, Southern Italy).

The pore network was characterised through an integrated approach combining Mercury Intrusion Porosimetry (MIP) and Image Analysis (IA), allowing a representative reconstruction of the bimodal pore-size distribution.

Building on previous single-ring infiltration tests performed under falling head conditions, both at the bench scale and in situ, the experimental setup was revised to better reproduce realistic boundary conditions. In the present study, a series of laboratory investigations was carried out on cylindrical calcarenite samples which were subjected to water input delivered through a sprinkler system simulating low-intensity rainfall, thus promoting a more distributed and gradual infiltration process. Particular attention is paid to the role of initial water content and rainfall intensity, considering conditions ranging from dry to wet states and analysing their influence on the resulting drainage hydrograph.

The experimental results are used to validate a numerical model capable of reproducing the observed drainage response while accounting for both capillary and gravity-driven mechanisms. The model is based on the pore bundle conceptualization and on the advection–diffusion form of Richards’ equation. A comparison with classical unimodal approaches, such as the Brooks and Corey model, highlights their limitations in representing the hydraulic behavior of calcarenites and their bimodal pore structure.

The findings indicate that the flow dynamics observed can be effectively replicated by the suggested non-parametric model, which provides a clear representation of the progressive transition from capillary-controlled conditions to preferential flow.

Therefore, these results highlight the necessity of explicitly incorporating pore-scale heterogeneity into the analysis of infiltration processes within calcarenite media.

Photomonitoring per il rilevamento di fenomeni di instabilità in strutture storiche: metodologia e applicazioni

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Abstract. Il rilevamento tempestivo di deformazioni e dissesti strutturali in edifici storici rappresenta una sfida critica per la conservazione del patrimonio monumentale, particolarmente in contesti urbani soggetti a pericolosità geologica. Il presente contributo illustra una metodologia di photomonitoring sviluppata per il monitoraggio sistematico di fenomeni di instabilità strutturale, validata attraverso implementazioni pluriennali su strutture murarie storiche.

La metodologia si basa su tecniche avanzate di elaborazione digitale delle immagini per il rilevamento e la quantificazione di variazioni temporali indicative di processi di instabilità in atto. Il confronto multi-temporale mediante algoritmi di Structural Similarity Index (SSIM) consente l'identificazione automatica e la quantificazione di fenomeni quali propagazione di lesioni, apertura di fessure, dislocamento di elementi murari e distacco di materiali, con sensibilità millimetrica. Gli sviluppi metodologici includono la calibrazione adattativa dei parametri per garantire l'affidabilità del rilevamento in diverse condizioni ambientali e l'implementazione di protocolli sistematici per la coerenza geometrica delle acquisizioni.

L'applicazione è stata condotta su strutture monumentali in due siti italiani UNESCO, utilizzando diverse piattaforme di acquisizione, da dispositivi consumer a sistemi di sorveglianza permanenti. I dataset pluriennali hanno consentito di documentare quantitativamente l'evoluzione temporale dei quadri fessurativi e dei fenomeni di degrado strutturale. La tecnica ha dimostrato particolare efficacia nell'identificazione precoce di cinematismi di danno e nell'evidenziazione di porzioni strutturali caratterizzate da evoluzione accelerata, consentendo la correlazione tra manifestazioni superficiali del degrado e fenomeni geotecnici sottostanti.

I risultati documentano la capacità del photomonitoring di fornire informazioni distribuite sull'intera superficie delle strutture, colmando il gap tra misure puntuali tradizionali (inclinometri, estensimetri, monitoraggio topografico) e la necessità di caratterizzare l'evoluzione spaziale dei fenomeni. La metodologia genera dati quantitativi oggettivi sull'evoluzione dei quadri fessurativi, essenziali per l'interpretazione dei meccanismi di instabilità e per la valutazione dell'efficacia di eventuali interventi di stabilizzazione.

La scalabilità dell'approccio risponde alle esigenze del monitoraggio a lungo termine di strutture storiche in aree soggette a pericolosità geologica, dalla documentazione ad alta risoluzione di elementi critici a rilievi periodici su estesi complessi monumentali. L'accessibilità della tecnica, basata su tecnologia ottica ed elaborazione computazionale, consente implementazioni sostenibili anche per patrimoni diffusi. La generazione di archivi digitali permanenti abilita analisi retrospettive fondamentali per la comprensione dell'evoluzione dei fenomeni di instabilità e per la calibrazione di modelli di comportamento strutturale.

Automatic 3D Image-Based Reconstruction for Tunnel Inspection and Monitoring

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Abstract. Underground transport infrastructure interacts closely with the surrounding geological environment, and its performance and durability are highly influenced by ground conditions and natural processes. In countries like Italy, characterized by complex orography, active geological processes, and a dense tunnel network, the assessment of ground-structure interaction and the condition of ageing tunnels is essential to ensure safety and long-term serviceability. In this context, modern monitoring and digital inspection tools play an important role in supporting predictive maintenance strategies and data-driven asset management. This work presents an automated methodology for the three-dimensional (3D) reconstruction of tunnel surfaces using high-resolution images acquired by a mobile mapping system. The method was specifically developed to process images captured by line cameras along the tunnel lining, overcoming the limitations of traditional photogrammetric approaches. The tool assigns spatial coordinates to each image pixel, enabling the generation of a textured 3D model that accurately represents the geometry and visible condition of the tunnel surface.

A key aspect of the proposed approach lies in the parametrization of the tunnel cross-section geometry. The tunnel profile is modelled through an ellipse-fitting procedure that retraces the actual shape within a local reference system. This allows precise alignment of the image data with the 3D coordinate framework. Additionally, a sensor position optimization algorithm was implemented to refine the spatial configuration of the camera within the tunnel cross-section. This optimization minimizes projection errors and ensures consistent geometric accuracy throughout the reconstructed surface. The combination of these geometric refinements with automated image processing enables the creation of a high-resolution, metrically accurate 3D model of the tunnel lining. The resulting reconstruction allows direct visual and quantitative assessment of surface conditions, including the detection and measurement of cracks, spalling, or other defects at a millimetric scale. The method has been applied to real tunnel datasets, providing comprehensive and detailed representations that can significantly enhance the understanding of structural conditions and their relation to the surrounding geological context.

The obtained 3D dataset offers strong potential for integration within digital platforms for infrastructure management and visualization. To enhance the interpretation and accessibility of the reconstructed models, an interactive 3D open-source visualization environment by web-based platforms for rendering and managing large-scale point cloud datasets can be used. The reconstructed model can be employed as “digital twin” of the infrastructure, i.e., point clouds can be combined with geotechnical monitoring data and with geomorphological information or, moreover, they can be analysed with artificial intelligence algorithms for automated defect recognition. This integration facilitates cross-comparison between different data sources, supports temporal analyses, and contributes to informed decision-making for maintenance planning.

Aperture, roughness and infilling characteristics of rock joints investigated through 3D X-ray Computed Tomography and Deep Learning techniques

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Abstract. This contribution presents an integrated workflow for the automatic detection, segmentation, and quantitative characterization of rock discontinuities from X-ray computed tomography data, combining advanced image processing, deep learning, and multi-method validation. The proposed approach was applied to calcareous samples Umbria–Marche succession (Northern Apennines, Italy), characterized by fractures with variable aperture, infilling, and mineralogy.

A convolutional neural network (U-Net architecture), trained on a curated multi-material fracture dataset, was employed to segment complex and low-contrast fracture networks with sub-millimetric precision. The segmentation results were further processed through convolution-based filtering and Matlab-based 2D and 3D image analysis algorithms to compute fracture aperture, infilling thickness, and Joint Roughness Coefficient (JRC). These parameters were extracted across multiple subvolumes (top, center, bottom) to capture spatial variability within the samples.

To address major sources of uncertainty—such as limited X-ray computed tomography spatial resolution, contrast variability, and reconstruction artifacts—the workflow integrates multi-angle scanning, intensity normalization, and Gaussian/median filtering. The segmented outputs were converted into high-resolution 3D point clouds, enabling the direct computation of roughness and aperture metrics. Validation was performed against independent measurements from high-resolution digital microscopy, Barton comb profilometry, and manual caliper data, confirming the robustness and accuracy of the method.

Additionally, complementary analyses (X-ray diffractometry, Energy Dispersive Spectroscopy, and optical petrography) were carried out to characterize fracture infillings and assess grey-level contrasts between matrix and discontinuity. The results demonstrate that the deep learning-based X-ray computed tomography workflow provides a non-destructive, scalable, and objective solution for the comprehensive quantification of fracture geometry and surface properties in heterogeneous geological materials, enhancing the reliability of discontinuity analysis at both meso- and microscale.

On the identification of runoff generation thresholds

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Abstract. Understanding the thresholds for surface runoff generation is a complex task with practical implications for predicting floods, flash floods, and soil erosion. Many factors interact in the runoff process, making it difficult to study through modeling due to the lack of information, especially in mountainous and hilly areas. At the plot or very small catchment scale, efforts have been made to understand runoff behavior, aiming to identify specific hydrometeorological factors that control runoff generation caused by rainfall events. At the event scale, several authors highlighted a correlation between the Antecedent Soil moisture Index (ASI) combined with rainfall depth (P) and surface runoff (R), proposing a threshold behavior for runoff generation (e.g., the hockey stick shape). Some questions remain open regarding this empirical method:

- Is the definition of the runoff generation threshold scale-dependent?
- What are the main important controlling factors?
- How do runoff thresholds vary with meteo-climate conditions?

To answer the above questions, a procedure is developed to analyse the runoff behaviours at different scales, considering different meteo-climate, lithology, and land cover conditions. Moving from the plot scale to the basin scale, several issues need to be addressed first, including the proper definition of events, the quantification of runoff, and the collection of soil moisture data that are not typically measured in most catchments worldwide. The present work aims to develop a procedure for identifying runoff threshold behaviour and apply it to various European catchments equipped with reliable stream and pluviometers gauges. Using digital filters capable of separating baseflow from the time series of discharge data, and thanks to satellite reanalysis products, such as SMAP L4 (NASA global, 9-km, 3-hourly estimates of surface and root zone soil moisture), the ASI+P values have been related to each runoff event, allowing for the identification of the runoff generation thresholds. The proposed approach can be used for flood early warning and to enhance hydrological and erosion modelling, contributing to a better understanding of catchment-scale hydrological processes and their sensitivity to the meteo-climate, land cover, and lithological settings.

Fault detection in a highly urbanized area through sensitivity-based optimization of ERT measurements

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Abstract. The accurate identification and mapping of geological structures is essential for assessing seismic hazard. In this context, the main objective of this work is to determine, as precisely as possible, the location of the Sassuolo fault within a highly anthropized area, where geomorphological evidence of tectonic activity is poorly preserved.

The Sassuolo fault is a segment of the Pede-Apennine Thrust Front (PTF), an out-of-sequence thrust system of the Apennine mountain front, active since the Pleistocene. The PTF has clear geomorphological evidence corresponding to the hilly margin of the chain. This evidence is masked by fluvial erosion and deposition at the outlet of the major river valleys.

Fault mapping is pursued through the integration of stratigraphic and geophysical investigations, carefully planned after an extensive collection of existing subsurface data. The highly urbanized setting and the scarcity of direct geological evidence make indirect geophysical methods crucial for detecting and characterizing the fault zone.

To this end, Electrical Resistivity Tomography (ERT) is employed as the principal geophysical technique. ERT is a well-established method for subsurface characterization, relying on multi-electrode systems capable of acquiring large datasets through automated measurements. The investigation depth and spatial resolution are mainly controlled by the quadrupole geometry and the signal-to-noise ratio, both of which can be adjusted to enhance sensitivity toward specific subsurface targets. By integrating measurements from multiple quadrupoles, the accuracy and resolution of resistivity images can be significantly improved, providing a more detailed visualization of underground structures.

In this study, an innovative approach based on sensitivity analysis and Green's function formulations is developed to identify optimal electrode configurations. This method allows for a significant reduction in the number of field acquisitions by selecting only the most informative measurement configurations, rather than testing all possible ones. Consequently, it reduces survey duration and data processing time while maintaining, or even improving, image quality and interpretability. The sensitivity-based optimization framework enhances the overall efficiency of ERT surveys, providing an effective balance between resolution, depth of investigation, and operational constraints.

The results demonstrate that this approach significantly improves the capability of ERT to detect and delineate structural discontinuities, such as the Sassuolo flexure fault. The outcomes highlight the potential of combining geological interpretation with advanced geoelectrical modeling to achieve accurate and efficient imaging of complex subsurface structures, particularly in urbanized and data-limited environments.

Lithology-informed Machine Learning for large-scale spatial prediction of subsurface geotechnical properties

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Abstract. Modeling spatial variability in subsurface geotechnical properties remains a major challenge. This comes from limited direct testing data and the natural heterogeneity in geological media. This task is critical in urban environments, where designing and building underground structures relies on reliable geological and geotechnical models. In this context, Artificial Intelligence (AI) can support modeling geological media through its ability to capture complex, nonlinear relationships among diverse data sources.

This study presents a methodology for geotechnical modeling that integrates sparse quantitative data from in-situ tests (e.g., NSPT, CPT) with denser qualitative information from borehole logs (e.g., litho-textural descriptions) and its application in the Milan metropolitan area. An ensemble of supervised machine learning and neural network regression models was built to predict the spatial distribution of geotechnical parameters. The regression framework incorporates spatial coordinates (x , y , z), and auxiliary features derived from borehole descriptions (i.e., predicted abundance of gravel, sand, and fine materials), and hydrogeological conditions (i.e., piezometric level). The models were implemented and trained in MATLAB®, achieving a best validation RMSE of 14.8 over a target range of 0-100 NSPT values.

Comparison with a conventional 3D kriging approach demonstrates that the AI-based models provide a more accurate representation of both vertical and lateral heterogeneities, owing to the incorporation of lithological information. Overall, this work highlights the effectiveness of lithologically enriched spatial regression for geotechnical modeling in an urban setting. AI allows turning existing large-scale qualitative datasets, such as public borehole logs, into valuable resources for quantitative geotechnical characterization.

Morphological and morphometric analyses of watersheds for the evaluation of the river quality index

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Abstract. A watershed represents a fundamental morphological and hydrological unit within which meteoric waters are collected, concentrated, and drained into surface watercourses. The structure of a river basin, along with the morphological quality of its watercourses, is strongly influenced by slope morphology, the hierarchy of the drainage network, and topographic relief, as well as by anthropogenic and temporal factors. Therefore, the geomorphological study of a river basin is a fundamental procedure for understanding how these processes have shaped the territory.

This study is based on a combined approach that integrates both morphological and morphometric analysis of a river basin in eastern Sicily (Italy) with the assessment of the quality of its watercourses.

Field surveys included the observation of landscape forms and the estimation of key geomorphological parameters of the basin, supported by the interpretation of aerial imagery acquired via drone.

Morphometric analysis, carried out using QGIS software, allowed for the calculation of a series of key quantitative parameters on a high-resolution Digital Elevation Model (DEM). Thematic maps that graphically represent the morphological and morphometric parameters of the basin were drawn to facilitate spatial and structural interpretation of the surveyed features.

These analyses laid the foundations for assessing the quality of the watercourses through a parametric procedure, which was carried out in the frame of an agreement between University of Catania and the regional Sicilian Autorità di Bacino. This procedure is based on the calculation of specific natural, human-made and temporal parameters, such as the presence of vegetation, structures crossing and running along the river, and the comparison with previous maps. The combination of these parameters yields the river Morphological Quality Index (IQM), which quantifies the degree of anthropogenic alteration of the watercourse relative to its natural morphology.

The results achieved confirm a strong interaction between fluvial dynamics and morphological quality parameters, demonstrating how a watershed with specific characteristics can influence the outcomes of individual indicators related to functionality, artificiality, and temporal variation in the quality of surface water bodies.

This integrated approach has proven to be particularly effective not only for advancing scientific knowledge of the territory, but also for possible future practical applications such as hydrogeological risk assessment, identification of potentially unstable areas, sustainable water resource management, and the planning of protection and mitigation measures.