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BOOK OF ABSTRACTS

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THEMATIC SESSION 1

ADVANCING COASTAL DYNAMICS: MULTIDISCIPLINARY APPROACHES TO RELATIVE SEA-LEVEL CHANGE AND TECTONIC UPLIFT

Chairpersons

Ciro Cerrone, Giuseppe Corrado, Nelly Valkanou, Efthimios Karymbalis

Sea-level fluctuations along the southern Brazilian Atlantic coast during the Late Quaternary

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The present work is part of the WARMCOAST Project, which is funded by the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovative Program (Grant Agreement No. 802414).
This study presents the findings from the field campaign conducted along Brazil's southern coast in October 2023. A classical geological and geomorphological approach was carried out along the western Atlantic coast of Brazil, from Rio Grande do Sul to São Paulo and field data on geological sea-level proxies (i.e., fossil intertidal or foreshore deposits) were gathered. The fieldwork aimed to collect samples for Optically Stimulated Luminescence (OSL) dating, along with granulometric and micropaleontological analyses. The samples were collected from shallow-water marine sand outcrops located a few meters above sea level. The elevation of the measured proxies was referenced using the local geoid model (MAPGEO2015) via a GNSS RTK station, with an elevation error margin of just a few centimetres. The analysed sample presents an unimodal distribution, varying mostly between 180 µm and 200 µm.
The collected data provide a more comprehensive understanding of regional sea-level changes, contributing to the broader goal of reconstructing past climate and environmental conditions, as well as improving predictions for future coastal dynamics under climate change scenarios.

KEYWORDS: last Interglacial, southern Brazil, coastal geomorphology, sea-level changes, Optically Stimulated Luminescence dating

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The million-year-old coral reef sequence in southern Cuba: a reference for sea-level reconstructions

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Fossil coral reefs, known as coral reef terraces, are key geological features in the interpretation and quantification of relative sea-level changes. An exceptional sequence of coral reef terraces flanks the southern coast of Cuba (Cape Maisí). However, uncertainties remain regarding the age of the oldest coral reefs (1 to 4 million years old) and the long-term tectonic uplift rates affecting the area. In this study, we combine high-precision field surveys and satellite imagery with a stratigraphic forward model (DionisosFlow®) to elucidate the spatial variability of the long-lasting sequence at Cape Maisí. As well as refining the age of the sequence and the tectonic uplift rates affecting it, we are explaining the genesis of coral reefs over several million years, with a particular focus on the last four glacial cycles (i.e., the last ~430 ka). The formation of such a geological feature is the result of close interactions between sea-level variations, tectonic uplift, hydrodynamics and ecology. The fossil coral reefs at Cape Maisí could therefore serve as valuable records in the future to reconstruct past sea-level fluctuations.

KEYWORDS: coastal geomorphology, sea level, fossil coral reef, stratigraphic forward modelling, tectonic uplift

Quaternary evolution of the main Tyrrhenian coastal plains of central and southern Italy: interaction between climate and tectonics

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The influence of tectonic deformations on the evolution of coastal areas along the Mediterranean coasts is now well-known and studied. The current configuration of coastal plains results from the interaction between long-term tectonic movements and changes in sea level during the Quaternary period. During the last glacial and interglacial cycle, the overall variation in sea level in the Mediterranean exceeded 130 m, considering that during MIS 5. 5 the sea level was about 6-8 m above the current level, reaching -120 m below the current level during the last glacial maximum (MIS 2). The main goal of this work is to acquire new elements useful for a better definition of the morphotectonic events and sedimentary and climatic processes that have influenced the evolution of the main Tyrrhenian coastal plains of central and southern Italy, especially starting from the Upper Pleistocene, through a multidisciplinary approach. To achieve this objective, a large amount of data relating to geomorphological and stratigraphic surveys of Quaternary deposits was collected. Structural analyses to constrain the chronology of brittle deformation were also carried out. The stratigraphic data mainly comes from the many subsurface data (cores and seismic sections), fundamental for creating the geological sections and UBSU-based maps. They were constructed by integrating the data available in the literature with newly acquired data, homogenizing the state of knowledge to conduct a comparative analysis of the evolution between the different plains. To achieve this objective, the architecture of the sedimentary bodies for each plain was defined (or redefined) and the different depositional environments were identified. Thanks to all these data it was possible to outline the entire geomorphological and sedimentary compared evolution of the plains here studied starting from the MIS 5.5 interglacial period.

KEYWORDS: Tyrrhenian coastal plains of central-southern Italy, Late Quaternary, relative sea-level changes

The influence of tectonic and climatic oscillation on the evolution of Fondi alluvial-coastal plain (Italy) since Late Pleistocene: new constraints from core analysis and surface investigations

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Understanding coastal evolution over geological timescales is essential for evaluating natural dynamics and assessing future vulnerabilities. The present study focuses on the Fondi alluvial-coastal plain, a low-lying area located along the Tyrrhenian flank of the Southern Apennines in Italy. The plain experienced tectonic-induced subsidence at least up to the Late Pleistocene, balanced by sedimentary inputs from the carbonate ridges bounding the plain. This geomorphological setting renders the area an ideal open-air laboratory for investigating the interplay between glacio-eustatic sea-level fluctuations, sedimentary inputs, and tectonics.

New borehole and surface investigations have been acquired as part of the PRIN 2022 GAIA project and analysed by high-resolution stratigraphic, sedimentological, and palaeoecological approaches. These datasets have been combined with reinterpreted data from previous studies carried out in the Fondi area.

A comprehensive geochronological framework was established using radiocarbon (^{14}C) dating, optically stimulated luminescence (OSL) dating, and amino acid racemization (AAR) dating on ostracods, thereby providing robust chronological constraints on the morphostratigraphic evolution of the plain and relative sea-level (RSL) changes.

Late Pleistocene marine infralittoral sands and lagoonal sediments gradually passing into beach ridge-dune deposits have been identified. The new AAR dating of ostracods from upper shoreface deposits indicates an age of approximately 115.2 ± 22.1 ka at ~−21 m Mean Sea Level (MSL) near the base of the SF2 core, providing the first chronological constraint for this interval.

Furthermore, previous AAR dating of *Glycimeris* shells from lagoonal deposits yields a MIS 5.5 age for sedimentary units found at ~−6 m MSL. These values are misaligned to the ~7–8 m MSL recorded in nearby tectonically stable areas, suggesting tectonic subsidence.

During the Holocene, chronological constraints reveal an initial rapid rise of RSL from approximately −19 m MSL to −5 m MSL between 9 and 7 ka BP. New radiocarbon data from semi-enclosed lagoon environments in the SF2 core indicate that RSL ranged between approximately −5.6 ± 0.8 m MSL at 7.13 ± 1.16 ka BP and −2.8 ± 0.8 m MSL at 3.84 ± 0.12 ka BP.

These results suggest a deceleration of the rates to near present-day levels by the mid-Holocene, indicating a period of relative coastal stability and coastal progradation between 7 and 4 ka BP.

This finding is corroborated by Roman coastal structures distributed from Fondi to Formia municipality, which consistently record a RSL position of approximately −0.55 ± 0.29 m MSL during the 1st century CE. A comparison of these observations with regional glacial isostatic adjustment (GIA) models confirms a tectonically stable environment with subsidence rates of -0.017 ± 0.23 mm/y over the past 2.0 ka.

Our multidisciplinary approach provides robust constraints on the morphostratigraphic evolution and relative sea-level changes of the Fondi Plain. The interaction between glacio-eustatic fluctuations, sediment supply, and local tectonic subsidence demonstrates the long-term vulnerability of the Fondi Plain to future sea-level rise and extreme

events. These insights offer therefore a high-resolution framework for coastal risk assessments and sustainable management strategies.

KEYWORDS: Late Quaternary, relative sea level, absolute dating, core stratigraphy, coastal evolution

Inundation scenarios along the northern coast of Amvrakikos Gulf (Western Greece) due to sea-level rise induced by climate change

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The latest climate change predictions indicate that sea-level will continue to rise in the coming decades as a direct consequence of global warming. The anticipated future sea-level rise driven by climate change is expected to be seriously threaten low-lying coastal areas worldwide, resulting in morphological changes, frequent and severe coastal flooding, and shoreline erosion. These processes will have significant socio-economic impacts, leading to the loss of coastal settlements, exploitable land, and natural ecosystems. The main objective of this study is to identify potential future inundation zones along the northern coastline of the Amvrakikos Gulf—a deltaic complex formed by the Arachthos, Louros, and Vouvos rivers in Western Greece—due to both long-term and short-term sea-level rise induced by climate change. For this study, a detailed 2 m resolution Digital Elevation Model (DEM) was used, along with local long-term sea-level projections and the contribution of storm surges by the years 2050 and 2100. Additionally, subsidence rates due to the compaction of deltaic sediments were taken into account. To assess the area's vulnerability to sea-level rise, the extent of each land use/land cover type, the Natura 2000 Network protected area, the total length of the road network, and the settlements located within the inundation zones under each climate change scenario were estimated. The analysis revealed that under the optimistic SSP1-1.9 scenario of the Intergovernmental Panel on Climate Change (IPCC), areas of 33.5 km^2 and 61.6 km^2 could potentially be inundated by 2050 and 2100, respectively. Under the pessimistic SSP5-8.5 scenario, the corresponding inundation zone areas increase to 35.2 km^2 and 76.5 km^2. Considering the additional effects of storm surges, these areas expand significantly - by approximately 80%. Five settlements with a total population of 1,163, and 23 businesses are expected to face considerable challenges in the near future due to sea-level rise. Additionally, a significant portion of the Natura 2000 protected area, consisting primarily of ecologically valuable wetlands, is projected to be inundated. Under the SSP1-1.9 scenario, the affected Natura 2000 area is estimated to range from 30.8 km^2 by 2050 to 42.5 km^2 by 2100, while under the SSP5-8.5 scenario, it is expected to increase from 32.4 km^2 by 2050 to 52.2 km^2 by 2100.

KEYWORDS: sea-level rise, coastal inundation, river delta, Amvrakikos Gulf

A 5,500-year sedimentary record investigating coastal evolution, past tsunamis and extreme wave events in the Messenian Gulf (Southern Peloponnese, Greece)

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The Messenian Gulf, situated along the Hellenic Trench in southern Greece, is highly vulnerable to extreme wave events, including tsunamis and severe storms. Historical records indicate that the southern coasts of Peloponnese have experienced destructive tsunamis for over 2.000 years and these coasts are also vulnerable to extreme wave height events from the eastern Mediterranean, posing a major threat to the shoreline environment and human activities concentrated along the coasts. However, the coastal area near Kalamata city remains underexplored. This study applies to a multi-proxy approach - encompassing field surveys, sediment statistical analyses, and numerical dating - performed on exploratory drillings (up to 4 meters deep)- to investigate Holocene extreme wave events deposits. We present the preliminary results two drill cores, and the grain size results from over 250 samples using a laser diffraction spectrometry analyzer (Laser Mastersizer 3000 Malvern) and employing the marine sediment pretreatment protocol 'PT4SD' to ensure high-quality outcomes. The grain size statistics of sediment samples from one of the cores, including mean, mode, sorting, skewness, and other relevant measures, were calculated using moment and Folk and Ward graphical methods with the assistance of GRADISTAT. Principal Component Analysis (PCA) and Factor Analysis (FA) were also applied to investigate the relationships among discrete samples characterized by multiple variables. Based on our preliminary findings, we have identified a minimum of eight stratigraphic imprints in the cores, from the coastal areas near Kalamata city, that are likely associated with extreme wave events. According to the ages, that have been estimated so far, it seems that the events happened in the last 5.500 years or so.

KEYWORDS: extreme wave events, palaeotsunamis, grain size analyses, Messenian Gulf, Greece

Detecting fault-controlled subsurface structures in coastal environments: a case study from Marinello

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Spits are unique natural environments whose evolution is linked to the adjacent coast and near shore morphology, sediment supply, coastal dynamics and sea-level change. Over the past century, Global Mean Sea Level (GMSL) has risen by 10 to 20 centimetres and many coastal spits represent the first sentinel against coastal submersion (Randazzo et al. 2015).
This study investigates the geomorphological and tectonic evolution of the Marinello-Tindari spit, a gravel-sandy barrier located in the Gulf of Patti along the Tyrrhenian coast of Sicily (Italy), an area where the rapid sedimentary dynamics is due to the combined effects of both Climate Change/human pressure (Crisà et al. 2015) and an active tectonic trend (Catalano et al., 1997). This research integrates electrical resistivity tomography (ERT) surveys and geological analysis to explore tectonic influences on landscape evolution (Lamansson, 1998). It focuses on detecting subsurface structures, stratigraphic interfaces, and tectonic features shaping sedimentary architecture and geomorphology.

Figure 1 - Schematic representation of the geophysical transects performed

Six offshore and three onshore ERT profiles were acquired, reaching depths of up to 40 meters below the sea floor. The surveys used a Wenner-Alpha configuration and advanced inversion techniques (Loke et al., 1996a, 1996b) with RES2DINV software for detailed resistivity mapping. In the algorithm used, the depth to the deepest layer in the model is set to be about the same as the largest depth of investigation of the data points, and the number of model cells does not exceed the number of data points. The thickness of each deeper layer is increased to reflect the decreasing resolution of the resistivity method with increasing depth. This produces a model where the thickness of the layers increases with depth, and with thicker cells at the sides and in the deeper layers (Corrao et al., 2021).
Bathymetric corrections and georeferencing were integrated to improve result accuracy. Onshore profiles revealed a disarticulated substrate with lateral resistivity variations, suggesting subvertical, high-angle faults influencing sediment deposition.

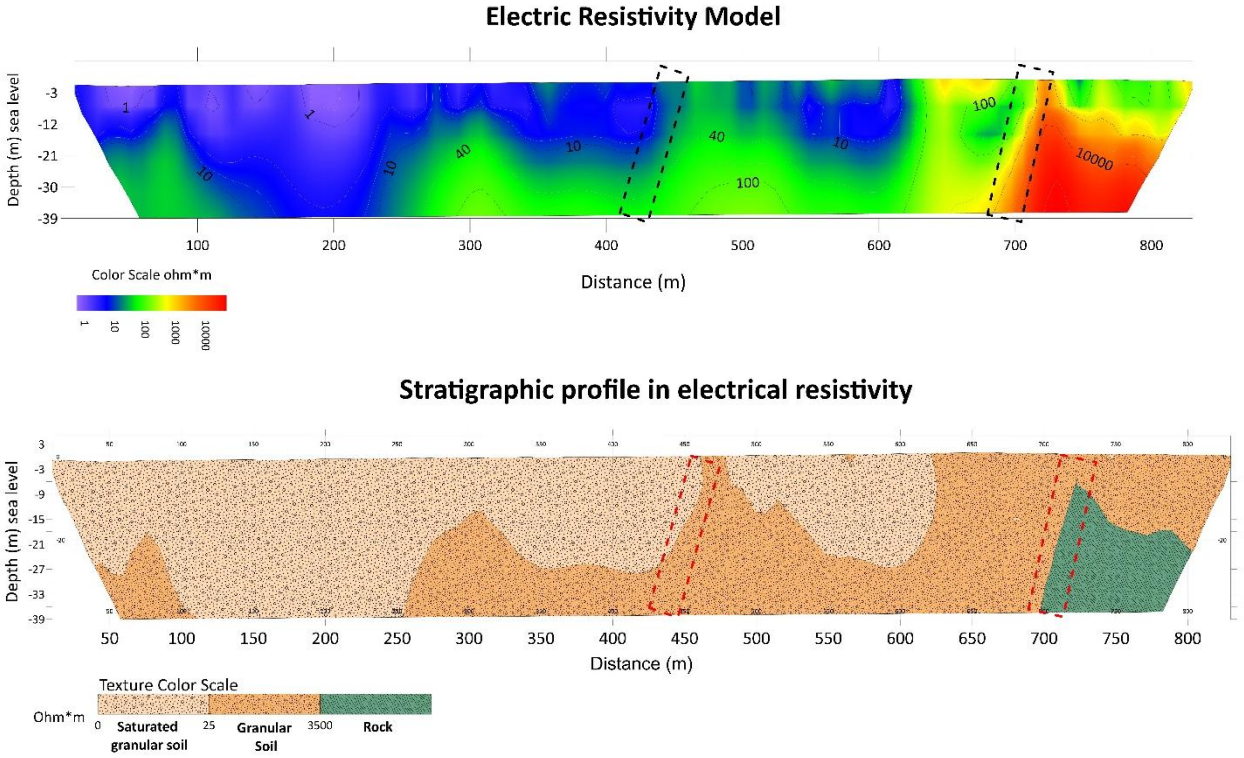
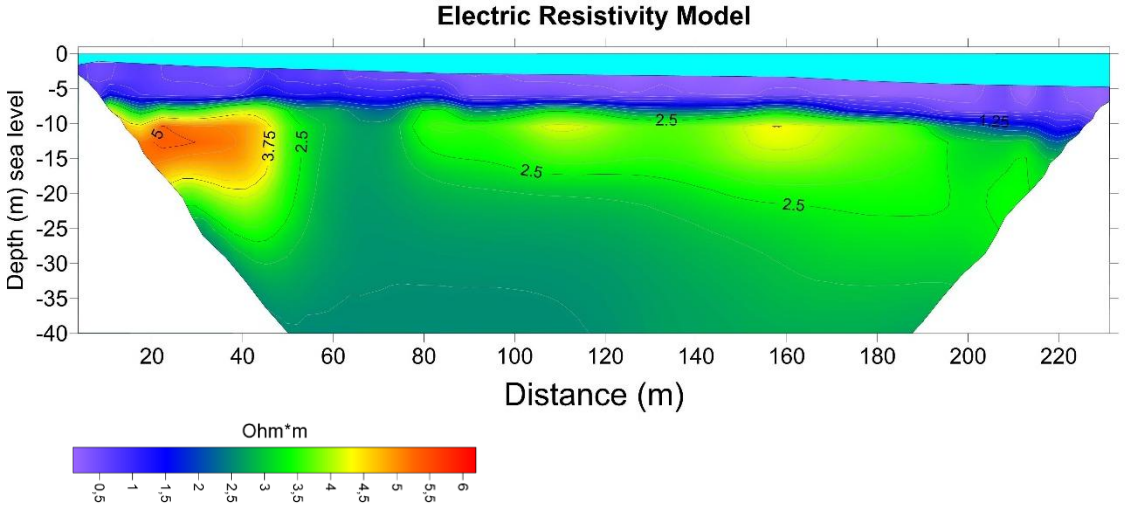


Figure 2 - Electrostratigraphic model with lithological interpretation

Off-shore profiles exhibited lower resistivity values, consistent with water-saturated sediments, and revealed localized high-resistivity zones (>3.5 Ohm*m). These anomalies were interpreted as lithoid blocks potentially linked to tectonic collapses or fault-induced fragmentation.



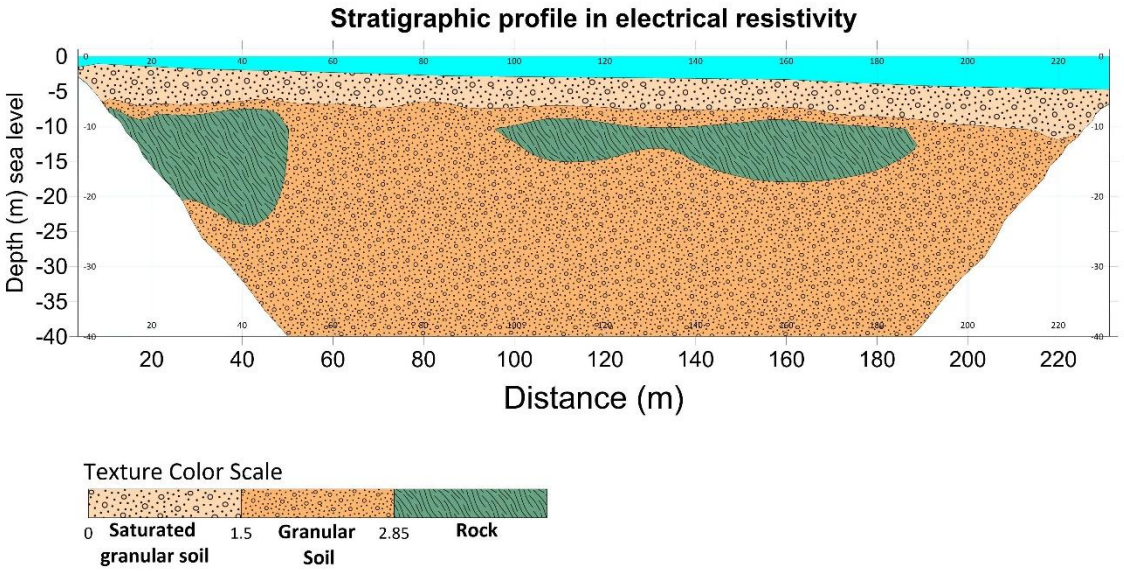


Figure 3 - Electroresistive model of the most representative section

Integrating geophysical and geological data reveals the dynamic interaction between active tectonics and sedimentary processes. The study area, within the Sicilian segment of the Apennine-Maghrebian orogen, has undergone significant crustal deformation and uplift due to African-Eurasian plate convergence.

The results suggest that fault systems have played a key role in controlling both the stratigraphic architecture and the spatial distribution of sedimentary deposits, contributing to the morphological evolution of the Marinello spit. The observed displacements of the metamorphic substrate, combined with evidence of fault-induced collapses, underscore the importance of tectonic activity in shaping the coastal landscape.

This study contributes to the field of tectonic geomorphology by showcasing electrical resistivity tomography's effectiveness in detecting active faults, stratigraphic discontinuities, and subsurface heterogeneities. It highlights tectonic influences on coastal sedimentary systems and underscores the value of interdisciplinary approaches. The proposed framework aids future research on tectonic impacts, informing coastal hazard assessment and sustainable management.

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KEYWORDS: coastal geomorphology, sea level rise, electrical resistivity tomography, active faulting

Integrated geomorphological map of terrestrial and submarine landforms of the Gulf of Corinth and surrounding region (Greece)

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This study presents a geomorphological map of the Gulf of Corinth and its surrounding region, in central Greece, encompassing both terrestrial and submarine landforms at a 1:150,000 scale. The research aimed to explore the relationship and continuity of emerged and submerged geological and geomorphological features including the land-sea interface. The Gulf of Corinth, a WNW-ESE elongated and asymmetric half-graben, is characterized by an uplifting southern flank and a downward flexed northern one. Renowned as the most dynamic neotectonic area in the eastern Mediterranean, the Gulf is characterized by N-S crustal extension and normal faulting. A multi-disciplinary approach, combining field surveys, a 25-m DEM, and advanced GIS techniques was employed to delineate landforms across the area. The terrestrial portion of the study area exhibits evidence of tectonic uplift in its southern segment, featuring uplifted marine terraces, perched Gilbert-type delta deposits, uplifted tidal notches and reversed drainage features. In contrast, the northern terrestrial zone showcases a distinctive morphology including submerged tidal notches, indicative of a recent coseismic subsidence, karst landforms, drowned valleys and extensive landslides. Both the southern and northern coastlines are marked by active alluvial fans in correspondence of the major rivers flowing into the Gulf. Edges of structural scarps and crests are prominent along both margins, further reflecting the tectonic imprint of the region. As for the submerged part, the central basin of the Gulf lies at depths of 800-900 m, featuring a flat and ellipsoidal shape. The northern margin descends gently to a depth of 400 m, characterized by numerous landslide scarps and deposits, and a few single channel canyon valleys, before transitioning to a steeper zone extending up to 800 m. Conversely, the southern margin exhibits steep slopes (30-40%) incised by numerous gullies, single channel canyons and valleys, cyclic steps and submerged fans. Both terrestrial and submarine features reflect the active tectonic and Quaternary deformation of the region. The geomorphological map produced within this study provides a holistic perspective on the complex geomorphology of the Gulf of Corinth, by bridging the gap between terrestrial and marine geology.

KEYWORDS: emerged and submerged landforms, integrated geomorphological map, tectonic activity, Gulf of Corinth, Greece

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The uplifted marine terraces of the Laconic Peninsula (Greece): insights into the tectonics of the Hellenic Subduction Zone

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Coastal regions above subduction zones are crucial for understanding tectonic processes due to their preserved geomorphic markers, such as marine terraces. This study investigates uplifted marine terraces along the western and eastern coasts of the Laconic Peninsula, SE Peloponnese, Greece, using GIS-based digital elevation model (DEM) analysis, AI, and field surveys. Marine terraces, which record past sea levels and tectonic movements, provide insights into crustal deformation, uplift rates, and coastal evolution.

The study area lies within an active tectonic setting near the Hellenic Subduction Zone, where the African plate subducts beneath the Eurasian plate at a rate of ~36 mm/yr. The Laconic Peninsula consists of two main tectonic units: the Phyllites-Quartzites Unit and the non-metamorphic Tripolis Unit, overlain by Quaternary marine deposits. The presence of uplifted marine terraces, reaching up to ~460 m above sea level, highlights the significant influence of regional tectonics.

Using high-resolution DEM data (5 m cell size), geological maps, and Red Relief Image Map (RRIM) techniques, marine terrace surfaces and inner edges were identified and mapped. Field validation was conducted using differential GPS (DGPS) to refine terrace elevations and spatial distribution. Three study sectors were examined: (A) Kokinia–Cape Xilis, (B) Plytra–Cape Koulenti, and (C) Paralia Kastraki–Kato Kastania.

Results indicate up to eight orders of uplifted marine terraces in all three sectors, ranging from 5 to 460 m asl elevation. Differences in terrace preservation and elevation suggest variable uplift rates influenced by local faulting, particularly the Molai normal fault, which separates sectors A and B. The highest terraces in sector A likely reflect greater footwall uplift, whereas sector B, on the hanging wall, exhibits lower elevations and more fragmented terraces. Sector C lower terraces and better lateral preservation suggest reduced tectonic activity compared to sectors A and B.

Comparisons with previous studies suggest that the T1 terrace in sector B corresponds to Marine Isotope Stage (MIS) 5a (~80 ka) with an estimated uplift rate of 0.36 ± 0.11 mm/yr over 215 ± 5.5 ka. However, differential uplift rates necessitate further absolute dating to refine correlations between sectors. The presence of multiple marine terrace levels suggests episodic uplift driven by local faulting and broader regional tectonic processes associated with the Hellenic Subduction Zone.

This study confirms the importance of marine terrace analysis in reconstructing long-term coastal tectonics. The findings contribute to a better understanding of the tectonic evolution of the Laconic Peninsula, emphasizing the role of fault-controlled differential uplift.

The proposed methodology provides a robust framework for the paleo-landscape and sea-level reconstruction at a regional scale since Late Pleistocene through a comprehensive analysis of terrace distribution by integrating new technology, GIS, and AI analyses.

KEYWORDS: marine terraces, GIS, tectonic uplift, Hellenic Subduction Zone, Laconic Peninsula, Greece

Active deformation and faulting on Kythera Island: insights into offshore subduction zone dynamics

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Offshore islands provide valuable insights into deformation rates, their controlling mechanisms, and the dynamics of the upper crust in offshore subduction zones, where direct observations are otherwise challenging. In this study, active deformation and faulting are investigated over glacial-cycle time scales on Kythera Island, located in the southwestern Hellenic subduction zone between Crete and the Peloponnesus. Kythera Island preserves an exceptional sequence of more than twelve marine terraces, reflecting its active uplift. These terraces are offset by multiple active faults, oriented NNW-SSE and NNE-SSW. High-resolution topography and morphometric analysis are employed to map the marine terraces and estimate the heave and throw rates of the island's primary faults. The marine terrace sequence is classified into two groups: higher marine terraces (260–480 m a.s.l.) with composite rasa surfaces and lower terraces (20–220 m a.s.l.) displaying staircase morphologies. The analysis focuses on two major faults, which exhibit both right- and left-lateral as well as dip-slip displacements, disrupting terrace risers and treads. The activity of these faults is linked to intermediate-depth, high-magnitude earthquakes, such as the Mw 6.6 and 6.7 events that struck Kythera in 1903 and 2006, respectively. Further research will involve dating marine terrace surfaces and conducting structural analysis to correlate the terraces with Marine Isotope Stages and refine estimates of heave and throw rates. This study underscores the importance of island-based observations in quantifying deformation rates in offshore subduction zones.

KEYWORDS: crustal dynamics, fault kinematics, relative sea-level change, TerraceM, Greece

The impact of sediment erodibility on levee breaches

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Distributary channels play a crucial role in the distribution of sediments in deltas. These channels are confined by natural levees—elevated ridges of sediment that accumulate along channel banks and slope toward the delta plain. However, levees are dynamic structures that can breach, creating new flow and sediment pathways. While levee breaches can pose hazards, such as rapid topographic changes and flooding, their mechanisms are typically analyzed through two key factors: channel aggradation relative to levee thickness (superelevation) and levee slope relative to channel slope (gradient advantage). These indicators are primarily linked to hydrodynamic conditions and accommodation space, but the role of sediment properties, particularly sediment erodibility, in levee breaching remains poorly understood. This study evaluates the impact of superelevation, gradient advantage, and sediment erodibility on levee breaching and recovery using the model Delft3D. Since sediment erodibility is influenced by compaction, we conducted modeling scenarios in which variable compaction rates (from 0 to 5 mm year^{-1}), while all other parameters remained static. To determine the primary control on levee breaches, we analyzed which indicators exhibited a clear trend with simulated levee breaching. Our results indicate that superelevation and gradient advantage align with field estimates but show no discernible trend across different compaction scenarios during both pre- and post-breach periods. In contrast, sediment erodibility demonstrates a positive correlation with compaction rates. As sediments compact locally, it reduces the elevation of the levee making it more prone to breach at that location. Yet the local compaction increases the critical bed shear stress for erosion of the muddy levee sediments at that location significantly reducing the erodibility of the levee sediments during a breach. High compaction rates therefore reduce the effectiveness of levee breaches. This finding highlights the critical influence of sediment erodibility on breach dynamics and underscores the need for further investigation with larger datasets.

KEYWORDS: levee breaches, superelevation, gradient advantage, sediment erodibility, compaction, modelled deltas, Delft3D

Mapping uplifted marine terraces along the Southeastern Coast of Messiniakos Gulf, Peloponnese

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Coastal regions above subduction zones offer important insight into active tectonic processes, particularly when geomorphic markers enable the quantification of crustal deformation. The eastern coast of the Messiniakos Gulf, located in the forearc of the Hellenic Subduction Zone, presents a valuable setting for studying long-term tectonic movements. This region experiences rapid crustal deformation due to the ongoing subduction of the African plate beneath the Eurasian plate, with deformation rates reaching ~36–40 mm/yr. A combination of Geographic Information Systems (GIS), Digital Elevation Model (DEM) analysis, and field surveys was employed to map and analyze uplifted marine terraces along the western coast of the Tenaro Peninsula. Thirteen distinct marine terraces were identified, with inner edge elevations ranging from 3–6±2 m for the lowest terraces to 397–464±2 m for the highest. The lower terraces exhibit well-defined abrasion platforms, whereas the higher terraces display greater width and continuity. Fluvial incision and tectonic activity have disrupted the lateral extent of these terraces. The observed uplift is attributed to the proximity of the Hellenic Subduction Zone and the activity of a major offshore normal fault, striking NNW-SSE and dipping westward. Terrace elevations decrease southward, and the absence of terraces in the southernmost part of the peninsula suggests localized subsidence. Submerged archaeological sites near Kyparissos provide additional evidence of ongoing vertical crustal movements. The results highlight the influence by both subduction-related tectonics and fault activity. Further dating of marine terraces is necessary to establish correlations with Marine Isotope Stages and refine estimates of long-term uplift rates during the Quaternary.

KEYWORDS: palaeoshoreline indicators, subduction zone, relative sea-level change, Quaternary uplift, Greece

THEMATIC SESSION 2

ADVANCING THEORY AND MODELLING OF RIVER SYSTEMS

(organized by the IAG WG Advancing theory and modelling of river systems)

Chairpersons:

He-Quing Huang, Paul Carling, Ian Rutherfurd, Gabriela Toroimac

Riverine forest dynamics through the lens of remote sensing

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Riverine forests are essential components of floodplain landscapes, which are crucial for maintaining biodiversity, stabilizing channel banks, and preserving aquatic ecosystem integrity. In this study, we aim to evaluate the application of different remote sensing data by focusing on the spatial dynamics of riparian vegetation. Multi-spectral satellite images, high-resolution aerial images, and LiDAR point cloud data have been used to assess vegetation cover structure, vegetation indices, and time-series changes in vegetation dynamics. Satellite images, which are freely accessible and commonly used by researchers, have great potential for monitoring and analysing large-scale environmental changes with high spatial and temporal resolution. High-resolution aerial images complement satellite data by providing finer detail and greater precision, particularly for localized studies. These images are instrumental in identifying small-scale features such as submerged vegetation, species composition, and vegetation patterns. LiDAR point cloud data, however, offer a unique and detailed source for capturing the three-dimensional structure of riverine forests. Unlike traditional imaging techniques, LiDAR provides precise measurements of canopy height, vegetation density, and the vertical stratification of the forest. Furthermore, combining these remote sensing datasets allows for a more comprehensive analysis of riparian ecosystems, enabling a better understanding of the spatial distribution and structural complexities of vegetation. Such a framework could be applied to various environmental research studies by adapting different methods to extract detailed information for specific purposes.
This work was supported by the Slovak Research and Development Agency under Contract No. APVV-23-0265 and grant VEGA 2/0016/24.

KEYWORDS: riverine forest, remote sensing, satellite data, aerial images, LiDAR, vegetation dynamics

Morphological quality index in Sicily: application to the San Bartolomeo basin (North-western Sicily)

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To estimate the ecological status of the Surface Water Bodies (SWB) the IDRAIM multiparametric approach has been applied in Sicily, which adopts the general communitarian framework established in the WFD (Water Framework Directive). IDRAIM (stream hydromorphological evaluation, analysis and monitoring system) is in general based on the expert-based assignment of each reach in which a SWB is split to one of the classes of a set of indicators, expressing the Geomorphological Functionality, Artificiality and Channel Changes status.
In this study, a focus is given to the sensitivity analysis of the Indices so to recognize the main causes of current and potentially future quality status.
The San Bartolomeo River Basin stretches in the northwestern part of Sicily, with an area of about 420 km^2. The geological framework is primarily given by the outcropping of Meso-Cenozoic carbonate successions, clay-marly sequences and clastic deposits. In the coastal areas, these geological successions are covered by Quaternary detritical-organogenic deposits. The climate regime of the basin can be classified as temperate-Mediterranean, characterized by a rainy period (October–April) and a dry period with minimal precipitation (June–August), during which the highest temperatures are also recorded.
Five Surface Water Bodies (SWBs) within the San Bartolomeo drainage network were selected for assessment using the IDRAIM methodology: the Sirignano, Freddo1, Freddo2, Caldo, and Bartolomeo streams. The Morphological Quality Index (MQI) values for these five fluvial segments are as follows: 0.73, 0.79 and 0.77 (good quality) for Sirignano, Freddo1, Caldo and Bartolomeo streams, 0.69 (moderate quality) for Freddo2 stream. The quality status of these streams is primarily influenced by the F1, F2, F11, F13, A1, A2, and A5 indicators.
To evaluate the potential effects of variations in the assignment classes of each indicator, the analysis of the reaches was divided into two groups based on their confinement type: the first group consists of confined reaches (a total of five), while the second group includes semi- and unconfined reaches (a total of thirty-three). By iteratively modifying the assignment class for each factor, new MQI values were obtained for each reach. A total of 192 modifications were applied to a set of 21 indicators (48 classes) for the confined reaches, and 2,343 modifications were applied to a set of 25 indicators (59 classes) for the semi- and unconfined reaches. The results showed effects on MQI values of individual reaches of up to 80% (42% on average) for two of the five confined reaches analysed and up to 70% (52% on average) for twelve of the thirty three semi- and unconfined reaches analysed. The confined reaches shifted from an excellent to a good quality status, while the semi- and unconfined reaches transitioned from good to sufficient quality.
The sensitivity analysis is a mandatory procedure when adopting expert based multiparameter ranked approaches as it open a view on the real reliability of the quality estimation. At the same time, it furnishes useful indications regarding the more sensitive reaches and more influent factor changes which is an important tool to support management decision.

KEYWORDS: Morphological Quality Index, IDRAIM, sensitivity analysis, San Bartolomeo River, Sicily

Application of hydrodynamic modeling and geostatistical analyses for assessing spatial variability and sedimentation conditions of suspended solids in dam reservoirs

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Changes in flow velocity within dam reservoirs are shaped not only by inflow discharge but also by reservoir bathymetry and the water level regime at the dam. Accurate representation of the spatially complex variability of flows within a reservoir is made possible through the use of hydrodynamic models. These models also serve as an effective tool for predicting and analyzing changes in the functioning of dam reservoir ecosystems in the era of climate change and water scarcity threats.

A two-dimensional depth-averaged Adaptive Hydrodynamics (AdH) model was applied to visualize the hydrodynamics of the Włocławek Reservoir. The simulation, conducted for eight different hydrological conditions, allowed for the calibration of model parameters. Model predictions regarding the depth-averaged planar water velocity field were compared with real measurement data. For each of the eight-calibration series, inflow values were tested by increasing and decreasing them by 5% relative to their initial values. The correction that yielded the best fit ranged from -5% to +40%, with an average value of +11.9%. This suggests that the discharge values obtained from the rating curve are, on average, about 10% lower than the real ones.

To describe the transport and sedimentation conditions of suspended mineral particles in the reservoir, hydrodynamic modeling was integrated with geostatistical analysis methods. Stochastic particle tracking (Particle Tracking Model, PTM) was applied using a Lagrangian approach, followed by geostatistical analyses to interpret the simulation results. The study results demonstrated that sedimentation of suspended solids is highest in the distal parts of the lacustrine and riverine sections of the reservoir, with an average of 79% of the inflowing suspended solids retained in the reservoir. The key process determining the deposition of suspended solids is the gradual decrease in particle size towards the dam. The model revealed that hydrodynamic conditions allow for the deposition of clay fractions in the upper part of the reservoir, even during flood events, while sand grains can reach the dam even at very low flow rates. Analysis of PTM results and geostatistical modeling enabled the determination of the influence of hydrodynamic conditions on the spatial variability of suspended sediment deposition, both in terms of quantity and grain-size distribution. It was found that the former pre-dam river channel still functions as a transit zone for suspended solids, while finer particles accumulate in slow-flowing zones.

Based on the obtained results, an original indicator, ADDRESS (Accumulation or Discharge of Dam REservoir Suspended Solids), was developed. This indicator allows for a quick assessment of the ability of polymictic reservoirs to either retain or pass through suspended particles of different diameters. Information on whether all or only specific fractions of suspended solids pass through the reservoir and dam is crucial for understanding many natural processes affecting both the reservoir ecosystem and the river ecosystem downstream of the dam.

KEYWORDS: suspended solids, reservoir siltation, hydrodynamic model, geographically weighted regression

Investigation of the spatial and temporal relationship between floodplain levels along the Hungarian and Serbian sections of the Danube

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The main objective of the research is to investigate the past development of the Danube along a 300 km stretch from the Hungarian Danube Plain to the Titel Plateau. Previous research has only touched upon the formation of landforms in this area due to the lack of numerical age data. OSL (Optically Stimulated Luminescence) is one of the most accurate dating techniques for studying fluvial processes. Understanding the river's past dynamics can also aid in evaluating present-day changes and processes. Therefore, we aim to determine the rate of incision during the Late Pleistocene and Holocene.

Even today, landforms associated with former fluvial activity, such as natural levees, point bars, and schutes, can be identified and mapped in the floodplain. During the survey, elevation data from cross-sections and swath profiles were retrieved at regular intervals from DDM to enable the identification of fluvial surfaces at different elevations and to determine their downstream slope.

In all four converging floodplain levels were identified. Based on OSL data, incision along the Danube between Baja and Titel occurred between 18–15 ka and 10–8 ka. The incision rate ranges between 0.2 and 0.5 mm/year, which is an order of magnitude lower than the rate observed since river regulation measures were implemented in the 19th century.

KEYWORDS: floodplain evolution, floodplain levels, incision, OSL dating, Danube

A physical method for distinguishing the factors controlling the formation of different river channel patterns

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The fundamental cause for rivers to develop many types of channel pattern is that rivers are often subject to the complex effects of multiple hydrodynamic, geomorphic and ecological factors. While this knowledge has generally been recognized, there has been lacking a physically based method to distinguish the effects. According to the variational method developed initially by Huang and Nanson (2000) for understanding the self-adjusting mechanism of river channel-forms, it appears physically reasonable to use the dimensionless number H (the ratio of the relative increase of the shear stress of flow on riverbed to the relative increase in the width-depth ratio of the river channel) defined by Huang and Chang (2006) to distinguish the effects of controlling factors on the formations of different river channel pattern. This method includes mainly two aspects: (1) When H = 0.3, hydrodynamics is the main control factor, the energy expenditure of river channel cross-section achieves the smallest, and a straight single-channel pattern is the only option of flow; and (2) When H < 0.3 or H > 0.3, a river takes a channel cross-section of either wide or shallow or narrow to expend surplus energy, and the hydrodynamic factor only plays a partial control role, and complex channel patterns of meandering, braided and anabranching need to develop. Using observations from river systems in Australia and China, detailed evaluations have demonstrated clearly that the H number is a very sensitive parameter that can be used to identify different types of river channel pattern and to distinguish the effects of the main factors on their formation.

KEYWORDS: river channel pattern, H number, shear stress, width/depth ratio, hydrodynamic-geomorphic-ecological factors

Using historical cartography and remote sensing to reconstitute the recent trajectory of the Lower Danube River's islands

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Islands and bars are sensitive landforms of the fluvial hydrosystem. As example, large rivers of Central and Western Europe lost their islands in the recent Anthropocene while high-latitude rivers are creating new ones under permafrost melting. Our study is focused on the Lower Danube River at the border between Romania and Bulgaria and it aims at reconstituting the trajectory of fluvial islands. This approach is mostly a GIS work on various documents over the last 150 years (maps, pilot charts and satellite imagery). Limitations of this approach are due to georeferencing and interpretation of old maps and pilot charts, and the variations of the water level in case of satellite imagery.
Going back to 1856, we found an anabranching fluvial pattern, with a main river channel, slightly more extended alluvial bars and less extended vegetated islands. At the end of the Little Ice Age and in the first part of the 20th century, intense changes probably occurred in the position of islands, but not necessarily in their dimensions and form according to our findings. In the second half of the 20th century ('major anthropic interventions period'), more spectacular were the bank erosion and change of the thalweg position. In the last four decades, the intensity of formation and migration of islands became slow, nowadays islands are relatively stable and only the bars are changeable until being recruited by vegetation. The recent trend of "stability" is probably continuing as the Lower Danube River recorded long periods with low discharges in summer.
The adjustments of the Lower Danube islands are considered to be of low intensity when compared to changes in the upper and middle course of the river where a large part of the islands disappeared. The Lower Danube River is a good example in Europe for the study of anabranching rivers with low energy – generally slow processes that can be reconstituted on multi-decadal or even centennial time scale.

KEYWORDS: fluvial island, fluvial pattern, sediment, vegetation, diachronic analysis

Evaluating discharge dynamics and geomorphic adjustments after river training on the high-energy river system in the Western Carpathians (Slovakia)

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The study focuses on the disturbed section of the braided-wandering Belá River after river training following the flood event with a 5-10-year recurrence interval in 2018. This study intends to identify natural geomorphic recovery phases within the affected river reach referred to the Natura 2000 area. The morphological response of the studied multi-thread river system to river training employs a comprehensive approach that combines remote sensing, field investigation, and advanced GIS capabilities, paired with HEC-RAS hydrological modelling. The river pattern changed significantly three times. First, after the flood event, recognized as a reference state, then after river training in 2018, referred to as degraded condition, and lastly, after several consecutive flood events in 2019 and 2020 with a 2-5-year recurrence interval with turning point effect on channel morphology. Discharge dynamics modelling proved significant changes in depth, but not so crucial in velocity. The mean maximum depth decreased from 2.27 m in 2019 to 1.87 m in 2021, while the velocity declined from 4.56 $m*s^{-1}$ to 4.29 $m*s^{-1}$. However, the observed reductions indicate a decline in channel capacity and hydraulic efficiency, a potential attribute of sediment retention and deposition. In 2019, the brand-new river pattern with vegetation succession and large woody debris distribution was observed after the degraded conditions of the river reach. The lower magnitude of consecutive floods supported the main channel lateral migration connected with channel erosion and the creation of new avulsion channels in 2021. The magnitude of flood events did not increase significantly in the next years. In 2023, we recorded main channel aggradation, increased vegetation patches, and LWD stabilization on the bar area. Under these conditions, the river processes transform from dynamic equilibrium to potential disequilibrium, significantly changing the quality of the natural value of this protected riverine landscape. These findings could provide scientific insight for nature conservation and future river management measures, and address a research gap in understanding the complex processes of natural recovery in braided-wandering river systems.

KEYWORDS: river training, geomorphic recovery, HEC RAS, Belá River

The transformative impact of dams on large river systems – insights from the Vistula, Dnieper, and Danube

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Hydroelectric power plants (HPP) and dams significantly influence river fluvial systems by altering hydrological regimes and disrupting sediment transport. These changes influence erosion and sedimentation, often causing channel deepening and narrowing due to intensified bed erosion. In some cases, lateral erosion leads to channel widening, particularly in resistant sediments. Dams commonly transform snowmelt-fed and multi-channel systems into more linear or sinuous forms by modifying natural flow dynamics.

The study examines changes in the fluvial systems of three major lowland European rivers: the Vistula in Poland, the Dnieper in Ukraine, and the Danube in Slovakia. Specifically, the analysis focuses on river sections downstream of the Włocławek Dam (Vistula), the Kaniv Dam (Dnieper), and the Čunovo-Gabčíkovo (Danube), characterized by multichannel systems.

The research employed a combination of topographic and bathymetric maps, aerial photographs, and satellite imagery to analyse changes in channel morphology. Additionally, geomorphological mapping of floodplains and sedimentological analyses of alluvial deposits were conducted.

The findings reveal significant alterations in channel systems and the relief of river valley bottoms. In the Vistula and Dnieper valleys, changes in channel width and depth were documented, along with the transformation of channel forms into valley bottom features. These results highlight the diverse geomorphological impacts of dams on fluvial systems, providing insights into the complex interplay between hydrological modifications and riverine landscape evolution.

The Vistula River underwent a rapid transformation from a braided to an anastomosing system. Much of the valley floor became part of the floodplain as side channels were abandoned due to concentrated flow in the deepening main channel. After an initial deepening phase, the channel slightly widened as erosion shifted from bottom to lateral, driven by incision into erosion-resistant clay sediments.

In the Dnieper valley, the study identified two distinct phases of riverbed transformation, driven by changes in the flow regime resulting from the operation of HPP. In the initial phase, following the construction of the dam in a hydropeaking regime, significant erosion occurred in the main channel. Decades later, after HPP transitioned to a run-of-river regime, the flow of water in the side channels stabilized, leading to a reduction in water levels and the eventual disappearance of flow in side channels. This resulted in the merging of islands previously separated by them and the formation of extensive interchannel areas. Furthermore, within a 10-kilometer section downstream of the dam, erosion processes intensified, while beyond this distance, sediment accumulation became more pronounced. In the Danube valley, the fluvial system underwent degradation and transitioned into a lacustrine system. It was primarily caused by changes in channel recharge, particularly the reduction or obstruction of water flow in the Danube's side channels.

The variations in the evolution of these fluvial systems can be attributed to differences in the types of HPP development, the operational regimes of the HPP, and the local lithological conditions of the river valley beds. These

factors influence the geomorphological responses of river systems to anthropogenic interventions, highlighting the complex interplay between hydrological modifications and fluvial landscape dynamics.

KEYWORDS: fluvial geomorphology, channel pattern, dam, hydroelectric power plant

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Objective river segmentation based on sinuosity and confinement indices: a multi-scale geomorphological approach with applications to Sicilian Rivers

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European States have transposed the Water Framework Directive (2000/60/EC), adapting it to their ecosystems and river morphologies. While the Directive allows flexibility in methodological choices, all Member States must subdivide watercourses into homogeneous sections, a key requirement for their characterisation and management. Nonetheless, the choice of scale of analysis can significantly affect river segmentation and characterization. This study proposes an approach based on the Sinuosity Index (SI) and the Confinement Index (CI), to achieve a more objective segmentation, consistent with morphological variations. The proposed method could serve as a rapid and valuable tool for river analysis at the European level, complementing existing methodologies across different Member States. The SI values are computed every 50 m along the river using multiple spatial scales, ranging from 100 to 2000 m. Each SI value represents the sinuosity computed within a moving window, covering a distance equal to its size. This multi-scale analysis helps understanding sinuosity variations across different spatial scales and identifying the most representative scale by comparing and analysing SI distributions along the river profile. In addition, the method evaluates SI variation along the watercourse through graphical analysis, highlighting sinuosity changes and measuring the distance between consecutive meanders to quantify morphological variations along the analysed stretch.

Once the optimal SI window is determined, the selected value is integrated in a Python script that combines the SI with the Confinement Index (CI), also calculated every 50 m, considering the ratio between the width of the riverbed and the alluvial plain. By merging these two indices, this method enables an automatic segmentation of the river into morphologically consistent stretches, overcoming subjective approaches. At the end of the process, the segmentation of the river sections allows a combined classification, distinguishing Rectilinear (R), Sinuous (S) and Meandering (M) sections according to the SI and Confined (C), Semi-Confined (SC) and Unconfined (UC) sections according to the CI. The method has been applied to several Sicilian rivers with different morphological characteristics, demonstrating its adaptability to these specific geographical contexts and its usefulness for geomorphological interpretation. In geographical contexts with wider meanders, it may be appropriate to increase the SI window size to better capture sinuosity variations. The results obtained show that the analysis scale significantly influences segmentation and the perception of river dynamics, underlining the importance of a well-considered selection of the SI calculation window for river characterisation and management studies. By integrating only parameters related to floodplain extent and fluvial morphology, this approach provides a fast and valuable tool for geomorphological analysis and river management, reducing subjectivity in river classification.

KEYWORDS: river segmentation, sinuosity, Phyton, Sicilian river

Long-term cross-sectional changes in the regulated Lower and Middle Tisza River in Hungary

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River regulation works of the 19th century caused major changes in the morphology of Hungarian rivers. Due to cut-offs, channel slope significantly increased, which led to incision and width change. However, comparing survey data from pre-regulation states with the data collected after the regulations is difficult. Because of this, researchers usually study riverbed changes compared to the first post-regulation general survey, made in 1890. The natural state of the river prior to the regulations and the strongly controlled conditions today are not directly comparable.
Our study area covers a 180 km long reach, including the entire Lower Tisza in Hungary, and parts of the Middle Tisza. In this study, we compared cross-sections surveyed using traditional methods between 1834 and 1845, with cross-sections retrieved from a sonar and LiDAR-based DTM made in 2017. Analyzing river morphology before the regulations is important because it shows the original, natural conditions. We have processed about 350 pre-regulation cross-sections and 230 recent ones. Where it was possible, recent profiles were generated at or near the location of pre-regulation ones, where not, the same spacing was applied as in 1834. To study spatial differences, we divided the river stretch from Szolnok to the Serbian border into 12 sectors based on past changes in the river's course. We visualized the long-term changes in terms of average width, depth, cross-sectional area, width/depth ratio, hydraulic radius, and channel slope using graphs and maps. To understand why these changes happened, we compared them to the rate of river shortening, sinuosity, and the rate of bank stabilization within the sectors.
The results show that the Tisza River has become 21% narrower on average, while its depth has increased by 25%. This led to a small (2%) overall increase in the cross-sectional area. The width/depth ratio has decreased by 13%, and the hydraulic radius has increased by 22%. These changes were different in each sector. The comparison suggests that changes in cross-sectional area and depth are mostly related to the amount of bank stabilization along the river.

KEYWORDS: cross-sections, Tisza River, regulations

Delineating the erodible corridor as a tool for predicting future river dynamics: the case study of the Serio River (Italy)

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Rivers are dynamic systems that evolve continuously under the influence of natural processes and human activities. In recent decades, climate change has led to an increase in extreme events, resulting in frequent floods. Floodings contribute to bank instability and induce episodic and/or progressive changes in river morphology. Understanding the future evolution of river systems requires a comprehensive analysis of both their current dynamics and historical channel changes. Past river changes provide valuable insights into long-term trends, while recent observations reveal active processes and responses to recent environmental and anthropogenic pressures.
The aim of this work is to investigate the historical geomorphological evolution and the present evolutionary trends of the valley portion of the Serio River (Italy) - ~ 80 km long - in order to define the erodible corridor area, the area where future channel dynamic of river is expected. Analyses were based on multi-temporal mapping of the active channel from orthophotos (from 1954 to 2023) in GIS environment (with higher temporal resolution over the last 25 years), multitemporal DTMs and field surveys.
Results of the historical channel changes indicate general narrowing from 1954 to 1988, and alternation of widening and narrowing from the 1990s until the present day. Current river dynamic is very high and results in bank erosion, that locally affects more than 40% of the banks (up to 95%). Bank erosion rates, calculated over the last 15 years at the reach scale, range from a minimum of 0.3 m/y to a maximum of 2.7 m/y.
The erodible corridor area was delineated combining (i) the corridor of historical channel shifting, obtained from the multi-temporal active channel mapping, and (ii) the future potential erosion areas, estimated by calculating the bank retreat rates. The delineation of river corridors, combined with predictive models, is a valuable resource for authorities, providing risk reduction for communities living near rivers.
Future work focuses on developing a sustainable river management plan aimed at the recovery of the Serio River channel within the erodible corridor area. This recovery will contribute to mitigating geomorphological risks and enhancing the morphological and ecological conditions of the river.

KEYWORDS: geomorphological river evolution, erodible corridor, future river dynamic, Serio River

DANube SEdiment Restoration (DANSER): towards deployment and upscaling of sustainable sediment management across the Danube River basin (Upper Danube DEMO activities)

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DANSER aims at addressing the urgent need for sustainable sediment management solutions at the river basin scale, focusing on the Danube River-Black Sea system. Foci are demonstration of multidisciplinary innovative and holistic solutions and developing deeper insights into the sediment status and cause-effect relationships (e.g. via spatiotemporal mapping of natural and anthropogenic fluvial processes, sediment transport modelling, sediment dating, 3D historical reconstruction, river processes forecast simulations, sediment budget analysis, connectivity modelling and interventions, stakeholder-engaged sediment parametric evaluation and co-management, interlinkages with biodiversity (patterns), water quality and climate change effects.
This EU-funded (HORIZON-MISS-Danube & Black Sea Lighthouse) project seeks to restore sediment balance, improve sediment flow and quality together with EU- and other international stakeholders (existing bodies, digital platforms, events and know-how). In an ample coverage throughout 3 DEMO (incl. 13 pilot) sites, 7 sibling locations, and 6 associated regions (AR), the DANSER approach will develop, validate, and promote key active and passive measures to mitigate human interference in the sediment flow, related biodiversity and ecological aspects and possibly recover the sediment balance and quality in critical stretches of the basin. In this presentation, we aim to provide an overview of the strategies and actions that are foreseen for the Upper Danube region, specifically in DEMO area 1 located in Lower Austria with a specific focus on hydro-geomorphic aspects.
This research acknowledges support from the EU Projects HEU DANSER (grant agreement No 101157942), H2020 MERLIN (grant agreement No 101036337), HEU Danube4all (grant agreement No 101093985) i-CONN' H 2020 research and innovation programme under the Marie Skłodowska Curie grant agreement number 859937. Furthermore, the Austrian Federal Ministry for Digital and Economic Affairs and the Christian Doppler Research Association supported the work via the Christian Doppler Laboratory for Meta Ecosystem Dynamics in Riverine Landscapes (CD Laboratory MERI).

New insights into the geomorphological and tectonic evolution of the Danube at the Iron Gates and the Western Moesian Platform

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The Iron Gates sector (Danube Gorge) and the downstream alluvial plain with well-developed fluvial terraces of the Danube River provides a natural laboratory for investigating long-term fluvial incision and landscape evolution at the interface between the Southern Carpathians and the western margin of the Moesian Platform. In this area, the Danube crosses three distinct morpho-tectonic units: the Carpathian Orogen, the Carpathian Foredeep, and the Western Moesian Platform.

Several competing hypotheses address the evolution of the Danube Gorge, most notably the antecedent drainage model (Cvijić, 1908) and the regressive river capture model (Posea et al., 1969; Vâlsan, 1919). The formation of the Iron Gates gorge is widely attributed to vertical fluvial incision initiated in the Late Pliocene and continuing into the Quaternary, in response to regional tectonic uplift and climate changes.

The present study aims to reopen the historical subject of the evolution of the Danube Gorge by performing morphometric analyses and obtaining absolute ages. Here we present the preliminary results.

The Ciucaru/Kazan surface (T8, ~270–320 m) represents the earliest fluvial morphological marker horizon along the gorge and reflects the initial stage of incision. Terraces T8 to T5 were shaped during this early phase and correlate with mid–late Pliocene alluvial plain fine sediments and late Pliocene–early Quaternary coarser alluvial fan deposits observed on the western Moesian Platform.

The transition from the upper (T8–T5) to the lower terraces (T4–T1) within the gorge corresponds with a similar transition in the western Moesian Platform from the upper plain (composed by deltaic, alluvial plain and alluvial fan deposits of the Danube) to the lower Danube plain, with 7–8 distinct alluvial terraces. This cross-regional longitudinal correlation reflects a change from dominant lateral fluvial erosion along the gorge and the corresponding downstream vertical aggradational environment toward dominant fluvial incision and terrace formation during the Middle–Late Quaternary, driven by both sustained uplift and glacial–interglacial climatic fluctuations.

Fossil evidence confirms a Late Pliocene–Early Quaternary age for the upper terraces. First available OSL dates for the younger terraces at the gorge exit (T3–T1) place them within Marine Isotope Stages (MIS) 3 to 1.

Morphometric analyses included longitudinal profiles of the Danube's tributaries on the left side of the gorge, as well as cross-valley sections on both banks, revealed a consistent pattern of knickpoints, terrace deformation, and altitudinal gradients, with the strongest uplift signals concentrated in the Almăj Mountains and Mehedinți–Miroc Plateaus.

Overall, the data support the antecedent drainage model for the Quaternary evolution of the Danube along the Iron Gates, a model that imply episodic fluvial incision superimposed on a tectonically active landscape. The evolution of the Iron Gates gorge results from the interaction between vertical tectonic movements and local base-level controls,

producing the stepped topography seen today. This unique geomorphic configuration offers key insights into the long-term Quaternary evolution of the Lower Danube corridor.
The study was supported by the ChronoCaRP project funded by Contract no. 760055/23.05.2023, project code CF 253/29.11.2022, PNRR-III-C9 2022-I8.

KEYWORDS: Lower Danube, Iron Gates, Quaternary

THEMATIC SESSION 3

BIOGEOMORPHOLOGY IN THE ANTHROPOCENE: CHALLENGES AND NEW APPROACHES

Chairpersons:

Daniel Germain, Ana-Neli Ianăș, Mircea Voiculescu

From soil disturbance to biodiversity loss: the environmental consequences of wild boar expansion in Parâng Mountains, Romania

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Wild boars (*Sus scrofa*) are among the most widespread and ecologically impactful invasive species, exerting substantial pressure on ecosystems, agriculture, and land stability. They also play a key role in modifying trophic interactions and ecosystem connectivity, affecting competition with native wildlife, predator-prey relationships, and plant-soil feedback mechanisms. Studies indicate that high wild boar densities can lead to a reduction of up to 95% in herbaceous cover, causing localized plant species extinctions and habitat degradation. Their rooting behavior, driven by their omnivorous diet, leads to extensive soil disturbances that disrupt plant communities (vegetation regeneration and biodiversity), alter soil composition (chemical properties, electrical conductivity) and accelerate erosion processes, ultimately reducing long-term ecosystem resilience. In forested areas, their activities inhibit the germination and regeneration of key tree species, affecting forest composition and carbon sequestration potential. Beyond their ecological impacts, wild boars contribute to land-use conflicts, particularly in agroecosystems, where their foraging activities cause substantial economic losses due to grassland destruction. Their population growth is fuelled by their adaptability to diverse habitats, high reproductive rates, and increased food availability due to agricultural intensification and climate change.

In the Parâng Mountains, these impacts are particularly pronounced, with wild boar disturbances leading to the abandonment of several hectares of grasslands. Based on quantitative field measurements, this study highlights wild boars as geomorphic agents driving significant environmental changes, emphasizing the urgent need for targeted conservation and mitigation measures to balance ecosystem integrity with agricultural and societal needs. By understanding the (geo)ecological role of wild boars in environmental changes, we can better anticipate their effects and implement adaptive management strategies to preserve biodiversity and landscape functionality in the Parâng Mountains. However, given the complexity of wild boar-induced disturbances, a multidisciplinary approach appears necessary to develop effective management strategies, which are essential for identifying population thresholds that mark the onset of unsustainable impacts.

KEYWORDS: zoogeomorphology, wild boar, soil disturbance, biodiversity, land degradation

How humans as geomorphic agents affect the spatial distribution of plant communities?

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Urban ecosystems' sustainability and resilience, threatened by ongoing urbanization trends, make essential to improve scientific knowledge about the relationships between urban habitats and species, on which the success of biodiversity conservation, ecosystem service provision, and human well-being depend.
The analysis of urban geomorphology in Rome (Italy) highlighted how prevailing landforms and processes in current landscape are related to anthropogenic erosion and accumulation. In such an historical city, anthropogenic morphogenesis deeply changed morphology. The Potential Natural Vegetation (PNV) types, strictly related to environmental land units defined by the combination of macroclimate, lithology and geomorphology, are highly correlated with topographic position.
In this context, we investigated urban geomorphology and its determinism on shifts in biodiversity support capacity and PNV. Understanding how anthropogenic alterations to geomorphology influences the spatial distribution of plants is vital for planning effective restoration actions and self-sustaining urban ecosystems.
In the case study of Rome (Italy), anthropogenic transformation of the landscape has been characterised, using morphometric analyses of landforms. Multitemporal digital elevation models allowed volumes of anthropogenic accumulation to be quantified (dem of differences, DoD), and soil and drainage changes due to changes in slopes shape (slope, curvature, aspect; raster of differences, RoD) to be estimated.
On the one hand, through functional connectivity and node-importance analyses, forests under more natural conditions and low anthropogenic disturbance were selected and surveyed for defining reference PNV systems. On the other hand, vegetation surveys were performed in artificial contexts, both inside (altered, landform plots) and outside (control plots) anthropogenic landforms, to assess the shifts from low-disturbed successional models due to geomorphological alteration and/or additional effects of urbanization (e.g. edge effect and isolation of residual forest patches). In conclusion, anthropogenic landform forests divert from natural ones in terms of specific composition being characterised by invasive, nitrophilous, and transitional species. Therefore, vegetation surveys have been conducted for investigating intensity and direction of eventual shifts in spontaneous dynamics.
The described interdisciplinary approach, based on modern investigation methods and field research allowed to increase knowledge about how humans as geomorphic agents interact with the biological world.
Project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 - Call for tender No. 3138 of 16 December 2021, rectified by Decree n.3175 of 18 December 2021 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU.

KEYWORDS: anthropogenic landforms, morphological alteration, potential natural vegetation, specific composition, Rome

Biogeomorphological interaction of large woody debris with river channels identified by remote sensing data

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The riparian zone represents a corridor entity with a specific ecological and spatial gradient along watercourses. In this space, water, sediments and vegetation interact with each other and shape river morphology. The landscape structure of the riparian zone reflects mutual interaction and feedback between hydrological processes, the different landforms in the watercourse and the successive evolution of vegetation. Vegetation prevents increased erosion during small floods and stabilizes the different geomorphological forms during the inter-flood period. Moreover, pieces of vegetation entered into the river system and interacted with hydromorphological features in the riparian zone. The aim of this work is to identify morphological processes in the river channel, resulting from large woody (LW) pieces accumulation in the meandering section of the gravel-bed river Topľa (eastern Slovakia, Western Carpathians). For the large woody (LW) survey, the river section (a total length of 3.7 km) with 14 irregular meanders, dynamic lateral shift and bank undercutting were selected. For LW monitoring, seven series of aerial and UAV images from 2009, 2012, 2013, 2016, 2019, 2022 and 2024 with resolutions from 25 to 2.8 cm/pixel were used. LW was manually delineated by vectorisation, including all LW pieces (logs) with lengths greater than 1 m in length and 10 cm in diameter. More than 3 clustered pieces of LW were vectorised as jams, and the length and width of the jam dimension were measured for statistical weighting. The volume of LW was calculated directly from their measured length and diameter, whereas whole tree volume calculation assumed a truncated cone geometry. Small branches of whole trees with branches less than 10 cm in diameter were excluded. Moreover, vectorisation error, detection limits and impact of pixel size were analysed. Finally, channel dynamics and the different morphological processes pointed to a significant transformation of the channel due to increased input of LW into the channel due to bank erosion and beaver activity. This work was supported by the Slovak Research and Development Agency under Contract No. APVV-23-0265 and grant VEGA 2/0016/24.

KEYWORDS: biogeomorphology, large woody debris, gravel-bed river, vegetation input

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Satellite imagery for monitoring badland evolution and vegetation dynamics in a global change context

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Satellite remote sensing provides consistent data collection over large areas. Programs such as Landsat offer the longest continuous space-based record, freely accessible, and have revolutionized the understanding of Earth's surface dynamics, particularly in regions hard to reach and with limited historical in-situ data. One of the most widely used indices derived from specific satellite bands is the Normalized Difference Vegetation Index (NDVI), a powerful tool for assessing changes in vegetation cover and linking these transformations to broader environmental and anthropogenic factors. A multidecadal approach based on satellite imagery data was applied to an Italian badland site (located in southern Tuscany), with the aim of contributing to the comprehension of its recent morphodynamics. Although this temperate landscape could naturally sustain vegetation due to seasonal soil moisture patterns, it has been heavily impacted by human activities, such as several historical deforestation phases, which removed the protective vegetation cover, leaving the soil exposed to erosion and leading to the formation of distinctive erosive landforms. Nowadays, with the widespread abandonment of rural areas, these landforms appear to be gradually decreasing, allowing the landscape to slowly return to its natural state. Moreover, this process is further triggered by climate change, which alters precipitation patterns and temperatures arising, significantly affecting vegetation dynamics. The specific objectives of this study are to address the following research questions: (i) Is the area undergoing a revegetation process that may lead to the gradual reduction of badland surfaces? (ii) Is there a seasonal trend characterizing the long-lasting vegetation changes? (iii) What is the role of global change, encompassing shifts in precipitation and temperature patterns as well as land use changes, in driving this dynamic? To address these questions, satellite imagery from the Landsat program (Landsat 5 TM, Landsat 8 OLI, and Landsat 9 OLI) is analyzed through Google Earth Engine to generate the 30-meter NDVI dataset for the period 1984–2023. Cloud-covered pixels are excluded based on the Quality Assessment band, and a monthly pixel-wise analysis was conducted using the Mann-Kendall test combined with the Sen's slope estimator, a widely used non-parametric statistical method for detecting monotonic trends in climate data. Only pixels with a confidence level greater than 95% are considered in the analysis. Additionally, in situ data on precipitation (monthly averages and intensity) and temperature (monthly min, max, and mean) are compared with monthly satellite-derived temperature data from the Landsat Surface Temperature product and precipitation data from the Global Precipitation Measurement Mission, using the same analysis period and statistical approach. Finally, land use changes are evaluated using the CORINE Land Cover datasets for 1990, 2000, 2006, 2012, and 2018, alongside a 1978 land use map from the Tuscany Region. The analysis reveals a steady increase in vegetation cover, suggesting a possible prolongation of the growing season. This trend is accompanied by relatively stable precipitation patterns and a general warming trend. These climatic drivers, along with expanding forested and agricultural areas and a decline in badland landforms, highlight the impact of both climate and land use changes on landscape dynamics.

KEYWORDS: satellite imagery, badlands, NDVI, global change, Mann-Kendall test

Wood and plastic: not fantastic! Exploring the interactions between woody debris and macroplastics in mountain rivers

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The increasing presence of plastic in the environment and its widespread, negative effects on ecosystems and human health have recently become a focus of many studies. In fluvial environments, plastic is now often referred to as a new type of sediment and understanding the mechanisms behind the formation of macroplastic accumulation hotspots within river systems is emerging as a critical research priority in plastic pollution studies. However, recent observations indicate that wood jams (a mix of wood pieces and mineral sediments) efficiently trap floating macroplastics and so act as hotspots of macroplastic deposition and retention in mountain river channels. This poses a serious threat to fauna and aesthetic values of the fluvial landscapes and likely further exacerbates widespread pollution from subsequent plastic fragmentation. Our study on the macroplastic storage in the Dunajec River, Polish Carpathians showed considerable differences in the amounts of macroplastics trapped in reaches of different morphology, with wood jams trapping 19-180 times more macroplastic debris than other forms such as wooded islands, or exposed river sediments; microplastic storage was also drastically higher in semi-natural reaches than in the channelized ones. Large wood accumulations seem key in macroplastic routing and deposition, although understanding of the patterns of macroplastic delivery, transport, retention and fate in the rivers is still limited and the processes and conditions underlying the formation of these new, specific features - plastic-wood jams - remain unexplored. This paper aims to synthesize current research on the interactions between wood jams and fluvial processes within the context of macroplastic pollution. Based on that, we propose a conceptual framework to address the following research questions: (i) what role do floods play in the formation and remobilization of plastic-wood jams? (ii) what are the spatial and temporal patterns of their formation in rivers with varying channel morphologies? (iii) how do plastic-wood jams behave dynamically across fluvial systems? and (iv) what risks do their presence pose to riverine biota? This framework aims to guide future research and support a more comprehensive understanding of macroplastic dynamics in river systems, that would inform effective river management practice.
This study is financed by research project SONATA 19 no 2023/51/D/ST10/01816 of the National Science Centre, Poland.

KEYWORDS: plastic pollution, wood-plastic jam, river channels

Quantitative analysis of the zoogeomorphological impact of rodents in the Semenic Mountains, Romanian Carpathians

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Our study was conducted in the Semenic Mountains, Romanian Carpathians, a tourist area of local and regional importance. Through field investigations, we identified the presence of the bicolored shrew (*C. leucodon*) at an altitude of approximately 1370 m in sectors of natural grassland developed on a geological substrate of mica schists and histosol-type soils. Although this species typically inhabits open and lowland areas up to 600 m altitude, including agricultural land and urban habitats, recent studies have shown that its habitat has expanded into mountainous areas at altitudes exceeding 1000 m, as is the case in the Semenic Mountains.

The zoogeomorphological impact of the bicolored shrew is well highlighted in the study area through bioerosion and bioconstruction processes. By digging tunnels, excavating sediments, and foraging for food, the shrew creates microrelief features such as mounds. Within five plots of 25 m^2 each, we measured and evaluated a total of 127 mounds, of which 97 were active, 22 abandoned, and 8 eroded, reflecting a certain dynamic of the mountain landscape. The mound density, ranging from 0.4/m^2 to 1.32/m^2, along with the size and weight of the excavated sediments, indicates that *C. leucodon* activity represents a significant source of sediment. The resulting mass transfer was calculated at 28.6 t/m^2/year/km^2, a value comparable to the biogenic activity of other, even larger, animals.

The sediments excavated to the surface are redistributed in the landscape by external agents such as wind, precipitation, snowmelt runoff, and also by trampling from tourists and pastoral activities, which are well-represented in these mountains. The erosion process intensifies with increasing slope gradient; however, in the study area, the gradient is relatively low, ranging between 7˚-10˚, resulting in a reduced erosion impact.

Through the combined action of tourism and zoogeomorphological processes, a certain level of environmental degradation occurs in this mountain area with a touristic vocation. We believe that future studies could focus on this research direction, where the use of specific matrices could help quantify the combined environmental impacts of zoogeomorphological and tourist activities.

KEYWORDS: zoogeomorphology, bicolored shrew, bioerosion, bioconstruction, Semenic Mountains

THEMATIC SESSION 4

COASTAL SYSTEMS UNDER PRESSURE – INTEGRATING METHODS TO REVEAL HUMAN IMPACT

Chairpersons:

Florin Zăinescu, Niki Evelpidou, Edward Anthony, Florin Tătui

Application of complex geo-ecosystem approach in assessing human impact on beach-dune landforms and habitats along the South Bulgarian Black Sea Coast

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The most recent study of the Bulgarian Black Sea coast defined a total area of 988 ha of coastal dune systems, which are distributed across various beach stipes on total length of 73 km. Most of these dune systems -68%, consist of various types of secondary dune landforms, remnants of older raised coasts or inland-formed blowouts of primary dunes. In Bulgaria, dune systems are protected both as natural heritage (as defined in the Constitution and the Law of the Bulgarian Black Sea Coast) and as protected habitats for vulnerable species of vegetation and wildlife (included in Natura 2000, as defined by the Law on Biodiversity and the actions outlined in European Commission Directives).
Bulgarian authorities have adopted an interdisciplinary approach to the thematic mapping of these areas, utilizing the expertise of geomorphologists and biologists to define dunes not only as specific landforms but also as natural habitats, in order to categorize the different dune types. Unfortunately, this complex approach has led to some misinterpretations and practical issues. The majority of these problems concern secondary dune systems, which, despite being typical habitats (primarily gray dunes), do not exhibit the typical dune morphology. These misunderstandings have had negative consequences in disputed areas—within just 15 years, 50.7 ha (5.1% of the total dune area) have shown signs of human impact. Due to anthropogenic activities, such as construction, road building, breaching, excavations, and levelling, 12 ha of dunes have been permanently lost. Additional risks include pollution, the spread of invasive species, tourism infrastructure, military activity, and natural processes such as coastal erosion.
In 2024, a comprehensive methodology for defining and classifying coastal dunes was discussed and adopted, in collaboration with state and scientific institutions. This methodology combines photogrammetric surveys for documenting and monitoring changes in dune morphology, assessing destructive structures and contamination, and field techniques for sedimentological studies, phytocoenological studies, and monitoring changes in plant communities. The southern Bulgarian Black Sea coast was selected as the pilot area for testing this complex geo-ecosystem approach. Archival materials and previous studies have been used to assess the human impact on beach-dune systems over a period of more than 100 years.

KEYWORDS: coastal beach-dune systems, complex geo-ecosystem approach, human impact, Black Sea Coast

High temporal-resolution satellite data analysis of deltaic coastal evolution via Google Earth Engine: impacts of climate change and increasing anthropogenic pressure

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Deltaic coasts can be highly sensitive to changes in key factors, such as sediment supply, hydrodynamic processes and climatic variability. Employing high temporal-resolution Landsat satellite imagery accessed through Google Earth Engine, this study focuses on the coastal dynamics in the most important deltas in the Mediterranean and Black Sea basins. Using annual composite images spanning 1984 to 2024, the deltaic coastal interaction areas of the Danube, Rhône, Nile, Ebro and Po rivers were analysed in relation with their geomorphological response to sediment accumulation, erosive processes and significant climatic events. Over the last 40 years, the Danube and Po Deltas revealed a positive (accumulative) trend, with an increase in coastal land area. On the other hand, the Nile and Ebro Deltas faced significant surface reductions, synonymous with erosion, whereas the Rhone Delta maintained quasi-equilibrium between sediment accumulation and erosion. Temporary surface reductions in the coastal areas are linked with the impact of significant storminess, including the 1997-1998 events in the Danube and Rhône Deltas, 2013 in the Danube Delta and Storm Gloria of 2020 affecting both the Rhone and Ebro Deltas. In contrast, the correlation with floods, particularly in the Danube Delta, indicates a slightly delayed response in surface growth, which needs further investigations also in other deltas. Most spectral indices used (ANDWI, AWEI, MNDWI, SCoWI and WI2015) generally showed consistent behaviour in identifying the land-water interfaces, while NDWI tended to overestimate the land areas, especially in shallow waters. The shorelines extracted from satellite imagery (derived from index-based binary maps) were validated using LiDAR and in-situ (GPS) measurements conducted in various sectors along the coasts of Danube and Rhône Deltas, showing consistent matches.

KEYWORDS: Google Earth Engine, deltas, coastal dynamics, spectral indices, climatic events

Investigating spatial variations in hurricane storm surge sedimentation: a follow-up study of hurricane Ike on the Texas Gulf Coast

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This study investigates spatial variations in sedimentation in the right-front quadrant of Hurricane Ike, on McFaddin National Wildlife Refuge on the East Texas Gulf Coast. Fieldwork conducted in summer 2017 and summer 2018 involved digging shallow pits on four transects between Sabine Pass, Texas and High Island, Texas. Eight pit sites were established on Transect 1, the easternmost transect, and six pit sites each were established on Transects 2, 3, and 4, with Transect 4 located farthest west. All four transects extend 880-1630 m, with pit sites beginning near the coastline and extending landward. Results obtained in the field indicate that the Hurricane Ike sediment deposit has been found on all four transects, and that the deposits decrease in thickness moving landward along each transect. On Transect 1, at Pit Site 1, the thickness of the Hurricane Ike sediment deposit was > 60 cm; this same deposit gradually tapers down to a thickness of 4 cm at Pit Site 8. On Transect 4, Pit Site 1 had a Hurricane Ike sediment deposit of 53 cm, while at Pit Site 6 the Ike deposit was 5 cm thick. Additionally, there is evidence that sedimentation has been impacted by the presence of man-made levees that lie perpendicular to the Gulf Coast at Transects 2, 3, and 4. The goal of this study was to discover spatial variations of the Hurricane Ike storm surge sediment deposit in relation to the landfall location of Hurricane Ike. The findings of this study provide useful guidance to public policy aimed at combating the effects of sea-level rise.

KEYWORDS: sedimentation, Hurricane Ike, Texas Gulf Coast, storm surge, sea-level rise

Impacts of Posidonia oceanica on coastal morphodynamics in Navarino Bay, Greece

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Coastal areas, as dynamic interfaces between land and sea, are increasingly vulnerable to natural and anthropogenic pressures, including climate change. These areas are of ecological and economic importance, providing vital ecosystem services and supporting densely populated human communities. The issue of coastal erosion is further exacerbated by human activities, including coastal development and the construction of tourism infrastructure. This study investigates the impacts of *Posidonia oceanica* (*P. oceanica*) meadows on the coastal morphodynamics of Navarino Bay, Peloponnese, Greece, and their role in mitigating coastal erosion. To achieve this objective, the MIKE 21/3 Coupled Model FM was employed for hydrodynamic and morphodynamic simulations. The study compares two scenarios: one with and one without the presence of *P. oceanica*, to assess its impact on sediment stability and shoreline protection. Field data, incorporating bathymetric and coastal morphology parameters, were integrated with wind and wave statistics from the Poseidon system. Utilizing advanced geospatial tools (ArcGIS Pro) and numerical modelling, the wave dynamics, current speeds, and sediment transport over a one-year period were simulated. Our findings indicate that *P. oceanica* significantly reduces current velocities and wave energy, leading to enhanced sediment stabilization and reduced erosion rates. Conversely, its absence has been shown to exacerbate hydrodynamic forces, leading to increased erosion and sediment resuspension. This research underscores the protective functions of *P. oceanica* and advocates for its preservation as a nature-based solution (NBS) to coastal management challenges.

KEYWORDS: coastal erosion, coastal management, morphodynamics, modelling, nature-based solutions

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Sea-level rise and coastal vulnerability in Kalamata (Peloponnese, Greece): a GIS and AHP-based socio-environmental assessment

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This research focuses on the coastal zone of Kalamata, Peloponnese, Greece, aiming to evaluate the natural and anthropogenic challenges in the area and to assess coastal vulnerability. The research involves field surveys and the compilation of inventory reports to facilitate a comprehensive understanding and analysis of the study area. The study area is structured into five zones identified through field observations, based on their distinct characteristics.
The representation of the current state of the study area is presented concerning the selected evaluation variables. It is worth mentioning that categorizing the values of these variables within a vulnerability assessment scale provided the initial visualizations of the area. Subsequently, using the Analytical Hierarchy Process (AHP), the evaluation and ranking of the criteria are conducted. Two main categories of factors were assessed: (1) natural factors, which included land use, sea level rise, coastal slope, beach width and (2) socio-economic factors that included land use, housing condition, population density, economic loss.
Comparison matrices were developed based on specialized criteria, and weights were assigned according to the significance of each factor in three different approaches: a matrix emphasizing natural factors, a matrix emphasizing social and economic factors and a combined matrix considering the overall picture. Saaty's scale allows for the calculation of variable weights, while the consistency of the matrix is evaluated using the Consistency Ratio (CR), which depends on the Consistency Index (CI).
After mapping the current conditions using Geographic Information Systems (GIS), the Analytical Hierarchy Process (AHP) is applied to prioritize and weigh the relevant criteria. Moreover, coastal vulnerability is assessed under a projected sea-level rise of 1.01 meters by 2100, as forecasted by the Intergovernmental Panel on Climate Change (IPCC, 2023).
Consequently, the study investigates the rational management of the coastal zone and its broader area. The research findings contribute to the spatial representation of coastal vulnerability by incorporating both natural and anthropogenic pressures derived from the evaluated criteria.

KEYWORDS: coastal zone, Geographic Information System (GIS), Analytical Hierarchy Process (AHP), coastal vulnerability

Assessing coastal vulnerability in Finland: a geomorphological approach using the coastal vulnerability index and Earth Observation data

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Finland's extensive and geomorphologically diverse coastline faces growing threats from climate change, including sea-level rise and coastal erosion. This study applies the Coastal Vulnerability Index (CVI) to assess the vulnerability of the entire Finnish coastline, integrating physical, geological, and socio-economic factors. Conducted under the EO-PERSIST project—a 4-year MSCA staff exchanges initiative funded by the EU focused on developing Earth Observation (EO)-based datasets for permafrost applications—this research leverages high-resolution EO data, including elevation models, land cover maps, and sea-level rise projections, alongside traditional datasets. The CVI calculation incorporates key parameters: coastal slope, geomorphology, historical shoreline changes rates, wave height and tidal range. Using GIS-based spatial analysis, these multi-source data layers are integrated and visualized. Preliminary findings highlight significant spatial variability, with low-lying archipelagos and estuaries showing heightened susceptibility due to flooding and erosion risks, while rocky, elevated shores exhibit greater resilience. The detailed mapping of coastal landforms underscores the influence of geomorphology on vulnerability patterns. This assessment not only provides critical insights for sustainable coastal management in Finland but also highlights the versatility of EO-PERSIST technologies in addressing interdisciplinary environmental challenges beyond permafrost studies. These findings contribute to the geomorphological understanding of coastal dynamics and support climate adaptation strategies.

ACKNOWLEDGEMENTS This study is supported by EO-PERSIST project which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 101086386

KEYWORDS: coastal vulnerability index, Finland, Earth Observation, climate change, EO-PERSIST

Sinking coasts – solving challenges in relative sea-level rise impact and coastal hazard assessments by projecting coastal subsidence and dynamic land elevation change

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Coastal lowlands worldwide are increasingly facing accelerating rates of land subsidence, which heightens their exposure to coastal hazards following relative sea-level rise. Coastal subsidence, downward vertical land motion, driven by both natural and anthropogenic processes, is particularly pronounced in densely populated coastal-deltaic regions, where human activities can accelerate subsidence rates to several centimeters or even decimeters per year, significantly outpacing climate-induced sea-level rise. The interplay between coastal land subsidence and relative sea-level rise governs changes in coastal land elevation and geomorphological landscape change, and increases vulnerability to flooding and other hazards of coastal landforms.

This contribution synthesizes ongoing research into coastal land subsidence and elevation change dynamics, predominantly in Southeast Asia, focusing on the Mekong (Vietnam), Chao Phraya (Thailand), Ayeyarwady (Myanmar) deltas, as well as the Pampanga delta and Manila Bay (Philippines). Current land subsidence rates in these areas reach up to 15 cm/yr. To provide reliable assessments of coastal hazards, it is essential to utilize vertically accurate elevation data that is properly referenced to sea level, a task that presents significant challenges.

Our integrated approach aims to disentangle the drivers and processes of coastal land subsidence, linking subsurface characteristics (geology, hydrogeology, geomechanics) with subsurface processes (groundwater flow, aquifer-system deformation) through advanced numerical modeling. This enables process-based projections of land subsidence and facilitates the integration of these projections into the latest accurate digital elevation models. By doing so, we can project future elevation evolution and associated morphological changes, such as shoreline erosion and retreat, ultimately leading to potential permanent inundation of coastal-deltaic areas.

The integration of subsurface processes and data on coastal subsidence, relative sea-level rise, and land elevation dynamics provides a fundamental basis for accurate projections of coastal elevation change. This holistic understanding of the sinking coastal lowlands and the interacting physical and human mechanisms involved is crucial for guiding risk-informed decision-making and developing effective adaptation and mitigation strategies to address the challenges posed by coastal hazards.

KEYWORDS: land subsidence, relative sea-level rise, river deltas, coastal elevation, coastal hazards

Advancing hydrological monitoring in deltaic environments: a high-resolution approach using SWOT and Machine Learning

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The interaction of the hydrological processes contributing to the construction of deltas is even more complex as these systems are constantly disrupted by floods leading to the deposit of pollutants, nutrients, and sediments. Deltas are incredibly active ecosystems, and to fully understand the impact of climate change on these habitats, it is essential to monitor these processes. It is critical for understanding the functioning of these systems and their adaptation to climate change. The Surface Water and Ocean Topography (SWOT) satellite project has made it feasible to conduct high-resolution water surface investigations, providing crucial temporal and spatial information about coastal wetlands and river deltas. However, the traditional SWOT raster output often overestimates the water area due to its 100-meter resolution, which makes it unable to detect finer land-water borders.

This study aims to increase the precision of water surface elevation monitoring, flow dynamics, and inundation mapping in order to improve SWOT-derived hydrological products for wetlands, including the Rhône and Danube deltas. We created a system that improves the classification of land and water at a 10-meter resolution in order to overcome the shortcomings of the existing SWOT products. This was achieved by using SWOT's original PIXC classes and correcting misclassifications through a statistical sampling threshold. The KNeighborsClassifier was applied to define the 10-meter grid boundaries, resulting in a more precise water elevation and extent product.

This enhanced dataset was then used as input for a Machine Learning model that integrates Sentinel-1 Synthetic Aperture Radar (SAR) data with ESA WorldCover (2021) to fill data gaps near nadir. Water occurrence maps more accurately depict the hydrological dynamics in coastal wetlands by utilizing this revised water extent product. In order to better understand wetland hydrology and its seasonal variations, elevation variation maps help to track changes in water levels over time. Using the full time-series PIXC data for each delta and applying error filtering, we removed open water pixel points and created a dense set of elevation points. These were then used to construct an enhanced Coastal Digital Elevation Model that reduces errors caused by vegetation, improving the reliability of elevation assessments in deltaic environments.

The elevation data generated by SWOT analysis was validated using in situ water level gauges, and the findings indicated a significant correlation ($R2 > 0.9$) in most of the areas. By fixing misclassifications in nadir and near-nadir regions, where land-water separation is frequently imprecise, this updated result significantly improves on the conventional 100-meter SWOT raster. The findings show that hydrological monitoring is much enhanced by combining machine learning with SWOT and Sentinel-1 data, offering a more trustworthy instrument for flood assessment and wetland management.

KEYWORDS: SWOT, deltaic wetlands, water surface elevation, inundation mapping, machine learning classification

Geomorphological implications of microbially induced carbonate precipitation in artificial reefs for carbon sequestration and coastal protection

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Anthropogenic greenhouse gas emissions are driving unprecedented climate change, leading to rising global temperatures, ocean acidification, and escalating sea levels. These changes pose significant threats to coastal environments, necessitating urgent and scalable carbon sequestration strategies. Carbon capture and storage (CCS) is widely recognized as a necessary supplement to emissions reductions for mitigating climate change, with microbially induced carbonate precipitation (MICP) emerging as a promising technique that not only facilitates carbon sequestration but also enhances coastal resilience.

MICP is a biochemical process wherein ureolytic bacteria induce calcium carbonate ($CaCO_3$) precipitation, which can mimic natural beachrock formation. Beachrocks, found in various coastal environments, serve as natural breakwaters by dissipating wave energy and reducing coastal erosion. By leveraging MICP to engineer artificial beachrocks, we propose a dual-purpose solution: enhancing CCS efforts while providing sustainable coastal protection.

In this study, we evaluate the feasibility of MICP-based CCS by examining its capacity to capture and store atmospheric CO_2 through carbonate precipitation and urea synthesis. The Bazarov reaction, which facilitates urea production by the reaction of CO_2 with ammonia, integrates carbon capture within the MICP process, thereby enhancing its sequestration potential. We quantify the amount of CO_2 stored in carbonate minerals and urea while assessing the energy efficiency of the process.

The results highlight MICP's potential as a viable CCS strategy, offering both carbon sequestration and coastal protection. By reinforcing shorelines and mitigating erosion, MICP-based artificial reefs present an innovative solution for addressing climate change and protecting vulnerable coastal communities. Further research is required to optimize large-scale implementation and assess long-term environmental impacts. This study underscores the urgent need for sustainable carbon sequestration solutions by employing nature-based solution such as reefs based on beachrocks.

ACKNOWLEDGEMENTS: This work was co-funded by (a) the project "Tracing Climate Change" (TRACE) under the Erasmus+ Program, (Project ID: KA220-HED-612216D9) and co-funded by (b) the Department of Geological Sciences, Stockholm University with Academic Supervisor - Prof. Alasdair Skelton.

KEYWORDS: coastal mitigation, coastal geomorphology, carbon capture storage, cement, beachrocks

Short term changes in the Arctic gravel beach morphology

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Decreasing sea ice cover and increasing storminess over the Northern Atlantic result in exposure of Svalbard coasts to more aggressive waves over an extended time period. Arctic beaches are often young environments uncovered from underneath glaciers in the recent past, which experience considerable morphological changes at the seasonal to inter-annual scales related to marine, terrestrial, periglacial and paraglacial processes. They are understudied compared to the lower latitude coasts partly due to their remoteness and the putative limited impact of coastal flooding and erosion on societies and infrastructure.

This study focuses on morphological changes on a ~2 km beach of Isbjørnhamna in Hornsund fjord, south-western Svalbard over 2 years (Aug 2022 - Aug 2024). The bay is home to the Polish Polar Station Hornsund with some infrastructure located meters from the beach. Understanding coastal morphodynamics is therefore critical for assessing the risk of flooding and damage. Eight Uncrewed Aerial Vehicle (UAV) surveys were conducted, and terrain models and orthophotomaps were created using Structure-from-Motion (SfM) photogrammetry. The goals of the study were (i) to assess the utility of UAV-derived topographic and RGB information for algae deposit mapping, (ii) to upscale the point information on grainsize to the entire beach, and (iii) to perform spatial and temporal analyses of changes in algae deposit and grainsize distribution.

Boulders, rocky outcrops, driftwood and ice blocks were mapped in a semi-automatic way using thresholds over smoothed surface. Supervised classification was used for algae deposit mapping. The maps of grainsize distribution were created by extrapolating field measurements. Spatial (along- and cross-shore) and temporal patterns of beach morphology were analysed and related to processes typical for Arctic beaches.

This study lays the foundation for interpreting results of the topographic change detection and for assessing the risk of infrastructure damage.

KEYWORDS: gravel beach, morphodynamics, grainsize, UAV, Arctic

Equilibrium states of wave-influenced river delta lobes and implications of reduced sediment supply

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Wave-influenced river deltas are shaped by the interplay of river sediment supply (Qs) and longshore sediment transport (LST) driven by waves. Using the Delft3D model, we simulated delta evolution under varying riverine and wave-dominated conditions, conceptualizing the resulting delta lobes as equilibrium morphological states. Our results reveal that wave-influenced deltas are highly sensitive to changes in sediment supply. A reduction in Qs, mimicking the effects of dam construction, can dramatically increase sediment bypass and decrease sediment trapping in front of river mouths, leading to accelerated coastal erosion and delta retreat. This highlights a critical inflexion point: even small changes in sediment quantities near the balance between riverine deposition and wave-driven transport can trigger significant morphological shifts. Human interventions, such as dam construction, rapidly force wave-influenced delta lobes to readjust towards a new, more recessed equilibrium state, often resulting in widespread erosion. Accurate quantification of sediment transport is therefore crucial for predicting delta response to anthropogenic and climatic pressures and for developing effective coastal management strategies.

KEYWORDS: river delta, Delft3D, longshore sediment transport, waves, sediment bypass, coastal erosion

THEMATIC SESSION 5

CONNECTIVITY IN GEOMORPHOLOGY

(organized by the IAG WG Connectivity in Geomorphology)

Chairpersons:

Ronald Pöppl, Laura Turnbull, Anthony Parsons

Spatial-temporal transformation of fluvial gravel bars and grain-size dynamics in meandering river

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The extensive construction of barriers, such as dams and weir, and human interventions has significantly European rivers, leading to severe ecological consequences. Recent studies estimate that over one million artificial barriers disrupt river continuity across Europe, impeding aquatic species migration and altering natural sediment transport processes. To understand the river dynamics and systems measuring grains is essential. This study focuses efficient and rapid methods to assess 3D river morphology with sediment input from repeated elevation model and comparing automated methods to continuous grain-size mapping with sUAS-derived lidar point cloud and orthophotomosaic products. Sampling of grain and lab-sieving analyses with field photosieving is used for statistical models with sUAS-derived data to spatio-temporal grain-size distribution detection on Ondava river (Western Carpathians, Eastern Slovakia). Temporal differentiation of elevation model (DoD – DEM of differences| and long-term aerial datasets (1949 – 2022) identified sediment connectivity. Grain-size distribution is laid on the relationship between sUAV image parameters, specifically, topographic roughness calculated from point cloud based on image texture with field samples and spatial patterns of gravel bar distributed along the rivers. By leveraging geomorphological survey techniques, such as Structure from Motion (SfM) photogrammetry, and photosieving tools BASEGRAIN and traditional methods for validation and accuracy. We aim to enhance the understanding of sediment transport processes and highlight the potential of sUAV imagery for detailed GSD analysis of river systems. Additionally, sediment yield over time is compared with historical data to access changes in the river sediment dynamics. This work was supported by the Slovak Research and Development Agency under Contract No. APVV-23-0265 and grant VEGA 2/0016/24.

KEYWORDS: gravel-bed river, sediment connectivity, photosieving, grain-size, gravel bars, river dynamics

Dirty Roads: how roadside macrolitter enters and moves through the environment

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Macrolitter (>0.5-2.5 cm in size) pollution is one of the most significant environmental issues, particularly in aquatic ecosystems. Understanding the entry path and movement of macrolitter in different environments is crucial for assessing the scale of pollution and designing effective mitigation measures and limiting associated risks. While extensive research has focused on oceanic and riverine pollution, particularly on macroplastics, the sources of waste emissions and the transport pathways from terrestrial environments to river systems remain poorly understood. To set stage for address this gap in future works, we synthetised existing knowledge and our pilot observations from Polish Carpathian, developing a conceptual model of waste dynamics in the environment that integrates information on waste emissions and transport dynamics. We identified roads as the primary source of waste emissions, distinguishing two types of road-related litter emissions: dispersed (individual litter items scattered along roads) and point (illegal dumping sites). In our model, we conceptualized how waste emissions are influenced by multiple factors, including infrastructure characteristics (e.g., road type, usage, and associated infrastructure), environmental factors (e.g., land use, vegetation, and relief), and socioeconomic factors (e.g., waste management efficiency and societal wealth levels). Beyond waste emissions and their movement through terrestrial environments, we also discuss potential control of macrolitter pathways from roads to river systems, which represent one of the most important global links between terrestrial and aquatic environments. We highlight that, environmental factors such topography, river valley morphology, land covers and climate (e.g., wind and precipitation) can play a key role in determining macrolitter transport rate efficiency through the environment. We also indicate that the entire process of waste emission from roads to terrestrial and aquatic ecosystem is subjected to temporal variability. Both emission rates and subsequent transport exhibit seasonality, influenced by periods of increased human activity, changing weather conditions, and seasonal variations in vegetation cover. Future understanding of these factors and their bidirectional interactions is essential for identifying critical areas most vulnerable to waste pollution. Conducting further research in this field will provide valuable insights into waste circulation patterns, ultimately supporting more effective environmental pollution management strategies.

KEYWORDS: road system, waste management, fluvial system, macroplastic, mountain stream

Watershed reorganizations controlled over 4 million years of escarpment retreat in the Patagonian tableland

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Retrogressive landslides play a key role in escarpment retreat on both sedimentary and volcanic tablelands, contributing to plateau consumption and the eventual formation of mesas, buttes, and other characteristic landforms. However, controlling factors of the landslides evolution and rate of the associated escarpment retreat remain poorly understood. In our study, we investigate how the late Cenozoic reorganizations of watersheds east of the Andes influenced landslide development along Patagonian plateaus and the rate of escarpment retreat. Focusing on the Lago Cardiel region (Argentina) and using $^{40}Ar/^{39}Ar$ dating of lava flows, we show that some plateau escarpments have not retreated in the last ~4 million years. Lava flows dated to ~3.8 Ma overlies well-preserved rotational retrogressive landslides, indicating exceptional preservation of these landforms. Conversely, some plateaus are affected by landslides that were active during the Holocene, as evidenced by the overlap with Lago Cardiel's shorelines. Reconstruction of valley evolution shows that inactive escarpments were once part of a Mio-Pliocene watershed of large river flowing from the Andes to the Atlantic, later abandoned due to river captures. In contrast, escarpments flanked by recent landslides align with contemporary rivers and lake shores. We conclude that escarpment retreat can be halted for millions of years if the landslide masses supporting the slope above are not removed by rivers, lake waves, or glacial scouring, allowing retrogressive shifts of plateau margins. Our findings suggest that, rather than climatic influences, long-term landslide activity and escarpment retreat in the semi-arid Patagonian tableland have been primarily controlled by watershed reorganizations causing slope (dis)connectivity to rivers and lakes.

KEYWORDS: volcanic tableland, escarpment retreat, retrogressive landslides, watershed reorganizations

Testing of OSL sensitivity and ESR parameters as proxies for geomorphological processes in fluvial and eolian environments

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In recent decades, electron spin resonance (ESR) and optically stimulated luminescence (OSL) methods have been increasingly applied to sediment provenance studies. While their combined use in age dating is common, the relationship between ESR and OSL parameters in provenance studies, particularly in comparing quartz grains across sediment types, remains understudied, as does the extent to which various factors influence these parameters.
Here, the separability of sediments from different source areas and transport processes is investigated using parameters of the ESR (E'1, Ti-h, peroxy, Al-h) and OSL (CW-OSL, Total LM-OSL, LM-OSL fast and medium component, 110°C TL) methods, complemented by the morphological analysis of quartz grains. Additionally, potential relationships between ESR, OSL, and morphological parameters are explored to enhance the distinction of sediment samples based on their origin. Quartz grains from modern fluvial and paleo-aeolian sediments of the Pannonian Basin offer a valuable opportunity for these measurements.
Comparing the average luminescence sensitivity values, Tisza fluvial sediments exhibit higher sensitivity across all studied parameters, except for the LM-OSL medium component. However, in the upper Tisza, the LM-OSL fast component and CW-OSL sensitivity are similar to those of the Danube and lower than in the middle and lower sections. This downstream increase is driven by high-sensitivity quartz grains supplied by tributaries. In the case of the Danube, these changes are less significant, and a recurring increase can be observed instead. The observed variations in luminescence sensitivity are primarily attributed to erosion. Among the aeolian samples, the Total LM-OSL and 110°C TL signals were higher in Danube sediments, whereas the LM-OSL fast and medium components, as well as CW-OSL, showed higher values in Tisza sediments compared to Danube sediments. The aeolian and fluvial samples can be clearly distinguished based on the average values of E'1. The Danube aeolian samples exhibited more than three times the E'1 signal of the Danube fluvial samples, while the Tisza aeolian samples showed an E'1 signal approximately twice as high as that of the Tisza fluvial samples. The Ti-h parameter proved to be the most effective in distinguishing between Danube and Tisza sediments. The largest difference was observed among the fluvial samples, where the Ti-h signal in Tisza sediments was 2.5 times higher than in Danube sediments.
In terms of the correlation between ESR and OSL parameters, for the Tisza fluvial samples, a positive correlation is observed between the E'1 and CW-OSL sensitivity, with CW-OSL sensitivity increasing as E'1 increases. Conversely, for the Danube aeolian samples, CW-OSL sensitivity increases as E'1 decreases. Overall, when considering the downstream direction, an increase is observed in the 110°C TL, E'1, CW-OSL, and LM-OSL fast component values for

both the Tisza and the Danube. However, while the LM-OSL medium component and Al-h parameters decrease downstream in the case of the Danube, they increase in the case of the Tisza.

KEYWORDS: luminescence sensitivity, sediment provenance, ESR parameters, SEM, quartz grain shape

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Sediment disconnectivity drove channel morphological changes: the case studies of two rivers in the Northern Apennines (Italy)

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Structural connectivity plays a crucial role in river systems, affecting sediment supply to the channel network and influencing sediment transport within rivers. These processes have a significant impact on channel dynamics and drive landscape evolution. Alteration of sediment connectivity can lead to channel bed erosion or sediment deposition, and can alter river stability and morphology.
This study analyses the multi-temporal evolution (since 1954) of two rivers located in the Northern Apennines (Italy): the Taro River (drainage area of 2026 km^2) and its main tributary, the Ceno River (drainage area of 540 km^2). The aims are to investigate: (i) the historical channel changes in the two rivers, (ii) the factors that have driven their geomorphological evolution, and (iii) the role of the sediment disconnection caused by land use changes and other in-channel anthropogenic activities. Channel changes analysis – in term of channel width and bed level changes - was based on the analysis of multi-temporal orthophotos (1954, 1976, 1988, 1996 and 2020) in GIS environment and of topographical cross-sections. Analyses of driving factors included: (i) land use changes at the catchment scale, (ii) variations of sediment connectivity at the catchment scale (by means the application of the IC- Index of sediment Connectivity by Cavalli et al., 2013), (iii) changes in activity and in connectivity of the main sediment source areas, (iv) gravel mining activities, and (v) in-channel work constructions.
Results show some differences in the evolution of the 2 rivers. In particular, channel changes were more intense in the Taro River that alternated phases of narrowing (up to 50% in 1996, with respect to 1954) and widening. The Ceno River progressively narrowed until 1996 (up to 38% with respect to 1954). Both rivers displayed widespread incision, with median values of -3.3 m (maximum of about -7 m) in the Taro River and -2.5 m (maximum of about – 3.5 m) in the Ceno River.
After the 1950s, an increase in forests has been observed in the Ceno catchment, and after the 1970s, a similar increase has been noted in the Taro catchment. This has led to a consequent decrease in agricultural areas. In addition, sediment source areas (i.e., landslides, badlands) have decreased, especially between 1954 and 1976, in both catchments. As a consequence, the overall structural sediment connectivity has decreased over time, particularly between the 1970s and 2020. This caused the sediment supply decrease in both catchments, with subsequent channel width narrowing and bed level incision. More intense morphological changes found in the Taro River were explained by the strong extraction of gravel carried out between the 1970s and the 1980s and by the construction of in-channel works since 1950s, documented only in this river.

KEYWORDS: sediment connectivity, land use changes, gravel mining, multi-temporal river dynamic

Cavalli, M., Trevisani, S., Comiti, F., Marchi, L., 2013. Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments. Geomorphology. 188, 31–41.

THEMATIC SESSION 6

EXTREME EVENTS, HUMAN IMPACT AND DENUDATION: SYNERGISTIC EFFECTS (organized by the IAG WG DENUCHANGE)

Chairpersons:

Eliza Placzkowska, Ionela Rachita, Zbigniew Zwolinski

Natural and human drivers of contemporary denudation in Mediterranean drainage basins in eastern Spain

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Denudation and the relative shares of chemical and mechanical processes and denudation are controlled by a range of environmental drivers and are in most environments and landscapes worldwide significantly affected by anthropogenic activities and disturbances. Anthropogenic pressures can significantly affect the sediment (dis)connectivity and fluxes in defined drainage areas. The Quisi, Pou Roig, and Mascarat drainage basins in eastern Spain (Calpe region) are located as neighbouring drainage-basin systems in a Mediterranean, mostly mountainous and anthropogenically modified environment. The drainage basins show significantly different characteristics. Quisi has the highest share of urbanized surface areas and has, at the same time, a comparably high availability of fine-grained sediments. Pou Roig and Mascarat have large shares of terraced surface areas, with Mascarat being the steepest of the three drainage-basin systems. The three intermittent streams drain directly into the Mediterranean Sea. The selected study areas are characterized by a mild Mediterranean climate with a mean annual air temperature of ca. 18°C and a mean annual precipitation sum around 435 mm. During the coldest months (January, February) frost and snow can occur in the highest elevations although the mountain ranges are situated close to the coast. In contrast, maximum summer temperatures (July, August) can easily exceed 30°C and south-facing hillslopes and rockwalls are exposed to high solar radiation. The lithology in the area is clearly dominated by marine limestones. Elevation ranges from sea level up to 1126 m a.s.l. Relevant geomorphological processes include chemical and mechanical weathering, rockfalls, debris flows, splash and slope wash, fluvial erosion, and fluvial solute, suspended sediment and bedload transport.

This ongoing GFL-research (since 2018) is focussed on the detection of sediment sources, sediment (dis)connectivity, spatiotemporal variability and rates of contemporary denudational processes and land-to-sea solute and sedimentary fluxes. Our work includes detailed field and remotely sensed geomorphological mapping and computing of morphometric drainage basin parameters, combined with the statistical analysis of high-resolution meteorological and rock-temperature data, and the observation and monitoring of sediment-transfers, runoff and fluvial-transport events. In the field, we are using a combination of different observation, monitoring and sampling techniques, including different tracer techniques and sediment traps in stream channels, remote time-laps cameras, and event-based high-resolution field monitoring combined with frequent water and sediment samplings.

Sediment connectivity is significantly reduced by extended terraced areas within the drainage-basin systems, particularly in Pou Roig and Mascarat. Sediment transfers, the intermittent runoff, and fluvial transport and land-to-ocean fluxes are almost entirely controlled by larger pluvial events. High runoff during extreme rainfall events forms a relevant hazard particularly in the lower parts of the drainage-basin systems. Mechanical fluvial denudation shows a clearly higher spatiotemporal variability than chemical denudation, with the highest rates of mechanical fluvial denudation being measured in the Quisi drainage basin. Altogether, drainage-basin wide chemical denudation dominates over drainage-basin wide mechanical fluvial denudation which is explained by partly limited sediment availability, sediment deposition and short- to long-term sediment storage at numerous defined locations within the drainage-basin systems, and by the predominant marine limestones found in the drainage-basin areas.

KEYWORDS: natural and human drivers, sedimentary fluxes, solute fluxes, denudation, Mediterranean

The extreme meteorological event of 29th-30th June 2024 in the Western Italian Alps and the effects on tourist settlements

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According to the IPCC reports, the recent trend of extreme meteorological events is showing an increase in frequency. During 2024 the Italian Alps were hit by several rainfall and storm events that caused serious problems to human settlements on the territory. Accompanied by late-spring snowfalls, very high zero-point temperature level (above 4000 m a.s.l.) and consequent snow and glacier melting and permafrost degradation, intense rainfalls can be considered as responsible factors for the triggering of diffuse mass wasting events. The focus of this contribution is related to the extreme meteorological event occurred on 29th-30th June in the Western Italian Alps. Several tourist destinations were hit by debris flows mainly, but also by floods, and sediment connectivity between proglacial areas and downvalley regions suddenly increased during the event in several locations. 5 sites are considered for this analysis: Cogne and Cervinia (Aosta Valley), Macugnaga and Alpe Veglia (Ossola, valley, Piedmont Region) and Alagna (Valsesia, Piedmont Region). In all the study cases, the accessibility for visiting sites of the geological and geomorphological heritage has been seriously damaged. Meteorological data for these areas were collected from various automatic weather stations within the regional networks of the Aosta Valley and Piedmont Regions. This data was then analysed to assess extreme weather events. Field survey using traditional and digital technologies have been performed to make an inventory of the effects of the events updating the geomorphological maps available, to analyse the source-to-store paths. The analyses were focused especially along tourist trails and thematic itineraries, but also on anthropic structures in general. For instance, in the Cogne valley, besides the great issues the villages and the roads underwent (the municipality was isolated for 1 month due to road destruction), the thematic trail "The garden of the glaciers" is temporarily not walkable in some sections due to several landslides from the head of the basins (e.g., proglacial and periglacial areas), which induced high solid discharge, huge debris flow deposits and floods in the valley, associated to the destruction of the trail infrastructures (i.e., trails, bridges). Despite the great efforts of local population to restore the pre-event conditions, the effects are still affecting the community during the winter season from a socio-economic point of view, since some nordic ski trails have been seriously damaged in the valley. A different iconic situation is the Cervinia area, where, despite the intense event, the economic impact of the debris flow on skiing activities was averted thanks to significant and costly restoration works on two ski slopes. The future climatic scenarios request, hence, for investigating to find suitable strategies for the management of such kind of extreme events also in touristic areas.

KEYWORDS: climate change, extreme meteorological events, geomorphological hazard, touristic trail network

Human impact and erosion susceptibility in high mountain areas: a case study of ski resorts in the Rhaetian Alps

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Human activities in high mountain regions can trigger and accelerate irreversible transformations of the terrain, especially when exacerbated by extreme hydrometeorological events. Zones lacking permanent vegetation cover are particularly prone to intensified morphogenetic processes such as surface runoff, mass movements, nivation, and deflation. This study aimed to compare areas susceptible to erosion on ski slopes at the Carosello 3000 and Mottolino resorts in Livigno, located in the Rhaetian Alps (Italy). The analysis focused on assessing changes in zones with discontinuous or absent vegetation cover, as well as alterations in forested areas due to the development of ski and bike infrastructure.

The study utilized aerial orthophotos from 2003, 2007, 2012, 2018–2019, and 2021, with resolutions of 1 m, 0.5 m, 0.5 m, 0.2 m, and 0.2 m, respectively, processed in ArcGIS Pro. Orthophotos from 1975 (0.3 m resolution), accessed via the Lombardy Region geoportal, were also used to analyze forest cover changes. Results showed a significant local increase in zones susceptible to erosion from 2003 to 2021, primarily due to vegetation removal or reduction associated with the development of tourist infrastructure, new ski slopes, and bike trails. Forest fragmentation was also observed in specific areas.

Field observations revealed that summer vegetation recovery is hindered by cattle grazing on slopes utilized for tourism. Unregulated expansion of tourist infrastructure and increased visitor activity in high mountain environments can lead to substantial, irreversible changes in ecosystem functioning, potentially reducing local biodiversity. In addition, a multitemporal analysis of historical aerial imagery and satellite data were conducted to analyze the evolution of the tree line in the area and the NDVI (Normalized Difference Vegetation Index). The study considers how the tree line varies based on anthropogenic impacts, including ski activities and the mowing of grasslands. This approach aims to understand how the landscape evolved, focusing on changes in vegetation dynamics and environmental conditions.

KEYWORDS: human impact, ski resort, tourist infrastructure, morphogenetic processes, Rhaetian Alps

Human geomorphology of the Cancano and San Giacomo reservoirs area (Northen Italy): a multitemporal analysis of landscape transformation in the Central Alps

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This study investigates the human geomorphology of the Cancano and San Giacomo reservoirs in the Fraele Valley (Upper Valtellina), central Italian Alps, based on the geomorphological evolution of the area after dams construction on the upper reaches of the Adda River. It was carried out in the framework of the GEOTRes (Geoheritage threating and resilience: mapping the impact of geomorphic and human processes in sensitive morphoclimatic environments" projects supported by MUR, PRIN2022 PI. R.S. Azzoni). Using a multitemporal analysis of historical maps (1885, 1931), aerial and field imagery (1930, 1945,1953), and comparisons with present-day high-resolution satellite data, we reconstructed the pristine fluvial landscape and its transformation after human interventions. The analysis of cartographic and photographic datasets reconstructs the pre-dam landscape providing insights into the natural setting of the Adda River and its associated landforms prior to significant anthropogenic changes. This historical perspective traces the river's evolution from a natural, dynamic system into a highly regulated environment tuned by human infrastructure. The construction of three major dams—Cancano I Dam (1920-1928), Cancano II Dam (1953-1956), and San Giacomo Dam (1940-1950)—caused substantial modifications to the river's dynamics, resulting in alteration of the hydrological regime, submerging vast areas of the valley, and capturing of local streams. This highlights a dramatic reshaping of the region's geomorphological process. New landforms, including terraces and modified riverbanks, reshaped as a direct consequence of these changes. This study highlights the role of dams and reservoirs on the Alpine landscape, emphasizing the long-term consequences of human activities on fluvial systems and their geomorphological evolution. As a consequence, the construction of dams significantly influencing the dynamic of the critical zone and triggering new landscape processes.

KEYWORDS: human geomorphology, geomorphic process, dams, Adda River, alpine region

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Extreme erosion in the Carpathians - long-term research on experimental plots

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Soil erosion is a critical factor contributing to land degradation, especially in mountainous regions. The aim of the study was to evaluate the dynamics of surface runoff and soil erosion in the Polish Carpathians using data collected over more than 30 years from experimental plots. The research focused on identifying the threshold for extreme soil erosion on agricultural slopes. Field experiments were carried out in the mountain catchment on plots cultivated with potatoes, cereals, and grassland. The results showed that the average annual soil erosion on potato plots reached 25.67 Mg ha^{-1} $year^{-1}$, significantly exceeding the erosion levels on cereal and grassland plots. Principal component analysis highlighted the influence of precipitation, soil properties, plant growth stages, and farming practices on erosion intensity. Statistically significant positive correlations ($p<0.05$) were found between soil erosion, total precipitation, and surface runoff. A multi-year study has identified rainfall thresholds for soil erosion and calculated extreme soil erosion thresholds for a single event and total annual soil erosion. These long-term experimental studies are essential for guiding sustainable agricultural practices and land management in mountainous environments.

KEYWORDS: soil erosion, land degradation, experimental plots, agricultural land, mountain

Impact of rainfall erosivity indices (EIt) on soil erosion in a small lowland catchment in Western Pomerania, Poland

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Soil erosion by water is a key factor driving landscape changes in lowland geoecosystems of Central Europe. The process is influenced by rainfall, soil susceptibility, relief, land use and anti-erosion treatments. This study investigates the relationship between rainfall erosivity indices (EIt: EI5, EI10, EI15, EI20, EI30, EI60) and soil erosion in the Chwalimski Brook catchment (NW Poland). Long-term observations and quantitative measurements spanning 16 hydrological years (2001–2016) form the basis of this analysis.

Annual rainfall erosivity (EI30) ranged from 144.7 to 782.1 MJ mm ha^{-1} h^{-1}, while soil loss varied from 0.074 to 4.471 kg m^{-2}. Significant variations were observed in rainfall erosivity indices, with EI5 exhibiting the highest annual mean (459.8 MJ mm ha^{-1} h^{-1}) and EI60 the lowest (271.7 MJ mm ha^{-1} h^{-1}). Despite strong correlations among the EIt indices (R^2 = 0.96–0.99), their effectiveness in predicting soil erosion and surface runoff differed. The relationships between EIt indices and soil loss were notably stronger (R^2 = 0.50–0.53) compared to those with surface runoff (R^2 = 0.23–0.28). These differences highlight that while rainfall erosivity strongly influences both processes, its impact on soil loss is more pronounced than on surface runoff.

The seasonal contrast in rainfall erosivity was evident, with average monthly EIt values significantly higher during the summer half-year compared to the winter months. Rainfalls occurring from June to August exhibited the greatest erosive power, followed by those in May and September, while rainfall from November to April had negligible erosive impact.

The study also highlighted the critical role of individual erosive rainfall events in driving soil erosion, with extreme years such as 2002 resulting in significant soil loss (almost 5 kg m^{-2}) and visible rill erosion on slopes. While the average annual soil loss at the black fallow site was 0.732 kg m^{-2}, this value underscores the importance of erosive events during periods of insufficient vegetation cover. These results emphasize the limitations of relying solely on annual precipitation totals for soil erosion estimation. Instead, the detailed analysis of rainfall intensity and erosivity indices, particularly EIt, is essential for assessing soil erosion risks.

The findings highlight the need for comprehensive, multiyear field studies conducted under standardized conditions to better understand the interplay of rainfall erosivity and land cover, particularly vegetation's protective role. Although modelling offers valuable insights, it cannot fully substitute for field measurements, which remain crucial for accurately determining the contribution of soil erosion to the modern denudation system and guiding effective land management strategies.

KEYWORDS: rainfall erosivity, soil erosion, soil loss, surface runoff, Western Pomerania

Tracing high-energy transport: microtextures of quartz grains in glacial lake outburst flood sediments from NE Poland

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Quartz is one of the most common minerals in sediments and rocks, and its surface can record environmental changes related to sediment origin and post-sedimentation processes. Analysis of microtextures of quartz grains by scanning electron microscopy (SEM), particularly in the sand-sized fraction (0.5-0.8 mm), allows the reconstruction of the environment in which sediments were transported and deposited (Mahaney, 2002; Vos et al., 2014). The subject of this study is the quartz-rich clastic sediments of a glacial-lake outburst flood (GLOF) that occurred at the end of the last glaciation in NE Poland (the so-called Suwałki Megaflood; Weckwerth et al., 2019). Detailed analyses of microtextures on quartz grains were carried out on sediments forming megadunes, whose ridges are perpendicular to the GLOF palaeoflow direction.

Sediments from four study sites representing GLOF megadunes sand weges and coversands were analysed. A total of 11 samples, including 220 quartz grains, were examined using SEM. Microtextures were divided into mechanical and chemical categories, following the scheme of Vos et al. (2014). SEM analysis revealed a range of microtextures, focusing on mechanical features, such as small (<10 µm) conchoidal fractures, potentially indicative of high-energy environments like GLOF. These fractures were at the edges of grains with minimal relief, often overlaying larger glacial conchoidal fractures. The most common mechanical structures observed included both large (>10 µm) and small (<10 µm) conchoidal fractures, as well as linear steps. These features were most prominent in the GLOF sediment grain samples.

SEM analysis indicates that GLOF sediments exhibit high microtextural variability, which may distinguish this environment from others. Quartz grains from these sediments showed a complex history of glacial, fluvial, and aeolian processes, with a clear contribution from glacial processes in some samples. In addition, quartz grains from sand wedges and coversands exhibited features indicative of post-sedimentary environments, such as periglacial and aeolian processes. The dominant characteristics of these grains include bulbous edges, percussion marks, and chemical features such as precipitatation or dissolution etching. Furthermore, silica precipitatation on the grains suggest the influence of periglacial processes (Dietzel, 2005; Woronko and Hoch, 2011).

Acknowledgements: The presented research results are the outcome of the National Science Centre grant (no. 2018/31/B/ST10/00976), entitled "Geomorphological evidence and palaeogeographic implications of catastrophic floods and glacial charges of the southern sector of the Scandinavian ice sheet in the Late Vistulian (MEASSIS)".

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KEYWORDS: microtextures of quartz grains; glacial-lake outburst flood; SEM analysis

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Geomorphic response of highly confined fluvial systems to severe storm events, Northern Apennines

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On May 1-3, and May 16-17, 2023, the eastern portion of the Emilia-Romagna region experienced two severe consecutive storms. Within 48hrs, each of them poured respectively about 200 mm and 250 mm of rain, with an estimated combined return period >500 years. The mountain streams hit by one or both storms are typically characterized by nearly complete (i.e., close to 100%) lateral confinement. At the headwaters, confinement is associated with entrenched bedrock meanders (i.e., marl-sandstone alternations), and becomes increasingly anthropogenic (i.e., bank protection structures and levees) across the mid to distal reaches, as one approaches the main Po River floodplain in Romagna, where the cities of Faenza, Forli, and Cesena are located. This structural arrangement, together with a post-WW2 history of gravel mining, has led to generalized depletion of alluvial storage, drastic narrowing, and widespread channel incision into weak pelitic bedrock, giving rise to vulnerable fluvial systems that nowadays hold little room for lateral migration and natural adjustment. In this contribution, we examine the effects of the May 2023 storms on the planimetric and topographic changes of highly confined streams in Romagna. In selected stream channels, we aim to: (1) reconstruct the 1954-2020 planimetric evolution of the active channel bed; and (2) evaluate the planimetric and topographic changes occurred immediately after May 2023, and the relevant state of recovery after one year (i.e., May 2024), in relation to natural and anthropogenic confinement. Methods include multi-temporal mapping of the active channel bed – including the characterization of the relevant margins (e.g., natural vs artificial; confining vs. open) – on sequential sets of aerial photo stereo pairs and ortho mosaics, followed by geomorphic change detection performed on sequential LiDAR-derived DTMs. We start by looking at the Savio River, which was struck by the second event only, and proceed westward with the Senio River that shares same lithology, channel typology, and degree of confinement, but was affected by both storms. Preliminary results across the 39 study reaches show that the Savio River may be split into two main segments with respect to the active channel widening occurred between May 2020 and June 2023. Specifically, in bedrock and mixed bedrock-alluvial reaches (i.e., 1-24) median channel width increased temporarily by 16%, whereas further downstream, in purely alluvial reaches (i.e., 25-39), this estimate increased by 82%, where the river in places breached and/or bypassed levees, flooding the alluvial plain in and around Cesena. By May 2024, we found that in reaches 1-24, median active channel width had remained 12% wider than in May 2020, whereas in reaches 25-39, this relative widening had dropped to just 6%. Comparative (currently incomplete) analysis across the Senio River reaches points to a combined larger flooded area and to greater damage brought to bank protections, which resulted in local avulsions and more permanent channel widening. Ongoing DoD analysis on the active channel footprints will constrain the volumetric budget associated with the storm events and the relevant degree of (im)balance attained after one year.

KEYWORDS: severe storms, active channel, confinement, planimetric adjustment, topographic change

Changes of the stabilized cliff coasts of the Szczecin Lagoon (Wolin Island, Poland)

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The Szczecin Lagoon is a relatively young reservoir, whose evolution took place mainly during the Holocene. During the Littoral transgression (about 6200 years BP), the area was a bay of the Littoral Sea. The systematic sea level rise caused intensive abrasion of the cliffs, resulting in the formation of a series of moraine cliffs on the northern shores of the gulf. As a result of the influence of littoral currents and the continuous development of the South Baltic coastal zone, the bay was cut off from the Baltic by spit forms and turned into a lagoon. Currently, the denudation system of the cliff coast of the Szczecin Lagoon is characterized by continuous changes caused by, among other things, abrasion, mass movements and water erosion, but these changes are not as dynamic as on the cliffs of the open sea. So far, there have been no studies in the literature on the dynamics of the cliff coast of the Szczecin Bay and the factors that determine the functioning of their denudation system. This prompted us to take a closer interest in this issue and fill the existing lack of knowledge. Our activities focused mainly on determining the morphological and morphometric conditions of the cliff slope system and analyzing the volumetric changes in the slope caused by denudation processes.

Analyses of the cliffs were carried out using LiDAR (ALS) data from 2011-2021, for the coastal fragment between the villages of Lubin and Karnocice (4.5 km), located on the southern shore of Wolin Island. The data were obtained from the national geoportal and the Maritime Office in Szczecin.

Based on the obtained DEM models, the morphological conditions of the studied coastal stretch were determined, along with models of morphometric parameters and morphological profiles.

The magnitude of volumetric changes within the cliff coast was calculated using Geomorphic Change Detection (GCD) software. The result of the calculations is quantitative data in tabular form and a DoD model describing the changes that occurred during the analyzed time interval.

Using the values of the indices Lb [m^3/m] - the balance of sediment per 1 m of coastal length and Ab [m^3/m^2] - the amount of sediment eroded per unit area of the cliff, a typology of cliff coastal dynamics was proposed and a comparative study was carried out with the results obtained on the cliffs of the open sea.

KEYWORDS: cliff coast, Szczecin Lagoon, denudation system

Source apportionment of solutes in a headwater stream: identification of runoff components

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Human-induced factors, such as land use and land cover changes or climate change, significantly influence denudation processes. One such process is chemical denudation, which, due to its relatively slow rate and underestimated effects, remains under-researched in terms of the impact of these factors. However, in recent years there has been a growing interest in this topic resulting in research initiatives such as the Critical Zone Network (CNZ) and Integrated European Long-Term Ecosystem Research (eLTER). The rate of chemical denudation is primarily governed by subsurface properties, such as bedrock lithology, solubility, soil thickness, and subsurface flow conditions. These factors play a dominant role in shaping the chemistry of surface water, which in turn determines the rate of chemical denudation. In contrast, surface properties such as vegetation cover, precipitation, or air temperature play a secondary role, as not all runoff components are equally affected by these surface factors. As such, studies on changes in the rate of chemical denudation should first focus on identifying subsurface flow conditions and the distinct components of surface runoff. This approach is being tested using the Wüstebach experimental catchment, part of the Terrestrial Environmental Observatories (TERENO) in Germany. The study aimed to identify the individual components of surface runoff through the source apportionment of solutes in the stream. To this end, hydrological data (stream flow, water temperature, pH, and water conductivity) and hydrochemical surface water monitoring data (ion concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NO_3^{-}, SO_4^{2-}, Cl^{-}, HCO_3^{-}, and DOC) were used for statistical modeling. The Positive Matrix Factorization (PMF) model was applied to reduce the complexity of surface water chemistry data by identifying source contributions – combinations of species that represent different runoff components. Based on the PMF model, four factors (source contributions) were identified, each corresponding to a distinct component of runoff: 1) summer component (base flow) characterized by high contributions of Ca, Mg, Cl, water conductivity, Na, and high water temperature; 2) winter component (interflow) characterized by high contributions of pH, K, water conductivity, Cl, Na, Mg, Ca, SO_4, and DOC; 3) rapid sub-component of the summer component (quick-flow) characterized by high contributions of DOC, water temperature, and HCO_3; 4) bioactivity component (interflow related to catchment biological activity) characterized by high contributions of NO_3, HCO_3, SO_4, and pH. The bioactive and winter components, being associated with shallow subsurface flow, appear to be the most responsive to surface factors and thus most suitable for assessing changes in the rate of chemical denudation due to shifts in land cover or climate.

KEYWORDS: runoff components, surface water chemistry, chemical denudation, PMF model, TERENO

Temporal trends of extreme avalanche events in recently deglaciated areas of Greater Caucasus Mountains

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Snow avalanches are a widespread geomorphic process occurring in both glaciated and deglaciated high-mountain environments. In glaciated mountain areas, snow avalanches are known to be one of the main contributors to glacier mass-balance and to the transfer of on-glacier debris cover, while in the recently deglaciated areas they frequently disturb the forest ecosystems. In remote mountain areas, the spatial and temporal occurrence of snow avalanches remains largely undocumented. This study aims to reconstruct the spatio-temporal variability of snow avalanches and to assess trends in snow-activity activity in recently deglaciated high-mountain environments, in the context of the ongoing climate changes. To this end, a tree-ring approach was developed to reconstruct the frequencies of large-magnitude snow avalanches in deglaciated areas of the Greater Caucasus Mountains. Tree-ring approach is based on the identification of growth anomalies recorded within the annual rings of the trees disturbed by snow avalanches. In this study, tree-ring methods have been applied to reconstruct past avalanche activity within two adjacent avalanche paths. Trees living within these two avalanche paths, which exhibit clear external signs of disturbances due to the mechanical impact of snow avalanches were sampled, and the growth anomalies (scars, traumatic resin ducts, compression wood and growth suppressed rings) identified within their annual rings served to reconstruct the history of extreme snow-avalanche events with an annual resolution. Reconstructed frequencies indicate a general decreasing trend of large snow avalanche occurrence over the last decades. Further similar studies extended to other avalanche paths in deglaciated areas of Greater Caucasus Mts are needed, to assess the long-term frequency trend in snow-avalanche activity at a regional scale.

KEYWORDS: snow avalanches, tree rings, deglaciated areas

Unravelling sediment dynamics in the Sikkim-Darjeeling Himalayas: extreme events, human impact, and hydrological alterations

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The Sikkim-Darjeeling Himalayan region is one of the most dynamic sediment-producing environments in the world, shaped by extreme hydrometeorological events, tectonic activity and increasing human intervention. This study provides a preliminary assessment of sediment dynamics in the Himalayan part of the Teesta River catchment (~8150 km^2), highlighting the interplay between natural and anthropogenic factors that control sediment transport. The analysis examines major sediment sources, reconstructs past variations in sediment fluxes, and assesses the impact of large-scale dam construction on sediment transfer. Extreme rainfall events and glacial lake outburst floods (GLOFs) play a crucial role in sediment mobilization. The catastrophic flood of 4 October 1968 significantly increased sediment fluxes, with elevated loads persisting for over a decade. Following extreme events, suspended sediment loads (SSL) in the Teesta catchment can reach four times the average, with annual sediment yields peaking at 20,000 t/km^2, among the highest in the Himalayas and globally. More recently, the 3-4 October 2023 GLOF from South Lhonak Lake mobilised an estimated ~270 million m^3 of sediment along a 70 km stretch of the Teesta River. This event resulted in extreme sediment bulking with a fivefold increase in flow volume, causing severe bank failures and landslides. Beyond extreme events, contemporary human activities exacerbate sediment production. Deforestation, road building and slope undercutting continue to destabilize slopes and increase sediment yield. However, the most profound anthropogenic change has been the construction of 13 dams over the last three decades, which have disrupted sediment transport along 70% of the main Teesta River and its largest tributaries. These reservoirs selectively trap coarser sediments, reducing SSL in the Himalayan piedmont. The efficiency of sediment management in reservoirs, coupled with irregular extreme events, will determine future sediment transport patterns.

KEYWORDS: suspended sediment, extreme rainfall, GLOF, dams, Teesta River

Reconstruction of snow avalanche activity revealed by tree-rings in Piatra Craiului Mountains (Southern Carpathians, Romania)

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Piatra Craiului Mountains (Baciului Peak 2238 m a.s.l, Southern Carpathians) is a calcareous ridge, oriented NE-SW which corresponds to a remnant flank syncline structure. Steep bedrock walls are common features below the calcareous ridge area, while a debris mantle covers the lower slope sectors. On both eastern and western slopes of mountain flanks, snow avalanches (SAs) are the dominant geomorphic process. SAs are naturally triggered from release zones covered by alpine meadows and subalpine shrubs between 2000 and 1850 m asl. Once released, they pass through forested slopes mainly composed by Norway spruce (*Picea abies (L.) Karst.*) reaching the valley bottom below 1400 m asl. The evidence of SA activity comes both from the presence of damaged forest stands, and from past events witnessed by National Park rangers and tourists. However, historical records regarding the past SA activity remains poorly documented. In such areas, dendrogeomorphic method can provide valuable information about the proccess frequency. The aim of study was to reconstruct the SA past activity along two paths located in the eastern slope of Piatra Craiului Mts. as recorded by tree-rings. In total, 235 heavily disturbed trees were sampled along the two investigated paths: 109 trees sampled within path (1) and 126 trees sampled within path (2). The sampling collection includes 402 increment cores and 34 stem discs. The analysis of growth disturbances indentified within tree rings allowed the reconstruction of a minimum 8 events in path (1), and 10 events in path (2), spanning the common 1950–2014 period. In the case of both paths, the first reconstructed event was in 1985. For path (1), the last event revealed by tree-ring analysis is 2009, while for path (2) the last reconstructed event is 2011. We assume that tree age is the main factor limiting identification of a higher number of event years and of a longer reconstructed period. The reconstructed 1997 and 2005 events were confirmed by the archival records, which reported multiple material damage and fatalities. The spatial distribution of trees showing growth disturbances in a specific year has been used to estimate the minimum SA extent for each reconstructed avalanche event. No particular pattern of snow avalanche activity in the different sectors of the investigated paths were identified. We assume that, during the recorded events, SAs spread downslope along the entire path. Dendrogeomorphic methods should be used systematically in the study area to add more evidence on the spatial extend of past geomorphic activity. This will further help to estimate avalanche return periods within the avalanche paths which are mandatory for hazard zoning purposes and risk management in area.
This work was supported by a grant of the Ministry of Education and Research – UEFISCI, project number PN-IV-P8-8.3-PM-RO-BE-2024-0012, within PNCDI IV.

KEYWORDS: snow avalanche, frequency, tree ring, Piatra Craiului Mountains

Climatic and anthropogenic drivers of Holocene dune formation in the Carpathian Basin

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Investigating past geomorphological processes can provide in-sight into the environmental parameters affecting the development of the present landscape. Aeolian activity in the past affected vast areas of alluvial fans built by rivers of the Carpathian Basin. Generally, the main period of aeolian activity is suggested to be in the LGM. However, there are numerous pieces of evidence that dune formation renewed several times during the Late Glacial and even during the drier phases of the Holocene. Nevertheless, earlier the timing of aeolian phases was assessed based on geomorphological analysis and a limited number of radiocarbon data. In the past decade, a growing number of OSL age data has been published from these areas, mostly by the Luminescence Dating Laboratory of the University of Szeged. The present study aims to assess the spatial and temporal differences in aeolian activity on the major dune fields of the Carpathian Basin by summarising and numerically analysing over 250 luminescence ages obtained from parabolic dunes and interdune areas. Based on the results, it was possible to reconstruct the timing and intensity of dune formation over the basin, and several minor reactivation events in the Holocene, which can mostly be related to the superposition of climatic events and human activity.

Evolution of the anthropogenic relief of the Bełchatów and Szczerców Outcrops (central Poland)

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This presentation analyzes the relief changes associated with the Bełchatów Open-Cast Lignite Mine. It is the only site in Poland visible from space. The relief changes result from the formation of two concave and two convex landforms. The concave landforms include the Bełchatów and Szczerców Outcrops. The Bełchatów Outcrop is 8.5 km long, 3.25 km wide, and 310 m deep, making it one of the deepest of its kind in Europe. The Szczerców Outcrop is approximately 6 km long, 3.5 km wide, and 120 m deep, with a planned final depth of 330 m. The convex landforms are dominated by Kamieńsk Hill, the largest man-made hill in Central Europe – a former external dump – which has reached an elevation of 395 m a.s.l. (approximately 200 m above the surrounding terrain). The second hill, Szczerców Hill, is still rising and currently reaches about 170 m (304.03 m a.s.l.). Mining began on June 6, 1977, in the eastern part of the mining complex (Bełchatów Plateau, Bełchatów Outcrop) and is expected to continue until 2038 in the western part (Szczerców Basin, Szczerców Outcrop).

For this study, Numerical Terrain Models (NTMs) covering the past 80 years were developed. These were based on archival cartographic materials and contemporary geodetic data obtained using various surveying techniques. The oldest cartographic materials include 1:25,000-scale topographic maps issued by the Supreme Command of the Armed Forces in 1944. More recent data include various NTMs, both global and local, with different spatial and temporal resolutions. These include SRTM (Shuttle Radar Topography Mission) data and models provided by the Head Office of Geodesy and Cartography (GUGiK). The scale of the maps used is 1:100.

The authors transformed morphometric data from different periods, collected using different methods and reference systems, to enable comparison. Based on the obtained raster models, differential maps (DEM of Difference) were developed, illustrating the successive stages of anthropogenic landscape transformation in the area. This allows for a quantitative assessment of the dynamics and extent of relief changes caused by mining activities.

KEYWORDS: DEM of Difference (DoD), Anthropocene, relief changes, external dump, central Europe

Spatial variation of the cliff top retreat rate of the Southern Baltic Sea (Poland)

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The Baltic Sea is one of the youngest seas on a global scale. It owes its genesis and subsequent development primarily to climate change, which contributed to the disappearance of the Scandinavian ice sheet at the end of the Pleistocene. The constant evolutionary process of the reservoir was most reflected in the formation of the coastal zone. On the coasts of the Southern Baltic, this was a period of intensive erosion, which delivered a very large amount of sediment to the sea. Cliff coasts were formed on the areas of moraine plateaus undercut by the sea, and elongated sandbanks were often formed on lower-lying areas, creating spit coasts. In general, coastal processes constantly led to the smoothing coastline. Currently, this process is continuing and manifests itself in the form of erosion of moraine plateaus and accumulation of spit sections.

The magnitude and rate of erosion of the cliffs of the Polish coast is characterized by clear spatial differentiation. This process is determined, on the one hand, by the dynamics of the sea (frequency and duration of storm surges) and, on the other hand, by the geological structure and morphometric parameters of the coast.

In the previous studies on the dynamics of the cliffs of the Southern Baltic Sea, most of the studies focused on the assessment of the cliff top retreat rate using archival maps of varying accuracy. There were relatively few studies using modern remote sensing methods (e.g. LiDAR, UAV). In addition, they were limited to a small spatial range (max. several kilometers) and for different time intervals. Taking this into account, we decided to use the available LiDAR data for the entire Polish coast to analyze and classify the current dynamics of cliff shores in one time interval. The analyses covered the displacements of the cliff top over a period of 11 years (2011-2022) on 15 test sections with a length of 29 km, located on all cliffs of the Polish coast. The obtained results allowed us for the presentation of the spatial characteristics of the cliff top retreat rate in connection with the dynamics of the sea, the geological structure of the cliff and its morphodynamic type.

KEYWORDS: coast dynamics, postglacial cliffs, Southern Baltic

Seasonal variability of morphodynamic types of the southern Baltic cliff coasts under conditions of climate change

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The functioning of the contemporary morphogenetic system of the cliff coasts of the Southern Baltic Sea is conditioned by the geological structure of the cliffs and the variability of the hydro-meteorological conditions of the moderate climate zone. Lithology determines the resistance of the cliffs to degradation processes and determines the type of relief that dominates within them, while the intensity of morphogenetic processes is determined by the characteristics of weather conditions.

Based on many years of observations of the cliffs of the Southern Baltic Sea, a morphodynamic typology based on lithological and morphogenetic criteria was presented. The distinguished morphodynamic types include: clay cliffs of the rockfall-flow type, sandy cliffs of the talus-landslide type, and cliffs with a complex structure of the rockfall-landslide and landslide-flow types. In turn, the morphodynamics of the distinguished types depends mainly on the strength and nature of the impact of hydrometeorological conditions (storm surges and precipitation, wind, temperature). It should be emphasized here that the geological structure is constant, while weather and hydrological conditions change throughout the year, creating a seasonal system. Then, periods of different morphogenetic potential are clearly marked. These periods are called morphogenetic seasons. Morphogenetic seasonality therefore determines the morphological variability of the cliffs.

The basis for distinguishing morphogenetic seasons are the dominant morphogenetic processes, their intensity and course, and the related cliff relief. In the contemporary functioning of the sea coasts of the Southern Baltic Sea, the occurrence of 4 basic morphogenetic seasons is observed: autumn-winter, spring, summer and autumn. During these seasons, the above-mentioned morphodynamic types of cliffs are subjected to the impact of various morphogenetic processes, thanks to which they are subject to continuous modification.

The development of cliff relief is characterized by several-year periods of coastal stability, which are interrupted by episodes of extreme processes (high storm surges). Based on many years of research, we can state that these periods usually occur on an annual, three-year and seven-year scale.

During the period of accelerated climate change, a systematic increase in air temperature, precipitation totals, as well as the strength and frequency of storm surges is predicted. It should be emphasized that the distinguished morphodynamic types for the cliffs of the Southern Baltic will be modeled with increasing intensity in the future, and the process of passing through individual stages of development will be significantly accelerated.

KEYWORDS: cliff morphodynamics, climate change, Southern Baltic cliff coast

THEMATIC SESSION 7

FROM LAND TO BADLAND – PAST, PRESENT AND FUTURE

(organized by the IAG WG Badlands)

Chairpersons:

Milica Kašanin-Grubin, Nevena Antić, Manel Llena, Francesca Vergari, Estela Nadal Romero, Aydogan Avcioglu

Uncovering new badland sites: a study of sediment properties in Aldearrubia, Spain

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Landscapes with variety of topographical features and lithology, of accentuated roughness and colours, named badlands may occur in particular climates in unconsolidated sediments and soft rock outcrops. Badlands can be formed naturally or triggered by human activities and present possible soil degradation-erosion and soil building interaction result. Poor soils can lead to desertification and if such condition is persistent over long time and affect larger areas, especially in arid and semiarid climates, bare and eroded landscape that can could be classified as a badlands. Such sites have been found all across the world and have attracted great attention from the scientist, but there are still many the badland-like sites remain to be discovered and studied.

In this study, in addition to the already well-known Spanish badlands areas, mainly located in the eastern half of the Iberian Peninsula, sediments from three lesser-known sites have been sampled. All three sites are located near Aldearrubia, a municipality in the provenance of Salamanca, Spain. Sediments from two study sites are fine-grained sandstones and red siltstones with some crusting (possibly with addition of quartzite and lydite gravels with a red clay-sandy matrix), surrounded by shrubs or irrigated land. The third site consists of red grained sandstones and clay silts with siliceous sands surrounded with leafy species.

For further physico-chemical characterization of these sediments, weathered and unweathered samples were taken from the top, middle and bottom of the slope of each site. Preliminary results suggest that the electrical conductivity values do not differ from the those of other well-known badlands described in literature, while pH values and CaCO3 content make a distinct difference. The sediments from the shrub- or irrigated land-surrounded sites are acidic, with pH values ranging from 5.67 to 6.95 and no carbonates. In contrast, the site surrounded by leafy species has pH values ranging from 6.03 to 8.99 and contains between 3-10% CaCO3.

Such preliminary results raise new questions, considering that known badlands are typically clayey silts to silty clays with pH values ranging from 8 to 10, and in those with carbonates, their content is higher, indicating the possible presence of carbonate-driven chemical weathering. Further investigations could provide a deeper understanding of the characteristics of these lesser-known sites and help determine whether they can be classified as badlands.

KEYWORDS: badlands, sandstones, chemical properties

Exploring volcaniclastic badlands: insights from Kazar and Djavolja Varos, Serbia

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Often described as natural field laboratories, badlands can develop under different climatic conditions. Badlands materials have a specific combination of physico-chemical properties depending on their mineralogical composition and they are mainly silty clays and clayey silts, but can also be material of volcaniclastic property. Worldwide known site of this type is Cappadocia, Turkey, while less known sites are Kazar badlands in Hungary, and Djavolja varos in Serbia.

In this research eight volcaniclastic rock samples from two neighbouring countries were analysed with the idea to broaden existing knowledge on materials in which badlands can form. Petrographic characterization, content of macro-elements, pH, electrical conductivity, sodium adsorption ratio and immersion test that were conducted on these samples.

Both of analysed badlands are acidic to intermediate acidic volcano-clastic sediments and based on the petrographic analysis samples from Hungary are typical porous tufts, while samples from Serbia are more compact hydrothermally weathered silicate tuff rich in quartz and characterized by intensive secondary sillification. Both their grain size distribution is of a similar texture and seem like other badlands that are silty clays to clayey silt materials and according to the sodium adsorption ratio they present potentially dispersive to dispersive material.

Since both sites contain material that could potentially be dispersive, and based on the similarities and differences observed from previously measured parameters, a short immersion test was performed on all eight samples. The results of the immersion test and all analyses suggest that the decomposition processes at both Kazars and Djavolja Varos in the natural environment are not extensive; weathering does not affect the deeper layers of these sediments; chemical weathering is predominant in Djavolja Varos, while mechanical weathering dominates in the Kazar badlands; and that the weathering rind and sillification processes, mechanisms occurring in these samples should be considered as characteristic features of the badlands material.

This study raises new scientific questions and suggests that, although volcaniclastic material is specific, it is "bad" enough to create unique badland formations.

KEYWORDS: badlands, volcaniclastics, weathering

An integrated expert-based methodological framework to map badlands in different morpho-climatic contexts: preliminary results

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Badlands are among the most complex soil and sediment erosion landforms and are widespread worldwide across different morpho-climatic contexts. In recent decades, several authors have mapped badlands based on field surveys, stereo-orthophotos, Google Earth imagery, topographic land surface models and other remote sensing data acquired from various platforms. The mapping approach is usually chosen based on a combination of badland occurrence and with the availability of data in specific study areas.

Different mapping methods were implemented by considering the entire badlands watershed, the badlands' erosion landform (including or excluding the vegetation growing inside badlands) and finally considering or not the badland's sub-watershed.
The mapping approach is the base on which further studies on landforms (e.g., susceptibility models, geomorphological dynamics etc.) are carried out. Thus, significant differences in mapping methods may lead to considerable variations in the model outputs.
The work here proposed aims to introduce an expert-based method to map badlands in different morpho-climatic contexts in a standardized way. The methodology was tested in a representative area close to Montalbano Jonico (MT), Basilicata Region, Southern Italy. In this area, the stratigraphic interval represented by the Ideal Section (IS) has been recently designated as a Standard Auxiliary Boundary Strato-type (SABS) for the Global Boundary Stratotype Section and Point (GSSP) of the Middle Pleistocene Subseries/Subepoch and Chibanian Stage/Age at the Chiba section, Japan.
The expert-based methodology was developed in collaboration with the IAG Badlands Working Group and aims to address the following questions: i) Is it possible to univocally map the badland surface in different morpho-climatic contexts in a globally consistent way? ii) Can a landform database be defined that contains basic morphological, lithological and morphometric features that allow homogenisation of the data associated with each mapped landform?
Three different badland types were defined based on mapping scale and morphological characteristics: i) Isolated Badlands, ii) Badland Surfaces, iii) Badland Landscapes. In addition, a specific geodatabase was associated with each mapped landform, implementing geological, climatic, and morphometrical attributes to obtain a useful database for each landform. The proposed methodology aims to standardize the mapping approach by defining cartographic and geomorphological rules that could allow for creating a homogeneous badlands inventory map at a global scale.

KEYWORDS: badlands, geodatabase, inventory map, mapping

Assessment of pseudo-badlands forms and features through multi scale-multi sensor geomorphological approach in alpine context: the 'Becca d'Aver DsGSD' case study, Aosta Valley, (Italy)

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The aim of this work is to characterize the pseudo-badlands morphology associated with deeply altered bedrock materials in a deep-seated gravitational slope deformation context through an integrated geomorphological approach. The area covers approximately 11.5 km^2 representing the Cretaz-Comba Basset basin, a portion of slope on the left side of the Aosta Valley, Norther Italy. The study area is characterized by several gravitational and runoff associated processes that interact with villages and anthropogenic structures. Moreover, semi-consolidated scree slope, glacial deposits as well as muck deposits mantle the area supplying sediments that can be eroded and transported as debris flow. However, pseudo-badlands landforms represent the main source of sediments providing loose materials highly connected with the main drainage system. The outlet of the basin reaches the village of Champagne built on an active fan. For this reason, a detailed geomorphological characterization of active landforms is essential to understand the potential geo-hydrological risk in the area.
The pseudo-badlands forms and features were mapped through field survey, Google Earth, remote sensing interpretation. In addition, a detailed geomorphological map was realized applying the MorphDB (Bosino et al., GFDQ). Furthermore, the geological strength index (GSI) was applied to evaluate discontinuity conditions of the rocks cropping out in the pseudo badlands systems.
Finally, dedicated terrain analysis, connectivity index model and remotely sensed data were applied to highlight the contribution of pseudo-badlands in sediment transport. In particular either radar and optical remote sensing data were implemented to support the mapping operations. On one hand, InSAR data, also through post processing tools such as Principal Component Analysis, were used to identify active sectors, on the other hand, optical multi- and hyper-spectral imagery was introduced to detect bare soil areas precisely.
The results of this study highlight how altered bedrock materials, as well as anthropogenic muck deposits can contribute to provide sediments that are related to hydrogeological risk in the area.
"This research was founded by funded and carried out in the Project FORMATION - Full cOveRage, Multi-scAle and multi sensor geomorphological map: a practical tool for TerritOrial plaNning - Progetto 2022C2XPK7_PE10_PRIN2022 - PNRR M4.C2.1.1 – Finanziato dall'Unione Europea – Next Generation EU - CUP: B53D23007010006."

KEYWORDS: pseudo badlands erosion, geomorphological mapping, hyperspectral analysis, connectivity index, WebGIS

Flood events in a Mediterranean badlands area - recording in suspended sediment concentration in an instrumented catchment

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Among the numerous erosion landscapes worldwide, badlands are characterised by particularly high erosion rates and surface dynamics. In many cases, they constitute the primary source of sediments within the catchment area. The methods used to assess sediment yield and surface changes in these landscapes can be categorised as dynamic or volumetric. The dynamic approach quantifies the amount of sediment transported from a hillslope or a catchment, while the volumetric method estimates material loss by analyzing surface changes over time. This study introduces an integrated approach to quantify the off-site effects of erosion at the catchment scale using a dynamic method while also analyzing geomorphodynamic processes at the hillslope scale through volumetric assessments.
Suspended sediment yield (SSY) and water discharge were monitored in the Scalonca stream catchment, located in the Upper Orcia Valley (Southern Tuscany, Italy). The catchment covers an area of 2.3 km^2. The catchment is predominantly agricultural - 1.02 km^2, with a forested area of 0.62 km^2 and areas without vegetation or bare soil are 0.66 km^2. The upper part of the catchment features badlands landform known as Calanchi, characterized by highly dissected, rapidly developing landscape, with rill, gully and gravitational landforms, and a dense dendritic drainage network. The presence of such formations increases the availability of fresh, unconsolidated material, which is transported by the stream out of the catchment.
SSY measurements began in December 2024, capturing the main hydrometeorological events of the 2024-2025 winter season. These events led to significant increases in suspended sediment concentration (SSC), water levels in the channel. In the Scalonca stream, the average water level was at 6.4 cm, with nephelometric turbidity of 140 NTU and a suspended sediment concentration of 6.3 g/l.
The data collected during several flood events of different intensity were statistically analysed to investigate the geomorphodynamics in the catchment and to determine the event-related hysteresis at the event level. The results show an exceptionally high variability in hydrological and SSY parameters and provide valuable insights to improve the process understanding of discharge and sediment dynamics of badlands streams. In addition, the high-resolution SfM-DTMs provided a better understanding of the morphodynamics in the catchment, supporting an integrated hillslope-channel coupling approach.

KEYWORDS: badlands, erosion monitoring, suspended sediment concentration

Image analyses as a tool for estimating fractal geometry of surface cracks in badlands

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Badlands are formed by weathering, and high erosion rates coupled with climate properties of poorly consolidated or poorly cemented materials are prerequisites for badland development. Weathering transforms the surface of the exposed sediment into a crust that is more easily eroded. The surface and subsurface cracks have an important role in infiltration and runoff generation. The surface cracks vary in size, shape and connectivity and influence material response to wetting and drying. The aim of this research is to characterize surface crust and cracks of weathered badland materials and determine whether the crack characteristics depend on lithological properties. For this purpose, image analyses of badlands field sites, and photos taken during weathering experiment conducted in laboratory conditions was used. In the experiment badland sediments were subjected to 10 cycles of simulated high intensity rainfall. Volume of collected leachate was measured, as well as electrical conductivity, sediment yield and sediment concentration after each cycle. Size, shape, connectivity, fractal properties and lacunarity of cracks were analysed on both sets of photos. Image analysis involved the use of certain procedures and filters in ImageJ software in order to obtain binary (black and white) images of satisfactory quality for the next step of the analysis. Obtained binary images were further processed in the program ImageJ plugin Using FracLac. The FracLac plugin is a collection of tools that are used to image analysis to obtain information about the fractal dimension and lacunarity. In this particular case Box-Counting method was used to determination of fractal dimension. Image analyses showed that depending on their composition, badland materials develop different crack patterns. Smectite-rich sediments developed denser crack networks, while on illite-rich sediments more uniform surfaces with thin and long cracks were formed. High correlation was determined between fractal properties and lacunarity, and leachate characteristics in smectite-rich sediments subjected to the weathering experiment. High correlation was also obtained between fractal properties and lacunarity on the surface crust seen during field work in badlands, and crust obtained during laboratory weathering experiments. Obtained results proved that image analysis is an efficient method for analysing desiccation cracks on badland materials.

KEYWORDS: image analyses, clay mineralogy, cracks, fractal geometry, lacunarity

High-detailed topographical change detection on small-scale *biancane* landscape in Basilicata region (southern Italy)

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Badlands represent natural landscape with distinctive landforms found on clayey, bare or sparsely vegetated slopes, subject to intense erosion rates that vary spatially and temporally over short distances. Erosion processes, including riling, splashing, creeping, piping, gulling and shallow landslides act on hillslopes with different intensity according to slope angles and catchment size. In small semiarid badlands catchments, these processes often occur at low intensity, making them difficult to detect and quantify. For this reason, high-resolution 3D models derived from both Structure-from-Motion (SfM) photogrammetry and Light Detection and Ranging o Laser Imaging Detection and Ranging (LiDAR) technology on Unmanned Aerial Vehicle (UAV) or from Terrestrial Laser Scanner (TLS) have become essential tools for advanced geomorphological analyses.

This study presents a multitemporal survey of a small badlands area (about 9000 m^2) near Aliano (MT), in the Basilicata region (southern Italy). Here, biancane landforms are the main morphological features, distinguished by small domes high even several meters, above gently sloping micropediments. We conducted three surveys to generate high-resolution 3D models and analyse topographical changes over a one-year period. Given the mean erosion rate in the area (approximately 2 cm/year), detecting significant changes is challenging due to processing and post-processing accuracy. To enhance accuracy, we compared two Point Cloud (PC) datasets acquired under identical UAV flight conditions and processed using consistent methodologies. This approach mitigates errors associated with raster resolution in Digital Elevation Models (DEMs) and systematic biases from RTK measurements.

Results show a heterogeneous erosion pattern on the biancane slopes, with more changes under vegetated caps. Sediment accumulation and erosional processes were also observed on micropediments at the base of the domes, though herbaceous cover influences topographic detection. Changes were considered reliable only where PC distances exceeded processing error thresholds.

Short-time monitoring of topographical changes aid to detect geomorphic processes involved in the erosion and sediment accumulation dynamics on badlands. Furthermore, detected changes can be correlated with weather events occurred between the two surveys, offering a better understanding of soil loss dynamics and sediment connectivity within the catchment.

KEYWORDS: badlands, high-detailed point clouds, change detection, erosion

Tracing sediment dynamics: present-day evolution of the Rio della Rocca badlands via multitemporal LiDAR

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Badlands are deeply eroded landforms marked by steep and unvegetated slopes with high drainage densities, and significant erosion rates. Italian badlands feature unique erosional forms known as "calanchi" that commonly develop from Plio-Pleistocene clays, making these landscapes relevant for studying geomorphic processes in regions undergoing rapid change. This study focuses on a sub-basin of the Rio della Rocca stream (a left tributary of the Secchia River, with a basin area of 7 km^2) in the northern Apennines (Italy). The selected sub-basin covers an area of about 0.074 km^2 and is distinguished by the presence of many well-developed "calanchi". The basin is characterized by low-permeability conferred by the high erodible bedrock made of clay lithologies. In this context, the temperate climate (average annual precipitation around 800 mm, average annual temperature varies between 3 °C and 22 °C) plays a pivotal role in driving erosion processes.

To investigate morphological changes in the selected sub-basin, a multitemporal analysis utilizing high-resolution topographic data from UAV-based surveys has been conducted. A first reference survey was carried out employing both LiDAR and orthophotos with RTK correction. Following photogrammetric surveys were meticulously aligned to the reference using Ground Control Points (GCPs). Our findings reveal significant seasonal fluctuations in sediment volume and surface elevation, closely correlated with precipitation intensity and frequency. Periods of heavy rainfall triggered accelerated erosion and sediment transport, reshaping the terrain and altering drainage patterns. In contrast, drier seasons exhibited relative stabilization with minimal topographic changes. The sparse vegetation cover was insufficient to protect the soil from erosive forces, exacerbating sediment loss.

These insights highlight the sensitivity of badland landscapes to the compounded impacts of climate change and human activities. The rapid changes observed in the Rio della Rocca valley mirror broader trends of badland degradation in Italy and similar environments worldwide. Understanding these patterns is crucial for informing sustainable land management practices and mitigating negative anthropogenic effects.

This work is part of the project BAD2BED - BADland morphodynamics assessment and hillslope-channel BED coupling in the context of global change.

KEYWORDS: badlands, landscape evolution, sediment dynamics, Lidar imaging

Can mineralogy explain weathering and erosion patterns in badlands?

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Badlands are dynamic landscapes with limited vegetation, minimal human activity, and in general very active geomorphic processes. As the formation and activity of badlands is influenced by factors such as lithology, weathering, and erosion, this study investigates how mineralogical and physicochemical properties influence weathering and erosion patterns in badlands, focusing on sediment responses under similar climatic conditions. Three unweathered samples with different mineralogical contents were collected from the Vallcebre and Bagà badlands in the Catalan Pyrenees, NE Spain, a region characterized by a humid Mediterranean climate. In addition to quartz and calcite as the dominant minerals, one unweathered sample contained smectite and gypsum, the second smectite, and the third neither smectite nor gypsum. The laboratory experiment for climate simulation was designed so that each sample contained two sub-samples, from which one was exposed to rain and the second to snow. In the first part, the samples were placed in a climate chamber at a temperature of -3 °C after rain (~140 ml) or snow (~150 g) had been simulated. After 15 cycles, in the second part of the experiment, all samples were exposed to rain (~140 ml) and placed in a climate chamber at a temperature of 50 °C. These treatments were repeated 8 times. Throughout the experiment, samples were photographed after each cycle to observe surface changes, while the leached solution was collected and its volume, pH, electrical conductivity (EC), and ion concentrations were measured. Additional analyses were performed to assess changes in morphology, mineralogy, chemical composition, and porosity. Results highlighted the high specific surface area of the smectite-rich samples and confirmed microstructural changes. Variations in pore volume and size distribution emphasized the relationship between mineralogical composition and susceptibility to weathering. The results showed that snow is a more destructive agent compared to rain, especially for smectite-rich samples. As the presence of gypsum increases the weathering resistance of the material, the sample with smectite and gypsum showed a lower degree of decomposition than the sample with only smectite, while the sample without smectite and gypsum showed the least decomposition of the structure. In addition, the sample with smectite and gypsum showed significantly different values for the pH value and the EC value of the leachate. The sulphate concentration was highest in the sample with smectite and gypsum, which is a consequence of the dissolution of the gypsum. These results emphasize the crucial role of mineralogical and physicochemical properties in controlling weathering and erosion processes in badlands. By linking sediment properties to degradation processes under different climatic conditions, this study offers insights into the dynamics of badlands and provides information for predictive modelling of land degradation under climate change.

KEYWORDS: clay minerals, gypsum, physicochemical properties, climate change

Seasonal and meteorological influences on erosion dynamics in mountainous badlands: insights from terrestrial laser scanning and sediment traps

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Badlands, characterized by their highly dissected morphology and intense erosion, serve as critical sediment production hotspots, particularly in mountainous regions. While the role of meteorological factors such as rainfall and freeze-thaw cycles in erosion dynamics is recognized, their specific interactions with these processes require further investigation. This study bridges this knowledge gap through a three-year investigation (November 2020–November 2023) conducted in the Upper Llobregat River Basin (Spain). Two badland slopes (8 m^2 north-facing and 12.5 m^2 south-facing) were monitored using a combination of sediment traps and Terrestrial Laser Scanning (TLS), providing a multiscale perspective on sediment production and morphological changes.

The results reveal distinct seasonal patterns: freeze-thaw cycles dominate in autumn and winter, degrading clay-rich material and inducing volumetric swelling up to 5 cm. Conversely, rainfall-driven processes, including sheet and rill erosion, are prominent in spring and summer, with peak erosion rates linked to intense short-duration storms. Over the study period, the south-facing slope exhibited an erosion rate of 30,000 Mg km^{-2} $year^{-1}$, while the north-facing slope recorded 16,500 Mg km^{-2} $year^{-1}$, aligning with regional estimates. TLS emerged as a superior tool for identifying erosive processes and morphological changes, complementing sediment trap data by providing high-resolution spatial insights.

This research underscores the critical influence of temperature and rainfall on erosion dynamics in mountainous badlands, highlighting the value of integrating advanced geomatic techniques with traditional methods for a comprehensive understanding of soil erosion processes. Findings emphasize the importance of addressing seasonal and meteorological variability in erosion management and contribute to improved strategies for mitigating land degradation in similar environments globally.

Human impact on erosion dynamics of Italian badlands over the last 70 years: insights from the BAD2BED Project

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This study investigated the changes in erosion dynamics across three Italian badlands' sites over the last 70 years as part of the BAD2BED Italian National Project PRIN2022, titled "BADland morphodynamics assessment and hillslope-channel BED coupling in the context of global change." The project's primary objective is to identify potential trends in the morphodynamics of Italian Mediterranean badlands, aiming to support decision-making actions in erosion-prone areas affected by land mismanagement and to inform the development of best practices for sustainable management of rural areas.

Taking into account the diverse climatic conditions of the Italian temperate zone, characterized by increasingly drier and longer dry seasons from north to south, three study areas were investigated: the Rio della Rocca catchment in the Reggio Emilia Apennines (northern Italy), the Upper Orcia Valley in southern Tuscany (central Italy) and the Agri catchment in the Basilicata region (southern Italy).

We defined standardized criteria for geomorphological mapping of multitemporal hillslope landforms, based on photointerpretation of historical aerial photographs. This allowed the creation of an inventory of key sediment source areas. In addition, we mapped planform morphology and temporal changes along the river corridors in the main channels, with special attention to landforms influencing lateral (dis)connectivity and to indicators of human impact on historical channel dynamics.

A multitemporal land use mapping was carried out to quantify changes in land cover over the same period. This analysis on catchment-scale, human-induced modifications provided insights into the recent morphoevolution of these landscapes, highlighting both reductions in hillslope denudation and variations in the fluvial system connectivity, driven by external factors such as human activity.

The selected Italian areas represent "open air laboratories" for research on erosion processes. The apparently decline in badlands landscapes presents valuable opportunities for disseminating knowledge on geomorphological dynamics. Their high educational significance makes them key sites for understanding, and communicating, landscape evolution processes.

KEYWORDS: Italian badlands, erosion morphodynamics, land use changes, geomorphological mapping

THEMATIC SESSION 8

GEODIVERSITY AND GEOHERITAGE FOR SUSTAINABLE DEVELOPMENT

(organized by the IAG WG on Geomorphosites and WG on Dynamic geodiversity of critical zones in mountain areas and polar regions DYNAgeoZONES)

Chairpersons:

Lucie Kubalíková, Paola Coratza, Fabien Hobléa, Zbigniew Zwolinski, Alicja Najwer, Marco Giardino

The natural and cultural heritage of the Sub-Tatra Region (Southern Poland, Northern Slovakia) in the light of the latest research on geodiversity and geoheritage

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The Sub-Tatra Region is located in the northern part of Slovakia and the southern part of Poland around the Tatra Mountains. It covers the area of 4 ethnographic regions: Orava, Liptov, Spiš and Podhale. From a physical and geographical point of view, it lies within the Oravská kotlina Basin, Orawa-Nowy Targ Basin, the Pieniny Mts., Fore-Tatra Foothills, Sub-Tatra Depression, the Podtatranská brázda Trench, the Magura Spiska Mts., the Spišská Magura Mts., the Oravská Magura Mts., the Oravská vrchovina Highlands, the Skorušinské vrchy Mts., the Chočské vrchy Mts., the Podtatranská kotlina Basin, the Kozie chrbty Mts. and the Hornádska kotlina Basin. The aim of this contribution is to summarize the current state of research conducted from 2018 to 2024 relating to geodiversity and natural and cultural heritage of this area. The analysis of geodiversity of the Sub-Tatra Region, which was conducted in 2018 and 2021, showed great diversity within individual physical and geographical units. The assessment of geosites carried out in 2016 showed their high scientific, cognitive and tourist potential, which is currently used by some of the authorities of this area. This is proven by another assessment carried out in 2023 as part of the International Visegrad Fund Project. Additionally, a detailed inventory of small folk-religious architecture carried out in 2023-2024 also emphasizes the uniqueness of this area in the context of neighbouring areas. Thanks to the research conducted in the field of social geography, which included in-depth interviews with selected authorities of cities and communes of the Sub-Tatra Region and surveys conducted among geography teachers, it was possible to initially determine the direction of further activities aimed at making tourist access and promotion of previously unknown or little-known objects, like geosites and roadside shrines.

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KEYWORDS: geodiversity, geoheritage, natural and cultural heritage, Sub-Tatra Region

Geoheritage and cultural heritage of the Dells of the Wisconsin River, WI, USA

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Wisconsin Dells is a town located in the central part of Wisconsin, United States. This town is famous for its water-related tourist attractions, especially the Wisconsin River, which flows through the town. The town itself is a typical tourist town, which can develop thanks to the promotion of available tourist attractions.
The purpose of this contribution is to indicate the natural and cultural heritage of the town based on the history of making the Wisconsin River accessible to tourists and the history of photography that took place in this region.
The Wisconsin River is one of the tributaries of the Mississippi River. In the southern part of Wisconsin, the river cuts through the terminal moraine that was formed here during the last glaciation, to then flow into the gorge called the Dells of the Wisconsin River. This gorge is the mail subject of this study. Its length is 8 km. The gorge in this place cuts into the Carboniferous sandstones, creating interesting morphological forms. The assessment of these forms has shown their high scientific, cognitive and tourist potential.
The Dells of the Wisconsin River is owned by the Wisconsin Department of Natural Resources. It was established as a State Natural Area in 1994.
Acknowledgement: The project no. VEGA 2/0072/24 financed by the Slovak VEGA Grant Agency, and the University of the National Education Commission Krakow Grant no. WPBU/2024/03/00098.

KEYWORDS: geodiversity, geoheritage, natural and cultural heritage, the Dells of the Wisconsin River

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Geosites and geotourism: unlocking the potential of Malta's Southern region for sustainable tourism and geoheritage conservation

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Despite its small size, the island of Malta exhibits a remarkable diversity of landscapes and landforms, characterized by a rich array of geological and geomorphological features. Identifying and assessing geosites play a crucial role in preserving, protecting, and promoting this geodiversity. Additionally, geosites hold significant potential for geotourism, which could contribute to the local economy. Tourism is a key driver of Malta's economy, with its direct contribution to GDP ranking among the highest in Europe.
This study explores the role of geoheritage and geotourism in fostering sustainable tourism and geoconservation, with a focus on southern Malta. Compared to the island's northern sector, which attracts more visitors due to its sandy beaches, the southern region remains less visited. To address this, potential geosites were inventoried and quantitatively assessed using an established methodology adapted to the local context. The evaluation identified 18 potential geosites that contribute both to Malta's natural heritage and to its tourism potential. Among these, four priority geosites were selected for integration into a proposed geotourism route, designed to showcase not only their geological significance but also the nearby cultural heritage. Furthermore, this assessment methodology, applied for the first time in this region, has proven effective for geosite identification and can be extended to other areas of Malta and Gozo.

KEYWORDS: geosites, geoheritage, Malta

Geoheritage of the Silesian Upland – appreciated, unknown, lost

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The Silesian Upland (southern Poland) is characterized by great geodiversity and numerous values of inanimate nature. The Central Database of Geosites of Poland includes 81 geosites from various ranks in its area: international (4), national (10), regional (36), and local (31). The largest group comprises mining remnants, artificial geological outcrops, and erratic boulders. The assessment of the values of geosites in terms of tourism, education, and science on a 10-point scale, from very low (1-2), through low (3-4), medium (5-6), high (7-8) to very high (9-10) indicates that the highest rated geosites (≥ 7 points) constitute 22%, 26%, and 25%, respectively. The state of 11 geosites is unsatisfactory, including three with high scientific and didactic values. The degradation of the geosite values is due to various reasons, e.g., flooding or overgrowing with vegetation, which makes it impossible to conduct observations. For many geosites with average value (5-6 points), this rating could be increased through appropriate development, cleaning works, marking out nature trails, and erecting information boards. In the Silesian Upland, several dozen geosites have at least average scientific value but are littered and require work to improve safety and legal regulations with the land owners. Unfortunately, sites with outstanding scientific values were irretrievably lost, the most striking example of which is the filling with ashes of the Brzozowica opencast mine in Będzin, with the thickest coal seam in Poland (24 m) splitting into two seams.

KEYWORDS: geoheritage, geosite, scientific values, Silesian Upland, Poland

Geomorphological heritage in Nevado Coropuna (Perú). A proposal for the future

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The Nevado Coropuna, a glaciated volcanic complex in the Western Cordillera of the Central Andes (Peru), rises to 6425 m above sea level above the high plateau to the north and the deep valleys of Ocoña and Majes that drain to the Pacific to the south. Within an arid tropical climate, its rainfall, on its southern slope, is between 100 and 400 mm and is concentrated in its summer wet season. It stands out for its high geoheritage values and those of a geomorphological nature related to its highest geoecological floors, from Quechua to High Mountain, are analyzed here.

The study covers an area where socioeconomic development is very limited and where the current context of global change means a loss of its most precious water resource from the melting waters of its glacial ice. In this way, its heritage value, its educational potential and as an ecosystemic and cultural service stand out as a first-rate geomorphological factor whose conservation must be guaranteed so that local communities, highly dependent on this resource for the maintenance of their agricultural-livestock economy, essentially Alpaca-like on the highest floors, can maintain their traditional economies and represent a socioeconomic alternative to mining operations.

In this study, a total of 14 sites of geomorphological interest (geomorphosites) would be invented, in which fundamental aspects of its volcanism, glacial and periglacial landforms and processes, hydrothermalism, hydrology and the transformation of its slopes into ancestral terraces are valued. A proposal is also made for a geotouristic itinerary surrounding the entire Coropuna. All of this is done by following a methodology already applied in other geomorphological contexts and with an approach to creating socioeconomic synergies taking advantage of the nearby and only existing geopark in Peru, the Colca and Andagua Volcanoes Geopark.

KEYWORDS: geomorphological heritage, geomorphosites, Nevado Coropuna, Perú

Geosystem services of [selected] abiotic nature resources in a small town within the peripheral tourist area in Central Poland

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The absence of traditional tourist attractions near the capital does not hinder the potential for the growth of nature-based and educational tourism. Studies by Albino et al. (2015), Budziewicz-Guźlecka (2017), Bifulco & Tregua (2018), and Hajduk (2020; Development Strategy, 2021) demonstrate that people increasingly seek to live in smart cities, characterized by innovative solutions and opportunities. Such cities integrate tourism, well-being, and geoecosystem services to meet society's evolving expectations. By managing natural resources responsibly, local governments—working in partnership with residents and/or supported by experts—can foster innovation aimed at achieving sustainable economic growth and enhancing quality of life (e.g., Górska-Zabielska, 2020; Carrión-Mero et al., 2021; Hamoud et al., 2021; Farabollini et al., 2022).

In 2022, a social participation project led to the construction of a small facility described by Van Geert (2019) as an ex situ geological museum exhibit. This site, designed for residents of Pruszków in the Warsaw metropolitan area and visitors who value the beauty of abiotic nature, serves to promote its preservation for future generations. Featuring objects of glacial origin, the installation offers various geosystem services, including educational, environmental, recreational, cognitive, and aesthetic benefits (Lima & Pereira, 2023).

The Pruszków short geo-trail consists of 12 Scandinavian erratic boulders, three informational panels, and a leaflet, enabling it to fulfil educational and pro-environmental functions aligned with geoethical principles. It provides local school students with opportunities to learn about nature while meeting the cognitive and recreational needs of residents and tourists through summer nature walks. This small yet significant collection of boulders demonstrates how abiotic natural elements can be leveraged for tourism in a manner consistent with conservation principles. It highlights the concepts of geoheritage and geodiversity within the local context of Pruszków's georesources, serving both aesthetic and environmental purposes in a compact pocket garden (Jasprizza, 1999). By effectively applying expert knowledge, the lapidarium contributes to the town's sustainable socio-economic development.

Moreover, the presentation addresses the discrepancy between the mission of the university and the dynamically changing market for geoecosystem services, as well as the needs of local residents in the Mazovia region (Regional Innovation Strategy, 2021). This gap can be bridged effectively, even using the example of a small lapidarium in Pruszków.

KEYWORDS: Scandinavian erratic boulders, geosystem services, sustainable development, peripheral tourist area, central Poland

Geomorphological, hydrometeorological and sedimentological surveys to support an inventory of geoheritage sites in the Jebel Demmer (Dahar Plateau, Southeastern Tunisia)

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Jebel Demmer is a mountainous area that is part of the Dahar Plateau, in southeastern Tunisia. Administratively, it lies between the governorates of Médenine and Tataouine. Jebel Demmer is rich in geodiversity, with components spanning stratigraphy, palaeontology, geomorphology, pedology, and hydrography. The geomorphological landscape features a triple cuesta, formed from Triassic, Jurassic, and Cretaceous strata, with a variety of structural landforms such as mesas, witness buttes, and outliers. The cuesta is dissected by a dense hydrographic network flowing in various directions, towards the Mediterranean Sea and the Grand Erg Oriental (Sahara). In the valleys, fine sand accumulations of aeolian origin were deposited during different periods of the Pleistocene and Holocene, and today, these deposits contribute to the region's soil resources.

Prehistoric sites in the area attest to the long history of human presence in the region. Settlement in Jebel Demmer has persisted through various historical periods. Today, the region boasts a rich and diverse cultural heritage, including Ksour (fortified grain storehouses) and perched villages, cave dwellings and Jessour (agricultural terraces) (Ben Ouezdou et al., 2025), all of which are in perfect harmony with the geomorphological context. The Jessour (plural of Jesr) are an ancestral hydro-agricultural system characteristic of the Dahar. On the slopes and backslopes of the cuestas, ravines that dissect the deposits of Quaternary aeolian fine sand are partially blocked by the construction of small dams across the talwegs. These dams help retain part of the sediments and runoff water, which is rare in this arid region where average annual rainfall does not exceed 200 mm. The soil formed in this way, along with the stored water, makes agriculture feasible, particularly olive plantations.

The research was conducted in two phases: (i) an inventory of geoheritage sites, particularly geocultural sites; and (ii) specific geomorphological, hydrometeorological, and sedimentological surveys at two sites to better understand the active processes in geoheritage sites and to support their management. The inventory of geoheritage sites followed the method established by the University of Lausanne (Reynard et al., 2016) and allowed for the characterisation of the intrinsic values (both central and additional) of 9 sites. The analysis of the temporal dimensions of the sites was based on the approach of Ben Fraj et al. (2023). The specific surveys at two sites, characterised by the presence of Jessour (Oued el Ghaba and Ouejh Ellgha), included geomorphological mapping using the new Tunisian geomorphological legend (Ben Fraj, & Ghram Messedi, to be published), hydrometeorological measurements over two years (starting in September 2023) with the installation of two stations to measure meteorological parameters (temperature, rainfall), as well as soil moisture. Sedimentological analyses were also conducted on several soil layers

at the two Jessour and their catchments. The combination of these three in-depth surveys allows for a better characterisation of the scientific value of the inventoried sites and will help inform their future management.

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KEYWORDS: geodiversity, geoheritage, Southeast Tunisia, Jebel Demmer, Jessour

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Geomorphological diversity of sandstone tabular hills of Ostaš and Hejda (Broumovská vrchovina, Czechia)

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Various landforms present within the sandstone-dominated tablelands are interesting from both a scientific and tourist perspective. Depending on accessibility and ruggedness of the terrain, some of them are popular geomorphosites whereas others are less known despite their geotourism potential. The aim of this work is to present landform diversity of two tabular hills (mesas) located in north-east Czechia. The mesas of Ostaš and Hejda are composed of nearly horizontal sandstone caprock layers overlying finer-grained rocks. Ostaš is open for tourists with marked hiking trails while Hejda, despite being in close proximity, is almost unknown. Both mesas were mapped in the field and subjected to geomorphometrical analysis to identify the diversity of forms and, implicitly, geomorphological processes. The mostly monotonous upper surface of Ostaš is surrounded by rock walls up to 25 m high. In the eastern part of the mesa there is a small rock city including many separated rock towers, accessible via a tourist path. Outer slopes of the mesa are almost entirely mantled by boulder covers of variable density. The relief of Hejda is more complex. The upper surface is divided into two parts by a deep central valley running in the NNW-SSE direction. The western part is mostly flat and lacks elements of ruiniform relief, which might attract visitors. In contrast, the eastern section is partly dissected to the form of a rock city composed of interconnected corridors and clefts, intersecting at right angles. Boulder covers are widespread on the outer slopes and within the central valley. The complex relief of these mesas is the result of a series of processes, acting both at the surface and in the subsurface. Rock cities and outer cliffs are a consequence of non-catastrophic in situ disintegration, with additional occurrence of mass movements such as rockfalls. At Ostaš, opening of edge-parallel clefts is present and examples of block tilting and gliding occur on the outer slopes. At Hejda one can find evidence of subterranean material transport in form of sand accumulations inside boulder caves. The variety of processes and landforms contributes to the scientific and touristic value of both mesas. Here, the question arises whether to promote the area for geotourism and how, considering challenges involved in creating tourist infrastructure in rugged topography and safety issues.

KEYWORDS: sandstone landforms, mesas, tablelands, geomorphological processes, geomorphosites

Risk assessment of geomorphosites and its implications for geoconservation measures

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The identification and preliminary evaluation of risks and threats has always been a part of geomorphosite inventories or classical assessment methods. However, due to the increasing pressure on geomorphosites (and geodiversity in general), risk assessment methods are gaining more attention in the last years and more sophisticated approaches focused directly on threat evaluation has been developed more in depth.
Although the character of particular threats may differ according to the area (e.g., urban or rural areas, coastal or mountain areas) and the purpose of risk assessment may also influence the selection of the appropriate methodological approach, the basic set of criteria used for the degradation risk assessment is quite similar and the main reason of elaborating the risk assessment is to deepen the knowledge about the origins of the possible disturbances and enable to find the best solution for site management that would contribute to the balance of needs of nature and human society.
Starting with simple geomorphosite assessment and SWOT analysis applied in first studies towards a more detailed degradation risk assessment and use of risk assessment matrices, this contribution illustrates the development of risk assessment approaches and discuss advantages and disadvantages of particular methods including their implementations for geoconservation and sustainable use of the geomorphosites. Specific examples within South-Moravian Region (SE of the Czech Republic) are presented and the further directions of risk assessment approaches are outlined.

KEYWORDS: geomorphosite, risk assessment, geoconservation

Geodiversity assessment in landscape geomorphosites: a macro-scale approach to geoheritage evaluation

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The increasing frequency and intensity of extreme events driven by ongoing climate change pose significant challenges for geoheritage management in protected and conserved areas (PCAs). Identifying the territories that exhibit high geodiversity and are most vulnerable to these changes is crucial for effective planning and conservation of geoheritage. This presentation introduces a macro-scale approach to geoheritage evaluation through geodiversity assessment using spatial multi-criteria analysis (S-MCA).

The study areas include three geomorphosites, some of which span up to several tens of square kilometers. Due to their extensive size, they are classified as landscape geomorphosites. Despite significant morphological differences—ranging from high mountain landscapes to postglacial lowlands—all selected sites have been shaped by geohazards. In the Swiss Alps, the Derborence and Illgraben valleys are distinct river basins featuring a rich mosaic of glacial and fluvial landforms, influenced not only by gradual erosional and depositional processes but also by extreme phenomena such as rockslides and debris flows. The Morasko Reserve in Poznań, Poland, exhibits a unique topography shaped by postglacial processes and meteorite impact event, with several depressions marking the impact sites. All three areas are recognized as national geosites for their exceptional geomorphological value.

Geodiversity was evaluated based on five criteria, for which factor maps were created: 1) relief energy (relative heights); 2) terrain fragmentation; 3) state of landform preservation; 4) geological setting; and 5) hydrological factors. These factor maps were then aggregated using the weighted linear combination (WLC) technique. Due to differences in area size and the spatial resolution of the available source data, the Morasko Reserve was assessed with greater accuracy (10 m) compared to the Alpine valleys (25 m). The accuracy and reliability of the final geodiversity maps were confirmed through field inspections, which provided qualitative validation of the spatial distribution of geodiversity. Geodiversity assessment enables the identification of the most valuable areas for the protection of key abiotic features, which is not achievable using traditional geosite evaluation methods. Additionally, the results provide essential insights that can support spatial planning, tourism management, and adaptive conservation strategies in response to accelerating climate change.

KEYWORDS: geodiversity, geodiversity assessment, geomorphosites, geoheritage, spatial multicriteria analysis

# Anthropogenic and natural morphogenesis: equal contributors to geomorphodiversity?

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Urban geomorphology helps explain landscape evolution, changes in natural morphologies, and the impact of urban development on geomorphological processes. Cities are built on diverse geological and geomorphological substrates, and human activities have long acted as geomorphic agents, particularly in historical cities, influencing surface heterogeneity and ecological sustainability.
Geomorphodiversity indexes, such as the land surface diversity index (GmI), can provide insights into human impact on the environment by approximating real-world geomorphological features. Digital Elevation Models (DEMs) and spatial data enable quantitative assessments of geomorphodiversity at various scales. In this study, the authors compared the GmI with geomorphological maps of urban and peri-urban areas in Rome, Italy. This comparison evaluated the GmI's representativeness at a local scale in urban settings, revealing that natural and anthropogenic morphogenesis contribute equally to urban geomorphodiversity. The goal to investigate the contributions of both natural and anthropogenic factors to urban geomorphodiversity addressed the following question: does anthropogenic morphogenesis contribute to geomorphodiversity?
The methodology involved a GIS-based comparison of five GmI diversity classes derived from raster indexes with the distribution of anthropogenic erosion and accumulation landforms mapped in the field and over time, in the geomorphological map. Most notably, the latter distinguishes natural and anthropogenic landforms, allowing us a different assessment for these substantially different geomorphological elements. Results highlight that both natural and anthropogenic processes contribute to geomorphodiversity in urban environment, and in areas having different urbanization levels. They are relevant to understanding the anthropogenic morphogenesis impact on geomorphodiversity in urban environment.

KEYWORDS: anthropogenic erosion-accumulation, geomorphodiversity, geomorphological mapping, landscape evolution, urban environment

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Lab2Go: a hands-on geoeducation program for high school student orientation in Rome, Italy

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In Italy, high schools offer students Paths for Transversal Skills and Orientation (*Percorsi per le Competenze Trasversali e l'Orientamento* – PCTO), an educational approach that integrates classroom learning with hands-on experiences. PCTO programs are designed for students in the final three years of high school and are provided by various institutions, including universities, to bridge the gap between education and the professional world.
The PCTO - LAB2GO project aims to enhance the value of laboratories, museums, and green spaces in secondary schools. It was launched through a collaboration between the National Institute for Nuclear Physics (INFN) and the Faculty of Mathematical, Physical, and Natural Sciences at Sapienza University of Rome, Italy.
Within this framework, the Earth Sciences Department (ESD) at Sapienza developed Lab2Go Earth Sciences, a multidisciplinary program designed for groups of students (class groups, school groups, or mixed groups) to introduce them to Earth Sciences. Schools can choose from three thematic tracks: rock classification, earthquakes, and landscape analysis. Each track follows a structured three-step process:
1. Two introductory seminars covering fundamental concepts, materials, and methodologies.
2. Two school-based laboratory sessions, where students identify and catalog relevant materials for their activities.
3. Three hands-on experiences at university laboratories, where students learn to use scientific instruments and explore innovative technologies.
This conference contribution focuses on Lab2Go – Landscape Analysis, which aims to enhance students' geographical and geological-environmental awareness, develop their observational and interpretative skills regarding landforms, and improve their ability to find and utilize scientific data.
The Lab2Go – Landscape Analysis activities center on geological heritage. At ESD, the first seminar introduces materials and methodologies for geomorphological surveys and geosite inventory, while the second seminar explores geodiversity and geoheritage concepts, highlighting case studies of geosites near participating schools.
The school-based activities focus on exploration:
1. Examining maps and documents related to the local area.
2. Conducting field surveys at nearby geosites, collecting data through direct observations and using Digital Field Survey tools.
During visits to the Photointerpretation, Digital Cartography, and Geomorphological Applications laboratories at ESD, students gain hands-on experience in stereoscopy by analyzing aerial photos of the geosites they are investigating. They consult both paper and digital topographic and thematic maps and create 3D digital models and elevation models using field-collected data.
The final step involves creating a geosite summary sheet, which describes its geological and geomorphological significance along with any additional values. The summary is organized using Google Earth's web-based project tool and is then published on the Lab2Go Science – Wiki platform.
Lab2Go takes place annually, with approximately ten schools per year selecting the ESD's PCTO program. It serves as an outstanding opportunity for scientific outreach, fostering enthusiasm and engagement in Earth Sciences.

KEYWORDS: Earth Sciences, geo-education, geoheritage, Paths for Transversal Skills and Orientation, high schools

Scientific research supporting geoheritage conservation. The case of La Baume cold talus slope, Haute-Savoie (France)

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During the last two decades, significant improvements have been made by the scientific community and natural heritage managers in selecting and inventorying geosites worthy of recognition and protection. Nevertheless, the process of "heritage making" is long and non-linear, and the scientific community faces a number of challenges, including: (i) the need for the value of these sites to be recognised beyond scientific circles, particularly in political and social spheres; and (ii) the need for scientific research to support the selection and inventory process to justify the classification and protection of a site. We address these two challenges and illustrate them through the classification process of La Baume cold talus slope in Haute-Savoie (France).

Cold talus slopes are found at mid-altitudes (typically 1000–1500 m a.s.l.), where alternating air circulation (referred to as the 'chimney effect'; Delaloye and Lambiel, 2005) creates a negative thermal anomaly at the bottom of the slope and a positive one at the top. This results in unique surface conditions that may lead to vegetation dwarfism (Celi et al., 2010). Several such sites have been described in the Alps, Prealps, and Jura Mountains. They face threats from climate change as well as degradation risks due to human activities, particularly forestry and recreation.

The La Baume cold talus slope extends from 1270 to 1340 m a.s.l. in the communal forest of La Baume, Haute-Savoie, France, at the base of a north-facing limestone rock wall, which provides significant shade. Dwarf spruces and typical subalpine species (e.g., *Salix retusa, Salix reticulata, Dryas octopetala*) have been observed (Jordan and Radet, 2016), attesting to the cold habitat conditions. Such dwarf vegetation is rare on a regional scale and could be impacted by forest exploitation, including the development of associated infrastructure. This is why a site classification project has been launched, involving the municipality of La Baume, the Chablais UNESCO Global Geopark, and the universities of Lausanne and Savoie Mont-Blanc. The process is divided into four steps: (i) monitoring of the ground surface temperature and pedological analysis to better understand the processes active in the talus slope; (ii) the assessment of the geoheritage value of the site using two methods – one developed at the University of Lausanne (Reynard et al., 2016) and the other used for the National Inventory of Geosites in France (De Wever et al., 2014); (iii) the definition of a management perimeter based on the approach by Ferrando et al. (2025); and (iv) the development of a geotope classification project according to French legislation (prefectural decree for the protection of geotope). During the whole process, the staff and the scientific advisory committee of the Chablais UNESCO Global Geopark accompanied the local authorities, which allowed the municipality to appropriate science, facilitated research activity and promoted protection initiatives This case highlights the importance of science-based characterisation of geosite value and collaborative research with stakeholders to support geosite classification by public authorities.

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KEYWORDS: geomorphological heritage, geoheritage assessment, geoheritage management, cold talus slopes, La Baume

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The contribution of geomorphodiversity to the sustainable development of the Apennine inner areas: the case study of the Matese Mountains karst landscape (Southern Italy)

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Mountainous areas are regions rich in natural resources, endowed with great beauty, but frequently subject to progressive depopulation and cut off from economic development. Nevertheless, their high degree of naturalness and geological heritage can act as a springboard for eco-sustainable - development of local communities. Such a context is largely representative for the Apennine Mountain areas, which are characterized by a rich geoheritage and by a high geodiversity, especially with reference to their high variety of landscapes, associated landforms and geomorphic processes, by a high geomorphodiversity.
A typical case is represented by the Matese Mountains (Southern Italy), particularly by its central, mountainous to high mountain sector, which is almost entirely made up of carbonate rocks and characterized by an elevated level of naturalness. Its southern portion falls in the Campania region and is part of the Regional Matese Park, while its northern portion refers to the Molise region. Together, these portions are the core of the recently established National Matese Park not yet taken off. So, this mountain area is designated for nature protection and valorisation based on biotic resources, while its geologic heritage is nearly unknown.
Our study has focused on the karst landscape and related landforms that clearly dominate the central Matese Mountain area. Characterizing and mapping karst landforms, as well as polygenetic landforms generated by the interplay of karst and other processes (particularly fluvial and glacial ones) has allowed to document the related geomorphologic imprint from the beginning of the Quaternary up to today. Among the main products, a map has been produced that illustrates the categories and distribution of both exokarst and endokarst features found in this area. Data acquired allowed for characterizing the central Matese area in relation to the typology, distribution and density of karst landforms, and their relationships to the bedrock, geosites, protected areas and water resources (karst springs). Overall, obtained products allow for improving our knowledge on the geomorphological setting and geomorphodiversity of the studied mountain area. Furthermore, they represent an essential basis for developing initiatives and interventions to enhance its fruition in an eco-sustainable way, from both a tourist and economic perspective, to contribute to the development of the Matese National Park.

KEYWORDS: geoheritage, mountain areas, karst landscape, geomorphologic mapping, Southern Apennines

Geomorphosites as geotouristic resource for local development: study case in Sierra de la Paramera, Spain

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Geomorphosites includes all those places of the abiotic heritage that are important for understanding the Earth's history, with a landscape and territorial component. These places may not have high scientific value at an international, national, or regional scale, but they hold local value due to their connection to the territory, environmental and cultural legacy, and their link to the populations that inhabit them, especially in Natural Protected Areas (NPAs) where there is already recognition of natural heritage but not geomorphological heritage. The first objective of this work is the recognition of geomorphological heritage, for which geomorphological maps and an inventory of geomorphosites in the NPA Sierras de la Paramera and la Serrota have been developed. The potential of these sites is currently diminished by the lack of recognition of geotourism, with no proper integration of geomorphosites in the planning of NPAs in Spain, particularly in Castilla y León, where the study area is located. This work proposes a methodology for evaluating the potential use of the inventoried geomorphosites focused on geotourism potential, to enable the development of a geotourism offer that promotes the dissemination of geomorphological heritage and the development of tourism infrastructure, benefiting the local population and ensuring the survival and use of this cultural service. In Sierras de la Paramera and la Serrota, 12 geomorphosites have been inventoried, with medium to high value, but lacking any tourism infrastructure. The first step is to evaluate their potential, study their geomorphological heritage, and carry out dissemination activities to enhance their value in this area.

KEYWORDS: geomorphosites, Natural Protected Areas, geotourism, local development

Geomorphological heritage and landscape in Canal Roya and Izas Valleys (the Pyrenees). Towards sustainable development based on a natural protected area

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The Roya and Izas valleys are located in the Aragonese Pyrenees and belong to the Axial Pyrenees and the Inner Ranges. They form two hanging valleys above the Aragon valley, bordered by peaks over 2000 m high (Anayet, 2574; Pala de Ip, 2783). Both valleys lack infrastructure but are surrounded to the NW and E by ski resorts; to the W by the communication and energy axis of the Aragon valley connected to Europe; to the south by hydroelectric plants; and to the north by France and the Pyrenees National Park. It is a natural landscape surrounded by heavily humanized territories.

A geomorphological map has been created along with an inventory and assessment of 18 significant geomorphological elements that constitute the most relevant natural heritage. These elements provide both valleys with recognizable values for landscape conservation and ecosystemic and cultural services.

Volcanic outcrops and the root of the landslide mantles are the basis of the structural relief, with dominant glacial landforms. Current processes include torrential, slope, nival and periglacial processes. It is a geomorphological heritage of exceptional value at Pyrenean and Iberian scales, combining unique elements (volcanism) with a wide geodiversity.

Both valleys contain an extensive and exemplary range of geomorphological phenomena related to their geomorphodiversity. The complexity and variety of landforms and processes, as well as the beauty and diversity of their peaks and valleys, offer a comprehensive range of educational, scientific, and recreational resources. Given the intense use of their immediate surroundings, a sustainable approach to the use of these valleys involves their conservation and traditional use. It is important to avoid the construction of infrastructure, such as proposals to link ski resorts, that may deteriorate or destroy their natural essence, landforms, and landscape.

KEYWORDS: natural heritage, geomorphosites, natural protected areas, sustainable development

Geodiversity of Orhei National Park, Republic of Moldova

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The incentive to prepare this speech, was the establishment 10 years ago of the first national park in Moldova - Orhei National Park.
The Orhei Park is located in the Codru range, in the central part of Moldova, a few dozen kilometers north of Chisinau. More than half (about 56 percent) of the park's area is forest. The park occupies the catchment area of the Reut River flowing into the Dniester. Deeply incised (up to 150 meters) valleys form a complex of meanders and rock spurs near Trebujeni. This is the site of the former city of the Golden Horde, now known as the Old Orhei archeological reserve - the biggest tourist attraction in the Republic of Moldova.
The diversity of lithology, relief, and the presence of various erosional forms made it possible to claim that the analysis of the area's geodiversity would yield interesting but predictable results.
The geodiversity map was made using Professor Zwolinski's classic method. Source materials (geological map, Digital Terrain Model, orthophotomap) from the collections of the Moldovan Academy of Sciences and the Agency for Geodesy, Cartography and Cadastre of the Republic of Moldova were used. The selection of the weight of individual source materials was made using the AHP method. To make it as objective as possible, 10 respondents, specialists in geology and geomorphology, were asked to solve the AHP diagram.
Both open-source software (Saga GIS, e.g., to generate an indirect map of landforms) and commercial software, ESRI ArcGIS Pro (e.g., raster calculator, map transformation) were used to create the resulting map

KEYWORDS: geodiversity, geomorphometry, Moldova

Assessing the potential of viewpoints in geomorphological education and geotourism (case study: Vistula River valley, E Poland)

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Effective actions for the development of geoeducation and geotourism should be based, first of all, on geosites that can arouse the interest of tourists due to their aesthetic value. Viewpoints fulfil this condition. The large number of visitors to such sites provides an opportunity to exploit their scientific and educational potential. Our study included an analysis of the visibility range of 26 viewpoints located within the potential Małopolski Przełom Wisły Geopark in relation to geomorphological landscapes and landforms. Within the Geopark, five geomorphological landscape types are distinguished: 1) valley, 2) denudation, 3) loess, 4) dune, 5) edge. Their geotouristic values have been assessed according to the author's method. The comprehensive evaluation of the viewpoints included 2 groups of criteria - scientific-educational and tourist-functional. A total of 11 criteria were evaluated. The analysis of visibility from the viewpoints was carried out on the basis of a digital terrain model using GIS tools (ArcGIS, ArcMap). Within the Geopark, the dominant landscapes are those of glacial and fluvioglacial accumulation plains (27.8% of the Geopark area) and denudation plains on calcareous rocks (16%), as well as a strongly dissected loess landscape (12.8%). A combined comparison of the visibility of the different types of geomorphological landscapes shows that the viewpoints provide the opportunity to observe glacial and fluvioglacial accumulation landscapes, denudation plains and floodplain landscapes with meandering palaeochannels. The analysis also showed that from only three viewpoints it is possible to observe all types of geomorphological landscapes in the Geopark. Most of the viewpoints, which are characterised by a high scientific and educational value, also have a high tourist and functional value. This provides a good basis for their use in geotourism and geoeducation. The viewpoints of the highest geotouristic value allow to get acquainted with the following geomorphological elements of the Geopark area: a) fluvial relief forms, b) structural relief forms, c) anthropogenic relief forms, d) main relief elements of the Loess Plateau. It can be the basis for the development of a geotourist trail presenting the main geomorphological elements of the area.

KEYWORDS: geoeducation, geomorphological landscapes, geomorphosites

An overview of geoheritage in the tropical zone

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Tropical geoheritage represents a rich and diverse array of geological and geomorphological features with significant scientific, cultural, and aesthetic value. This paper provides a comprehensive review of the current state of tropical geoheritage research based on a systematic literature review of common science databases such as the Web of Science. This work also highlights the unique geological formations, such as inselbergs, volcanoes, and karst landscapes, that characterize tropical regions from arid to humid realms. A bibliometric analysis of 484 studies published between 2000 and 2023 is conducted, identifying key contributors, countries, and thematic trends in selected evidence, promotion, and future challenges of geodiversity and geoheritage in the tropics. The review underscores the importance of geoconservation and geotourism as tools for preserving geoheritage in tropical regions, which are under increasing threat from climate change, deforestation, and resource exploitation. Various geoconservation strategies, including the creation of geoparks, national tourism promotion, and public education campaigns, are discussed as effective measures for enhancing the benefits of tropical geoheritage conservation. This study highlights the need for transdisciplinary approaches to protect these natural treasures and suggests future research directions focused on sustainable management and the integration of geoheritage into broader environmental conservation frameworks.

KEYWORDS: geoheritage, geoconservation, geodiversity, tropical countries, developing countries, tropics

THEMATIC SESSION 9

GEOMORPHOLOGICAL HAZARDS AND RISK MANAGEMENT

(co-organized, IAG IAGGeomHaz WG – International Geographical Union, Commission on Hazard and Risk)

Chairpersons:

Susana da Silva Pereira, Maria Carolina Villaça Gomes, Takashi Oguchi

Mapping and assessment of coastal erosion susceptibility using MARS-based modelling

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In this study, we propose a methodology for assessing and mapping the natural susceptibility to coastal erosion using MARS (Multivariate Adaptive Regression Splines) – based modelling. The method has been tested for the entire coast of Tuscany. A set of physical and environmental variables was selected as predictors in the models, including coastal slope, geomorphology, number and energy of detected storms, distance of the closure depth from the coastline and direction of drift. A value for all these variables was assigned to each transect (50 m equally spaced) in which the coastline was partitioned.

By comparing the coastline changes of the periods 2000-2010, 2011-2021 and 2000-2021, three independent inventories of retreating (erosion) and advancing (accretion) transects, were used to train and test the predictive models (M2000_2010, M2011_2021 and M2000_2021, respectively). These inventories were binarized, assigning 1 to erosion and 0 to accretion, once coastline variations within the range of -4 and 4 meters (estimated resolution) were excluded.

Model validation was carried out through two validation schemes: a self-validation, involving a random partition of each balanced inventory into a calibration (70%) and a validation (30%) subsets, and a grand-validation, where the models calibrated with 100% of the subsets were used to predict the not-extracted ones. To allow for the estimation of the model performances in terms of precision and reliability, 100 replicates were computed for each validation procedure by randomly multi-extracting different calibration and validation datasets.

The performance of the MARS models was assessed by computing the Area Under the Receiver Operating Characteristics Curve (AUC). All the tested models produced largely acceptable AUC values, as revealed in the results. In particular, the models show an AUC mean value above 0.8, 0.77 and 0.78 for M2000_2010, M2011_2021 and M2000_2021, indicating strong predictive performance.

Finally, a Natural Coastal Erosion Susceptibility Map was created to identify areas that are likely to be more susceptible to coastal erosion. The map was obtained from the model M2000_2021 by averaging, for each transect, 100 estimates of probability value and classifying the susceptibility scores using the Youden Index cutoff. The results showed an accuracy of 74.45%, indicating a good overall classification capability and a precision of 73.39% suggesting that most predicted erosion cases were correct.

These results demonstrate that MARS-based modelling can be a reliable tool for assessing and mapping coastal erosion susceptibility. At the same time, those coastal sectors where the models do not fit the retreat/advance can be interpreted as being controlled by anthropogenic factors (e.g., inland slope/fluvial erosion/sediment transport, coastal protection structures, and nourishment).

KEYWORDS: coastal erosion susceptibility, GIS, MARS, Tuscany, Italy

Considerations on snow avalanche activity. Case study: the Southern half of the Eastern Slope of the Bucegi Mountains, Romanian Carpathians

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Snow avalanches represent a major natural hazard in mountainous regions, severely affecting tourist infrastructure, communication routes, and forests, while also posing risks of injuries and loss of human lives.
Our study was conducted in the southern half of the eastern slope of the Bucegi Mountains, located in the eastern part of the Southern Carpathians, Romanian Carpathians. Our aim was to evaluate avalanche activity using a dendrogeomorphological approach, as it is the best method for reconstructing snow avalanche activity and determining avalanche size and frequency.
At altitudes between 1,700 and 1,900 m a.s.l., we sampled 42 *Picea abies* trees in the Târle 2 stand, 43 *Larix decidua Mill* trees in the Carp 2 stand, and 54 *Larix decidua Mill* trees in the Furnica stand during two field campaigns in October 2023 and October 2024. The first two stands are located within the Sinaia ski resort, while the third is in an area without winter tourism activities.
Trees affected by avalanches record ground disturbances in their growth rings, such as scars, rows of traumatic resin, reaction wood, sudden growth increases, or growth suppression. We obtained valuable spatial and temporal information on avalanche activity using the annual semi-quantitative index or the avalanche activity index, as well as the return period.
The avalanche chronology is relatively short, considering that the sampled trees are relatively young. In Tarle 2, the chronology spans 36 years, in Carp 2, 40 years, and in Furnica, 54 years. Our analysis revealed the following patterns: in Târle 2 stand we have identified 14 years with weak dendrogeomorphological avalanche signals, three years with probable avalanches, and four years with major avalanches; in Carp 2 stand we have identified 20 years with weak dendrogeomorphological avalanche signals, two years with probable avalanches and two years with major avalanches; and in Furnica stand we have identified 14 years with weak dendrogeomorphological avalanche signals, three years with probable avalanches, and four years with major avalanches.
Furthermore, the average return period was 12.2 years in Târle 2, 14 years in Carp 2, and 16.9 years in Furnica.
We believe that our results complement previous studies conducted in the same area but in different stands. These findings can contribute to managing winter tourism activities such as backcountry and off-piste skiing, identifying vulnerable areas, and enhancing overall safety for tourist activities.

KEYWORDS: snow avalanche, dendrogeomorphological approach, stand, chronology, return period, Bucegi Mountains, Romanian Carpathians

Geomorphological hazards in the Belvedere Glacier area (Italian Alps): a multidisciplinary approach to a complex and intensely-evolving environment

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High mountain environments are undergoing massive transformations, on short- and long-time scale, due to climate change and sprawling human impact. The frequency and magnitude of many geomorphological hazards, such as those related to ice transformation due to rising temperature, or such as mass wasting related to extreme meteorological events, are expected to increase. The Belvedere Glacier area (Monte Rosa Massif, Italian Alps) is an iconic debris-covered glacier attracting the interest of several scientists because of the occurrence of relatively frequent and varied geomorphological and glaciological hazards. GLOFs (Glacier Lake Outburst Floods), ice and rock avalanches, debris flows, moraine degradation and failure, are some examples of intense dynamics. The 4EU+ projects involving Charles University (Prague, Czech Republic), Heidelberg University (Germany) and University of Milan (Italy), developed from 2021 to 2024, and the current SEED 4EU+ project entitled "CREST - "Cryosphere remote sensing and hazards monitoring in environmental transitions", have been focused on revising the wide literature scope and data availability on the Belvedere Glacier area, to pave the way for new analyses starting from the results obtained in the past. In these five years of 4EU+ and SEED 4EU+ projects, several scientific investigations have been performed on geomorphological processes of the glacier and in its tributary basins: i) UAV surveys to acquire very high resolution digital elevation models to quantify volume changes; ii) satellite imagery and historical photography to monitor and to analyse changes of Belvedere glacier's surface and of glacial lakes in particular since the 19th century; iii) the collection of data for absolute and relative dating using Schmidt hammer, cosmogenic nuclide isotopes and dendrogeomorphology to define the temporal dimension of hazardous processes. All these activities have been accompanied by geomorphological mapping constantly updated each year according to the changes occurred between different field surveys. The performed investigations allowed to identify three phases of glacial retreat in the area (1951–1991; 2006–2015; 2018–2021), marked by the disconnection of some tributary glaciers. Moreover, the consequence of a surge event (1999–2002) has been an acceleration of retreat and downwasting rates from 0.24 m/year (1951–2009) to 1.8 m/year (2009–2023), which are spatially variable due to debris cover, meltwater flow, and supraglacial lake dynamics. The lateral moraine near tourist infrastructures is also sliding with rates of 1.87–1.98 m/year (2018–2023). Fluctuating supraglacial lakes, such as Lake Effimero (428–99,700 m^2), are closely tied to snowmelt and glacier dynamics. Then, in August 2023, a debris flow from the Castelfranco basin affected the glacier's surface, eroding and exposing ice cliffs. All these data will be available openly through a WebGIS platform, using as a thematic base the geomorphological map constantly updated due to the recurrent geomorphological changes affecting the area. This open access spatial database will be a showcase of the knowledge up to now attained, that will allow stakeholders to have a comprehensive view on the Belvedere status for an adequate territorial planning.

KEYWORDS: geomorphological hazards, debris covered glaciers, remote sensing, geomorphological mapping, 4EU+

The 2024 Thame glacial lake outburst flood (GLOF), Khumbu Nepal - causes, consequences, and lessons for GLOF hazard assessment

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Glacial lake outburst floods (GLOFs) are recognized as a major hazard in many mountainous regions of the world, and particularly in the Himalaya. Much of the efforts around GLOF mitigation and early warning in the Himalaya focuses on lakes classified as dangerous, which are generally large; however, even small glacial lakes can produce devastating floods. This was illustrated on 16 August 2024, when a glacial lake outburst flood struck the village of Thame, in the Khumbu region of Nepal. The GLOF originated from a cascade of two small lakes that had not previously been considered dangerous. We use a combination of seismic, remote sensing, meteorologic and gauge data, and field observations to examine the GLOF dynamics, impacts, and potential triggers. The combination of all the data suggests that a wet snow avalanche into the upper bedrock dammed lake was the most likely trigger of the GLOF. The resulting impulse wave overtopped the upper lake, sending a flow 650 m downstream to the lower lake, leading to a breach of the lower lake's moraine dam. Overall, we estimate that ~4-5 x 105 m^3 of water was released from the two lakes. Before and after Pleiades and HMA DEMs reveal a complex pattern of erosion and deposition as the GLOF propagated down the Thame Khola valley. In the village of Thame, damage resulted from inundation, coarse sediment impacts, and erosion of a paleochannel passing through the village. Despite the small initial volume of the GLOF, impacts continued far downstream on the Dudh Koshi, including landslide damage to a key road bridge ~45 km downstream of the GLOF source.

Our findings provide several lessons for GLOF risk management. First, it highlights the potential for small glacial lakes to produce far-reaching and damaging floods, indicating that GLOF risk reduction efforts need to address a wider range of glacial lakes. Second, the GLOF was not triggered by rainfall, but rather by a combination of snowfall and subsequent warm temperatures. This suggests that efforts to anticipate potential outbursts using meteorological forecasts need to consider compound weather events. And finally, the key role of sediment and erosion in the GLOF impacts, highlights the need to understand GLOF erosion and deposition dynamics in order to properly estimate hazard.

KEYWORDS: outburst flood, hazard, Himalaya

Benefits from the outputs of UAV Digital Photogrammetry technique in the investigation of lateral spreads and block slides

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Uncrewed Aerial Vehicle Digital Photogrammetry (UAV-DP) is transforming geoscience research by providing an affordable and efficient technique of acquiring High-Resolution (HR) data for terrain analysis and environmental monitoring. Researching lateral spreads and block slides poses significant challenges due to their extremely slow dynamics, necessitating long-term investigations and detailed field surveys, which are frequently unsafe, time-consuming and expensive. This study explores the efficacy of the use of a micro drone (weighing 300 gr) in investigating gravity-induced landforms and processes related to lateral spreads and block slides in the northern sector of the Island of Malta (Mediterranean Sea). The research focuses on the inventory of persistent joints and downslope megaclast deposits at four sites located along the NW coast of Malta, where spectacular lateral spreads evolve into widespread block slides.
Lateral spreads enlarge persistent joints that partially isolate limestone blocks along plateau edges, which subsequently slide or fall downslope, creating the unique "Rdum" landscapes characteristic of Malta. Using Google Earth (GE) imagery and UAV-based Digital Photogrammetry (UAV-DP), the study precisely identified and categorized persistent joints and detached blocks. Regarding boulder accumulations, the outputs of UAV-DP revealed about 9,000 megaclasts compared to about 5,000 identified using GE, representing a 76% increase due to the DP-derived orthomosaics and 3D models generated. The application of the UAV-DP technique, with a total cost of approximately $5,000, proved significantly more efficient and accurate than traditional GE imagery datasets. These results demonstrate the method's suitability for being extended to other rocky coastal areas affected by slow-moving landslides.

KEYWORDS: gravity-induced landforms, micro drone, Malta

A susceptibility oriented approach for regional landslide inventory implementation in Sicily

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Landslide inventories are mandatory both for picturing the current slope instability status and enabling effective calibration of predictive susceptibility/hazard maps. However, in regions characterized by very high landslide susceptibility conditions, frequently, the inventories are biased as they almost exclusively include landslides which have been noticed and reported for having produced damages, resulting vulnerability/risk oriented. Strategies for landslide hazard management have to be set considering incomplete inventories, so to capturing/representing the huge amounts of phenomena affecting very different geomorphological conditions. To cope with this limit, a strategy has been adopted in the framework of the SUFRA project, which aims at systematically assessing regional landslide susceptibility conditions in Sicily. In particular, exploiting the currently available incomplete landslide inventory (PAI), susceptibility models are first prepared and susceptibility maps obtained (one for each of recognized typologies). On the basis of these base maps (SUFRA1), for each of the susceptibility classes 30% of area is randomly extracted and submitted to systematic landslide (field/remote) recognition, leading to an increasing of the number of mapped landslides coherent with the spatial distribution of the susceptibility conditions.
The Platani river basin extends in central-southern Sicily for approximately 1780 km^2, with a geomorphological setting marked by tectonic contacts between brittle (limestones and quartz arenites) and ductile (clays and silty clays) lithologic complexes, in the head sector and smoothed to hummocky long slopes where clays outcropping prevails. Exploiting the PAI inventory, which reported around 600 among earth-flows and earth-slides, two base susceptibility models were prepared for flows and slides. Extracting the 30% of the area of each susceptible classes, systematic landslide recognition allowed to considerably increase the number of mapped landslides (14277 flows and 517 slides) and to prepare two new advanced susceptibility models. To attest the representativeness of the new inventories, base and advanced models were validated with respect to randomly extracted hidden subsets (of landslides. A marked increase both in terms of accuracy, specificity and sensitivity was observed attesting the new inventory together with an obvious magnitude increase allowed to more effectively calibrate the predictive models.
Preparing systematic regional landslide inventories configures time costs/money which are not compatible (about twenty-five times the number of mapped events in only the 30% of the test area) with any land planning policy. However, a key point is the suitability of the available inventories for preparing landslide susceptibility models and derived maps. According to the study case, the proposed approach can represent a cost-effective procedure to obtain reliable predictive maps from enriched (still uncomplete) landslide inventories.

KEYWORDS: regional landslide inventory, landslide susceptibility, Platani river basin, Sicily (Italy)

The Kagbeni flood event (August 13, 2023), Mustang District (Nepal): triggers, sediment cascades, aggravating infrastructures, and risk management

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Located in the northern, rain-shadow zone (<300mm/yr) of the Nepal Himalaya, Kagbeni village (2810 m, 1200 inhabitants, at the junction between Jhong khola and Kali Gandaki) was affected by a severe and unusual flash flood on the evening of August 13, 2023. It caused significant damage to property and infra-structures (worth about USD 7.4 million), fortunately without human losses thanks to early warning given by villagers living upstream.
In fact, for several years, increased rainfall has been observed from Jomsom station (2720 m), a trend confirmed by residents, leading to more local landslides (depending on lithology) and flooding.
In August 2023, rainfall data from Jomsom station show high rainfall, whereas in the upper Jhong khola valley where the flood originated, even higher rainfall were confirmed by CHIRPS rainfall data (resolution: 5 km). Videos taken by locals illustrate the hyper-concentrated, flash flood event, most likely triggered by a landslide-lake outburst. No accessible path prevented a visit to the landslide source area, but landslide existence was confirmed by analysis of Sentinel_1 Radar coherence time series (slumps upstream from Chongur gorges). Downstream, the flood spread over the entire valley floor with significant rise in water level, as evidenced by new deposits (thin plaster or debris deposition), bank cuttings reactivating landslides in the Spiti shales, hence providing additional debris and making downstream flooding even more destructive (tilted steel truss bridge). The volume of debris transported was estimated at 647,000 m^3, followed by rapid post-flood re-incision (215,000 m^3).
The inhabitants of Kagbeni are also contributing to disasters by settling on very low terraces or flood plains and encroaching on the local Jhong khola riverbed. In addition, the Upper Mustang Road bridge caused the most damage (bottleneck effect): its concrete deck collapsed, was torn apart, and its zigzag trajectory was very destructive (loss of numerous buildings, shelters, trees and gardens).
Given the general trend towards global warming, the possibility of future flash floods in Kagbeni remains high, but some residents have rebuilt their homes and continue to live on potentially threatened flood plains. We suggest some measures for managing future risks, such as (i) applying the functional space concept to avoid encroachment of floodplain by anthropogenic activities, and (ii) managing concrete ford type structure instead of poorly calibrated bridge deck along the main Kali Gandaki Road corridor.

KEYWORDS: flash flood, data acquisition, sediment cascade, risk management, dry Nepal Himalaya

Flood exposure aspect of environmental injustice against segregated Roma communities in North-Eastern Slovakia

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The Roma community is the second largest ethnic minority in Slovakia. Since the 1990s, an increasing number of them have lived in segregated, ethnically homogeneous settlements, which are associated with the highest poverty rates in the country. Such segregated communities concentrated in settlements are in many ways a showcase of environmental injustice, as people there live in worse living conditions in an environment with worse infrastructure than their neighbours from the majority population. Our work aimed to examine environmental injustice against the Roma communities living in segregated settlements also in terms of flood exposure. In the Topľa river catchment, we identified in the previous analysis in total 48 Roma settlements which was the highest number among all Slovak catchments and the highest amount of Roma settlements with flood hazard too (31). When examining environmental injustice, we further focused on the northern part of this catchment, where 26 Roma settlements were located, 10 of which had the highest flood hazard level. Those 26 settlements were compared with their adjacent municipalities by hydrologically modelled flood hazard. In the area of the Roma settlements and the adjacent villages, we also focused on their relative position concerning the watercourse, and the channel modifications such as straightening, changing the streamline of the main channel or relocation of sediment material. We found that as many as 21 of the Roma settlements surveyed were situated on the river banks, of which only 1 was located along the Topľa River and the others were located near the river's tributaries. In 7 Roma settlements, the channel of the watercourse was not modified at all, while in the adjacent villages this was the case in only 2 out of 22 cases. Regarding the relative position of the Roma settlement and the adjacent village in relation to the watercourse flowing through them, 14 Roma settlements were located downstream from the village. In 10 instances there was a noticeable channel straightening in the river reach that traversed the village, but this river modification did not involve the Roma settlements at all. Thus, the work showed that the most significant source of environmental injustice towards the segregated Roma population in terms of flood exposure is the difference in the presence of flood protection infrastructure.

KEYWORDS: Roma communities, flood exposure, environmental justice, Topľa River

Seasonal flood hazard assessment with usage of remote sensing

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Floods are the most frequent and costly natural hazards in Europe. Multiple factors affect its magnitude, scale and spatial layout. The influence of climate changes is uncertain and consensus on its impact on flood hazard is yet to be reached. Nevertheless, we can observe an increase in the average global temperature and fewer snowfall in a winter. Another important factor is in terms of change in land use which impacts rainfall-runoff conditions. The absence of leaves changes the roughness of the surface and uncut vegetation on permanent grassland can be swept due to heavy rain, leaving little place for infiltration. The cornerstone of flood risk management cycle is flood risk assessment, which aims to provide knowledge about size and spatial distribution of flood hazard. To provide a better understanding of processes which generate flood, usage of modern methods and datasets is needed. Remote sensing provides detailed data for generating digital elevation model and satellite scanning offers frequent data collection, with great quality and accessibility which can provide data about properties of land cover. Machine learning algorithms on the other hand offer quick processing of these data. In our contribution, we want to use machine learning algorithms of random forest on satellite data to identify properties of land cover, which will be input to rainfall-runoff modelling. With use of satellite images from different time periods of the year we are able to compare different properties of land cover and provide almost near-real time monitoring.
This study was supported by the Slovak Academy of Sciences (PostdokGrant) project APD0126 Využitie satelitných snímok pri štúdiu dopadov klimatických zmien a zmien krajinnej pokrývky na povodňové ohrozenie.

KEYWORDS: flood hazard, satellite images, detailed LiDAR

The influence of landslides on the modification of drainage divides parameters – a case study from the Polish Outer Carpathians

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Landslides can lead to huge economic losses and the death of people and animals, which is why they have been of great interest to a wide range of researchers for over 150 years. Their research is focused on issues related to safety and economics. This is the reason why issues relating to the influence of landslides on the transformation of mountain ridges and slopes as well as the modification of surface runoff and the river network are of less interest. These topics have been more widely discussed in recent years thanks to the popularization of high-resolution digital elevation models (DEM) obtained from airborne laser scanning (ALS). LiDAR data (light detection and ranging) make it possible to present the topography of the land surface under the vegetation cover, which brings new possibilities in geomorphological studies of mountain areas. The Outer Carpathians are an area particularly susceptible to landslides due to their geological structure – alternately layers of sandstones and shales.

LiDAR data for the Polish Outer Carpathians were obtained during two projects: the Information System of National Protection Against Extraordinary Risks Project (ISOK Project) – data from 2011-2014, and the Centre for Spatial Analysis of Public Administration Project (CAPAP Project) – data from 2019-2023, and were made available by the Head Office of Geodesy and Cartography (Republic of Poland). The usage of them enabled a detailed analysis of the occurrence of landslides, their influence on the transformation of mountain ridges and slopes and identification of the phenomenon of drainage divide migration in the area of the Polish Outer Carpathians. Drainage divide migration caused by landslide is associated with modification of drainage divide parameters such as their length, height and spatial location. This also leads to a change in the surface from which rainwater is drained, and thus affects the intensity of runoff down the slopes and the severity of slope erosion.

KEYWORDS: LiDAR data, DEM, landslides detection, drainage divide migration, geohazards

Combining remote sensing with species distribution models to assess flood impacts on wildlife patterns in Central Zagros

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The damage caused by floods to both the natural resources and cities are considerable. Although many research works have been conducted on flooding effects in cities, there is a scarcity of research among habitats of wildlife. Recent advances demonstrated the importance of monitoring in-situ as well as to perform calibration and validation of flood models in real-time by remote sensing. The Sefid Kuh Protected Area of Iran's Zagros Mountains hosts a large number of wildlife species. It faced an extremely heavy flood in 2019, which inspired this study to assess the ecological consequences as well as measure habitat destruction for some key species, such as brown bears (*Ursus arctos*), wild goats (*Capra aegagrus*), Persian squirrels (*Sciurus anomalus*), wild boars (*Sus scrofa*), Caspian Pond turtles (*Mauremys caspica*), and Greek tortoises (*Testudo graeca*). The extent of flooding was created using the Sentinel-1 Flood Service within ESA's SNAP software. Presented in this paper are results based on four remotely sensed metrics: normalized difference vegetation index (NDVI), soil-adjusted vegetation index (SAVI), normalized difference water index (NDWI), normalized difference pond index (NDPI) and on human activity as well as topography-derived data to analyze what changes occurred in habitat suitability prior and after flooding. It was revealed that the disruption caused by the flooding was widespread, with its most serious effects being felt by habitat loss in the wild goat, followed by the Persian squirrel. With climate change worsening and making such drastic flooding events highly probable, these mountainous species face increasingly endangered habitats. The combined use of Sentinel data and habitat suitability models in this study demonstrates how remote sensing and predictive modelling will prove useful for conservation measures in protected areas that will experience extreme weather events due to climate change.

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KEYWORDS: habitat suitability, species distribution models, MaxEnt, wildlife habitats, flooding

The influence of snow avalanches on the treeline and tree islands. Case study: Sinaia Ski Resort

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The timberline is represented by the compact forests found at the highest altitude, while the tree line refers to the highest-altitude ecotone, located between the upper forest limit and the subalpine or alpine environment, where trees can still survive. Like any natural or anthropogenic boundary, these limits are influenced by a variety of factors. It is well known that the altitude at which trees are found is primarily determined by temperature, a relationship that has been extensively studied. However, although temperature controls the presence of trees, there are local factors that have a real influence on trees at the timberline and tree line, such as wind, snow cover, and geomorphological processes. Among the geomorphological processes, avalanches are considered to play one of the most important roles. Snow avalanches act as a disruptive factor in the upward movement of the timberline, considering the process itself, but they also influence trees through snow patches, which, if they persist for a long time, act as a stress factor for forest vegetation.

In the Romanian Carpathians, avalanches are among the most significant geomorphological processes modifying the timberline, as they occur above this limit, impacting trees along their path. Intense avalanche activity in these areas leads to the formation of avalanche corridors, where one of the outcomes is the replacement of forest vegetation with shrubs or grasses.

The aim of this study is to assess the impact of avalanches on isolated trees or tree islands. The study area includes the upper sector of the Sinaia ski resort in the Bucegi Mountains. Here, at altitudes between 1650 and 1950 meters, we sampled 77 trees of *Picea abies* and *Larix decidua Mill*. Since the avalanche starting zone in the Bucegi Mountains has been identified at approximately 1900-2000 meters, this process directly affects trees at the highest altitudes. The impact is reflected in uprooted trees, scarred trees, decapitated trees, and chandelier-shaped trees. Of the total sampled trees, 24% show signs of avalanche passage, while the rest were affected by wind or other processes.

KEYWORDS: snow avalanches, dendrogeomorphological approach, uprooted trees, scarred trees, decapitated trees, chandelier-shaped trees, Bucegi Mountains, Romanian Carpathians

Integrating advanced remote sensing techniques and modelling for landslide and soil erosion risk assessment in Val d'Orcia (Tuscany), Italy

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Geomorphological hazards (namely landslides and soil erosion) represent a main issue worldwide, causing human and economic losses and also leading to changes in landscape forms and dynamics, especially in the current context of climate change. Therefore, the spatial prediction of their occurrence and the assessment of the associated risk could reduce their impact on society in European countries. Italy has the highest rates of soil erosion and is considered one of the countries most susceptible to landslides. In addition, the presence of urban settlements and infrastructures located in mountainous and hazardous areas requires detailed modelling of geomorphological vulnerability and associated risk. Within this framework, this research was funded and carried out within the Project FORMATION – Full cOveRage, Multi-scAle and multi-sensor geomorphological map: a practical tool for TerrItOrial planning - 2022C2XPK7 - CUP: B53D23007010006 funded by European Union (Next Generation EU) which has the aim to implement new approaches for the description of geomorphological processes and the representation of landforms, whose spatial distribution represents the most immediate tool for the detection of areas affected by geological risks, as landslides and soil erosion. The idea is to integrate remote sensing techniques into the new Italian guidelines for geomorphological mapping provided by ISPRA (Italian Institute for Environmental Protection and Research). In particular, the use of remote sensing techniques (e.g., Interferometric Synthetic Aperture Radar (InSAR) and optical images analysis) is a valuable tool for mapping and modelling geomorphological risks in large areas. In this work, the geomorphological susceptibility and associated risk were modelled focusing on the case study of Val d'Orcia, an area located in Central Tuscany (Italy) with a long history of landslides and erosive processes. Data from multispectral, hyperspectral and InSAR satellites were gathered to investigate the spatial distribution of useful soil properties (bare soil extent, clay content, percentage of organic matter, and carbonate content) and to map the ground deformation. The properties were used as parameters to train a machine-learning model to predict the spatial propensity for landslides and erosion. The associated risk was estimated considering potentially affected infrastructures, such as buildings and roads. The results highlight the urgent need for high-resolution tools for geomorphological mapping to detect and model hazard situations using "beyond the visible" techniques and up-to-date monitoring with the aim of reducing the hydrogeological associated risk.

KEYWORDS: landslides, soil erosion, remote sensing, InSAR, optical imagery

Research projects to analyze and compare landslides in Japan, Romania, and Italy

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Two ongoing research projects, funded by the Japan Society for the Promotion of Science, focus on landslides in Japan, Romania, and Italy. Researchers from the three countries have been collaborating to conduct analyses and regional comparisons to understand the nature of landslides. One of the purposes is to explore cost-effective approaches for topographic measurement of potentially inaccessible areas, such as steep slopes of active landslides, using three methods: uncrewed aerial system-based structure-from-motion photogrammetry (UAS-SfM), ground-based pole-camera SfM (PC-SfM), and terrestrial laser scanning (TLS). UAS-SfM enables medium-resolution (approximately 10 cm) coverage over large areas (~1 km^2) without requiring physical access on the ground, as data are collected entirely via aerial flights. The time for onsite acquisition was approximately 1 hour. For a smaller coverage area (~0.1 km^2), ground-based PC-SfM provides higher-resolution (~10 cm) topographic data and orthorectified mosaic images but necessitates walking throughout the study area for a longer time (several hours) for data acquisition. In contrast, the low-cost TLS generates medium-resolution (~40 cm) point clouds and digital elevation models without requiring access to the slope but lacks RGB or visible color information. The time needed for the measurement was less than PC-SfM. The selection and combination of these methods depend on the accessibility and specific resolution or quality requirements of each study site, ensuring that appropriate data are obtained for landslide-related applications. Another purpose of the projects is to apply machine-learning and deep-learning models to detect landslides and evaluate landslide susceptibility. Optical and InSAR satellite remote sensing data, topographic parameters from DEMs, geology, and other environmental data are analyzed. The employed models include Random Forest, UNet++, and DeepLabv3+. Modern field technologies and novel modeling methods significantly enhanced research results. Our approaches also provide implications for landslide occurrence due to different triggers, especially rainfall and earthquakes. We consider environmental diversities in the study areas of the three countries concerning both triggering and predisposing factors of landslides to obtain general insights through comparisons of results from distant regions.

KEYWORDS: landslides, field data acquisition, machine and deep learning, regional comparisons

Challenges in modelling landslide susceptibility on terraced slopes in the Douro Valley (Portugal)

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The study area is a hydrographic basin (0.42 km^2) located in the Quinta do Bomfim estate (Pinhão), composed of stratified levels of phyllites, quartz metagreywackes and schist intercalations dating from the pre-Cambrian, occupied with vineyards in terraces and land embankments, predominantly south-facing, with altitudes ranging between 62 and 394 m. Recently, the estate developed a renovation process with the re-construction of land embankments, mostly from large 2-row terraces to narrow terraces (1 row), along with new drainage systems. These changes in soil physical conditions promoted water erosion and slope instability.

This work discusses the main challenges and constraints of modelling and validating landslide susceptibility on a terraced area of the Douro Valley, where vineyard production must be profitable, and the effects of erosion on steep slopes should be minimized.

The main constraints in the landslide inventory are related to the small size of the shallow translation slides (average area 62 m^2, depth of the main scarp < 1 m), the intensive use of machinery in agricultural works that erases the landslide features in the field a couple of weeks after the landslide events. Other constraints are related to selecting the predisposing factors that are more adequate to access landslide susceptibility in terraced slopes. Additionally, it is challenging to select the modelling strategies using the information value method and logistic regression, with landslides represented as areas and points, and the validation strategies using different random partitions and ROC curves.

The methodology includes the following steps. (1) Landslide event inventory using fieldwork, orthophoto maps (10 x 10 cm) and Lidar (50 x 50 cm) images; (2) Map of predisposing factors datasets supported by a high-resolution DEM (10 x 10 cm): slope angle, slope aspect, slope curvature of the transversal profile, inverse wetness index, height of the superficial runoff depth and terraces height; geology (1: 50 000 scale) and the superficial formations depth; (3) Application of logistic regression and information value methods to assess each predisposing factor's importance and the landslide susceptibility zonation; (4) Computation of the ROC curve ; (5) Compare the two models susceptible areas.

Almost ~200 shallow translation slides were inventoried. Results show that slope, terrace height, superficial formation depth and superficial runoff depth were considered the more important variables in both models. The slope classes 25.1 – 30 and 30.1 – 35 degrees stand out (55% of the landslides). In the variable height of terraces, the 3.1 – 4 and 4.1 - 5 m classes present higher susceptibility values; however, 84% of landslides occurred on terraces with heights between 1 and 3 m. The highest susceptibility in the superficial formation depth is in the 1.1 – 1.5 m class (46.6% of landslides). In the variable superficial runoff depth, the infiltration process develops in classes <0.05 m located preferably on terrace platforms, where 96% of landslides were recorded, proving to be a good predisposing factor for slope instability.

The susceptibility models obtained present an AAC of the success rate curve > 0.80 and a prediction rate ~ 0.77, which are considered satisfactory results.

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KEYWORDS: Douro Valley, landslides, susceptibility, terraced slopes

Innovative approach for landslide vulnerability assessment using InSAR data at the regional scale

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The occurrence of landslides has the potential to cause considerable economic impact on a global scale, with the resulting in damage to exposed structures and infrastructures, including buildings. In order to identify the most suitable risk mitigation strategies, the scientific community is engaged in the pursuit of analyses aimed at estimating the expected consequences resulting from the reactivation/activation of landslides. The evaluation of vulnerability is typically conducted from two distinct perspectives: social and natural science. Social scientists interpret vulnerability as socioeconomic factors that delineate an individual's or community's capacity to withstand stress and adapt to change. Conversely, from the standpoint of natural science, the concept of vulnerability is centred on the impacts on the built environment. In this context, the term "vulnerability" is defined as the degree of potential loss of a given element or set of elements exposed to the occurrence of a landslide of a given magnitude or intensity. A range of research studies has been conducted with the aim of vulnerability assessment, which represents the most challenging parameter to determine within the definition of risk. The majority of the approaches refer to site-specific and local scale analyses, due to the necessity of in-depth knowledge of the characteristics of both landslide and exposed facilities. The collection of this information is a challenging process, and it is subject to uncertainties. In order to overcome the lack of specific information, alternative approaches have been developed by means of the aggregated data available, such as the percentage of area associated with landslide. Alternatively, in light of the difficulties and uncertainties, precautionary approaches adopted the vulnerability equal to the total degree of loss.
The proposed procedure employs a quantitative assessment of vulnerability for buildings exposed to slow-kinematic landslides, based on empirical fragility and vulnerability curves, which express the probabilistic relationship between the damage severity to exposed buildings and the landslide intensity. The vulnerability curve provides a quantitative assessment of building vulnerability, ranging from 0 (no degree of loss) to 1 (total degree of loss). A catalogue of landslide-induced damage to over four thousand buildings in the Northern Apennines, in central Italy, has been produced as part of the ASI-funded "DInSAR-3M" project. The landslide intensity is evaluated by exploiting the worldwide freely accessible Sentinel-1 SAR images processed through the Small BAseline Subset (SBAS) procedure. The Northern Apennines were selected as the study area to test the incorporation of the vulnerability curve into the quantitative risk assessment procedure, given the prevalence of slow-moving landslides. The Italian inventory has documented approximately 190,000 mapped landslides, which have pervasively shaped the landscape, depending on bedrock lithology and morphology. The region is widely recognised as the most susceptible in Italy to slow-moving landslides. A comprehensive evaluation of over 700,000 buildings was conducted in terms of their landslide risk, encompassing the parameters of hazard, vulnerability, and exposure. The total risk assessed for the buildings in the northern Apennines is estimated at approximately 1.8 billion euros.

KEYWORDS: landslide, risk, fragility curves, vulnerability curve, Sentinel-1

Putting regional landslide susceptibility maps to work: bridging statistical assessment to territorial planning and civil protection (the SUFRA project in Sicily, Italy)

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Applied geomorphology has to furnish society effective and reasonable tools for governing earth surface processes related risk issues. This is a challenge which takes a critical perspective in the case of landslides, which certainly are among the most hazardous morphodynamic phenomena, both in terms of magnitude and recurrence sensitivity to climate change scenarios.
In light of its geomorphological setting and meteorological/seismic/anthropogenic recurrent stressing, the regional territory of Sicily is strongly affected by landslide phenomena. In the framework of the SUFRA project, systematic regional susceptibility maps have been recently completed and delivered to the use of the Basin Authority of the Hydrographic District of Sicily (BAHD_Sicily), which is the regional administrative agency responsible for landslide risk compliant land use planning policies and rules. In particular, each of the SUFRA project activities have been carried out with a strict view toward the needs of (BAHD_Sicily). This perspective actually conforms to all the steps which structure reliable landslide susceptibility modelling and mapping: landslide classification, mapping unit and diagnostic landform selection (pre-processing); model building and validation strategies (processing); score classification and map designing (post-processing). Differently from a research prospective, optimal solutions had to be targeted to find the best trade-off between the quality of models and derived maps and their functioning.
Landslide susceptibility stochastic assessment is based on the concept that past and future landslides share common underlying causes (geo-environmental factors), which can be explored by evaluating the distribution between past events in the hyperspace of these geo-environmental predictors. A number of blind-testing methods can be then applied to estimate the quality of the models resolution/reliability/robustness/adequacy. However, the final maps should cope with the need of matching the local scale, which is the one typically involved in engineering geology. Objective, unambiguous susceptibility classes have to be set and associated with each specific site which has to be analysed by taking into account the geomorphological connectivity both for causative geomorphological factors and gravitational outcome.
The regional landslide susceptibility maps of Sicily were calibrated by exploiting inventories made of near 50000 flows, 4000 slides, for the twenty-one catchments or catchment groups in which the near 22.000 km^2 was split to preserve the required density of data. Independent landslide susceptibility models and maps were produced for: flows, rotational/translational slides, rebounds/falls, debris flows. To solve for the issues above recalled, slope units partition was used for slope phenomena (flows, slides), whilst pixel based models were prepared for debris flows and falls. Besides, criteria and laws and tools were established for defining the spatial connectivity of a specific site and its surrounding susceptibility scenario.
Multiple cross-validation strategies were adopted to check the models for adequacy, accuracy and reliability. Four classes of susceptibility were objectively derived by a recursive nested double application of the Youden-index criteria on the AUC plots. The results attested as the SUFRA procedure can be taken as an example of effective application of geomorphology, as attested by the ongoing implementation of new rules by BAHD_Sicily including the susceptibility maps which have been produced.

This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

KEYWORDS: regional landslide susceptibility assessment, land use planning, Sicily (Italy)

Assessing permafrost thawing hazard and risk for modern infrastructure and cultural heritage in Svalbard

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Permafrost is sensitive to climate change. The last decades, permafrost warming has been reported worldwide and the trend is amplified in the Arctic. Permafrost degradation can severely affect ground and infrastructure stability due to deepened active layer, ice loss and increased (sub)surface water availability, that may lead to thaw subsidence and enhanced gravity-driven slope processes.

Svalbard contains critical modern infrastructure (MI) and invaluable cultural heritage (CH) sensitive to changing permafrost conditions. Threats to the MI structure health can have a direct impact on the safety of Svalbard residents, and long-term consequences on the research and economical activities in the archipelago. In addition, there are 4590 CH sites officially registered in Svalbard, including buildings, human graves, and remnants of installations from the whaling, hunting, trapping, mining and scientific activities, until the end of World War II. The regional and local authorities, such as the Governor of Svalbard, the Longyearbyen Community Council and the Norwegian Directorate for Cultural Heritage, are responsible for MI/CH preservation and climate change adaptation (CCA). These stakeholders draw on the expertise of scientists from diverse fields to provide novel datasets and risk indicators that guide the design of effective CCA measures.

In this context, the Fram Centre PermaRICH project started in 2023. PermaRICH aims to assess the risks related to terrain movement in inhabited permafrost landscapes and the deformation of MI/CH in and around Longyearbyen and Ny-Ålesund (Central and Western Svalbard). The past years, we have focused on mapping the user needs and current policies for hazard/risk management in Svalbard, and applying a wide set of field/in-situ methods and satellite remote sensing techniques to map, monitor and model ground disturbances from permafrost thawing and their consequences on ground and structure stability. We generated maps of terrain movement using Synthetic Aperture Radar Interferometry (InSAR) and exploited the results to improve and upscale existing geomorphological maps. The results are used to assess the geohazard susceptibility in the study areas. We also modelled projected ground and infrastructure settlements and consequences on selected MI/CH structures in Longyearbyen and Ny-Ålesund. In parallel, we are measuring the ground and infrastructure deformation in the areas using InSAR and in-situ geodetic displacement time series. We are also acquiring ground temperature data in newly drilled boreholes.

In 2025, we are working on integrating the findings from the mapping, monitoring and modelling activities, to assess the hazard, vulnerability and risk of the MI/CH sites in the two areas. In this contribution, we will describe and exemplify how we generate permafrost-related geohazard susceptibility maps, and derive hazard scores based on the geomorphological map and the InSAR ground surface displacements. We will discuss the vulnerability assessment based on structure type and properties. Our final objective is to provide a qualitative risk estimate for the inventoried objects, as a product of the hazard and vulnerability scores.

KEYWORDS: permafrost, hazard, risk, Svalbard

Slope mapping and process modelling – new nationwide susceptibility map for debris flows and shallow landslides in Norway

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The varied topography of Norway, ranging from steep fjords to high-alpine mountains and clay-dominated plains, presents significant challenges for society's risk management due to the prevalence of slope processes like snow avalanches, rock falls, and debris flows. This presentation describes our approach to develop an improved nationwide susceptibility map for debris flows and shallow landslides, utilizing new high-resolution Digital Elevation Models (DEMs), adjusted modelling methodology and novel mapping to quantify landscape sensitivity.

Norway's large area and low population density represents significant challenges for comprehensive sediment and landform mapping, which is critical for landslide probability estimations. There is thus considerable variability in both the availability and quality of geological data across the country, and an absence of a unified, high-quality dataset that describes sediment properties on a national scale. To compensate for this lack, we initiated a comprehensive remote sensing mapping program to identify morphological traces of previous shallow landslides across Norway. Over 10,000 reference squares (1x1 km^2) in populated areas with slopes were analyzed using 1 m DEMs, derived hillshade images, slope angle datasets, and aerial photographs. The reference squares were categorized into three classes according to the number of observed open-slope shallow landslides (0, 1-2, >2). The assigned class values where then extrapolated to a nationwide ca 50 km^2 polygon network based on hydrological catchment data. This polygon-dataset was then used as a measure of landscape sensitivity to shallow landslides and debris-flow processes. The new landscape-sensitivity dataset was then used to calibrate input parameters for an index-based methodology to identify potential landslide and debris-flow starting points. The analysis incorporated three indexed parameters: angle of slope, flow accumulation, and slope curvature. The 1 m national DEM was down-sampled to 5 m resolution and utilized as base input for the index-analysis, to maintain high resolution while reducing spatial noise on rough surfaces, such as coarse talus and glacial tills.

Flow-R run-out models, empirically tuned to Norwegian conditions, were applied to the detected potential starting points. The resulting run-out polygons form the new high-resolution susceptibility map for debris flows and shallow landslides.

This innovative approach, combining extensive remote sensing analysis with index-based modelling and empirical run-out simulations, provides a more accurate and detailed nationwide susceptibility map than the pre-existing one from 2014. The new susceptibility map will help risk management strategies and inform land-use planning in Norway's challenging mountainous environment.

KEYWORDS: susceptibility map, debris flows, shallow landslides, mapping, Norway

Coastal multi-risk assessment in north-west Malta (Central Mediterranean Sea)

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Ongoing climate change is leading to an increase in coastal hazards in many regions, affecting natural ecosystems, anthropic activities, and coastal communities. In this context, the Mediterranean region is expected to face a high number of adverse impacts, being considered a hot spot of climate change. The Maltese Islands, located in the central Mediterranean Sea, are prone to the impacts of various climate, marine, and terrestrial processes, including rock falls, floods, coastal erosion, and permanent inundation due to sea-level rise. Taking into account the potential to harm the local natural ecosystems, tourist assets, and coastal infrastructures, these hazardous processes make coastal vulnerability a serious issue for the local economy. Therefore, the development of suitable methods for coastal risk assessment, that can be adapted to local geomorphological settings and can rely on easily collected data, can be of help in implementing adaptive measures and managing coastal areas effectively. In response to these issues, this study assesses and maps the level of multi-risk along the north-west coast of Malta, which hosts several sites of remarkable natural and tourist value.
An index-based method was used to estimate the level of exposure, vulnerability, and susceptibility of the coastal sites under investigation through the spatial combination of multidisciplinary datasets. To evaluate the exposure level, a set of key physical indicators, related to land use, anthropic assets, and natural assets were considered. Coastal vulnerability was analysed from a tourist and environmental perspective, using tourism indicators based on Google images and reviews, and environmental indicators based on natural protected areas. Furthermore, the susceptibility to multiple physical processes (temporary and permanent inundation, shoreline erosion, and rock fall) was assessed and mapped. The outcomes of the analysis demarcate the most critical areas around the bays. Approximately 23% of the investigated sites account for medium-risk zones, while 6% fall under high-risk zones making these areas particularly prone to the coupled impacts of sea level rise, its associated effects and rock falls. The obtained results not only improve the understanding of Maltese coastal risk but also lays the groundwork for efficient coastal management and adaptation strategies. Furthermore, the procedure is adaptable and accessible, making it replicable to other coastal locations experiencing comparable challenges.

KEYWORDS: coastal geomorphology, climate change, risk index, sustainable development, Malta

THEMATIC SESSION 10

GEOMORPHOLOGY AND COASTAL COMMUNITIES: A GEOARCHAEOLOGICAL APPROACH

(organized by the IAG WG Coastal Geoarchaeology)

Chairpersons:

Pietro Aucelli, Teresa Bardaji, Hayley Cawthra, Gaia Mattei

Holocene to near-future changes of the southern Molise coast (southern Italy) influenced by natural and anthropogenic factors

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Coastal areas are of high strategic value for the socio-economic development of their populations and for the human well-being, but at the same time are subject to environmental changes that can be also very rapid and impactful. Climate change plays a significant role in increasing coastal vulnerability. Rising sea levels, and intensities of storms, as well as changes in precipitation patterns, pose substantial risks to coastal communities and ecosystems. Particularly, sea level rise promotes the inundation of low-lying coastal areas, the erosion of shorelines, and the salinization of freshwater resources, exacerbating the vulnerability of coastal regions. Human activities and population growth along the coast also contribute to coastal vulnerability.

The present study has been developed based on the assumption that understanding the history, current dynamics and fragilities, as well as the potential future threats looming over a coastal area, is an essential step for its sustainable management and development. This is crucial both for designing adaptations to the effects of climate change that local communities have to face in the near future, and for effectively and sustainably promoting the socio-economic development of vulnerable coastal areas.

The investigative approach adopted in this work consists of reconstructing the geomorphological characteristics and modifications of a low-lying coastal area, namely the southern Molise coast (southern Italy), considering three-time scenarios: Holocene-1950s, 1950s-Present and possible future scenario. The first two scenarios allow a comparative view of the geomorphological and anthropogenic features and related modifications that have characterized the southern Molise coast in the two aforementioned time intervals. Third scenario, concerning the period Present-2040/2050, provides valuable insights into its possible near-future evolution, with particular reference to coastal erosion and inundation risk.

The analysis of individual scenarios, along with their comparison, allows for several observations, among the most significant: (i) the study area has shown a high shoreline mobility, particularly in the coastal alluvial plain sector of the Biferno River that has experienced a significant climate-conditioned shoreline advancement over approximately 300 years (1600-early 1900s), leading to the growth of the Biferno River delta, followed by its rapid destruction and an overall shoreline retreat, so highlighting a high sensitivity to erosion; (ii) the construction of hard defence structures to protect the eroding coast has not solved the problem, and erosion is still ongoing, particularly in the Biferno River mouth sector; (iii) future evolution scenarios concerning coastal vulnerability highlight that, in the absence of specific interventions, this stretch of coastline will most likely undergo significant erosion and localized permanent inundation in the near future.

KEYWORDS: shoreline changes, geoarchaeological data, climatic and human controls, coastal vulnerability

Landforms and distribution of archaeological sites in the Lower Thu Bon River Plain, Central Vietnam

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Many archaeological sites and cultural assets are distributed in the eastern coast of central Indochina Peninsula, now the central region of Vietnam. They are located along rivers that emanate from the Truong Son Mountain range, which is the watershed boundary with the Mekong River basin and the border between Vietnam and Laos. It has been pointed out that there was cultural exchange through networks of rivers.

According to archaeologists, the Champa Kingdom (ca. 2nd-19th century) is considered to be a federation consisting of multiple riverine powers that grew in each river basin (Trần, 1988). In particular, the Thu Bon River is the largest river in central Vietnam, and the basin has three important sites: the Sacred Temple (My Son), the Royal Capital (Tra Kieu), and the Port City (Hoi An). In this area, archaeological research and the compilation of databases of archaeological sites are in progress (e.g. Yamagata et al. 2019, Nguyen, 2020). This presentation summarized the results of previous studies on the topography and archaeological sites in the Thu Bon River Plain and discussed them using landform classification maps and other information.

The archaeological sites in the area have been located to consider the topography of each region. My Son is in a mountainous basin, Tra Kieu in a relatively flood-free area at the southern end of the floodplain, and Hoi An is located near the mouth of the Thu Bon River at the transitional area between the floodplain and coastal dune area.

In the upstream area, the remains of the Sa Huynh Culture (Iron Age culture, 4th-3rd century B.C. to ca. 100 A.D.) were found along the rivers. Near Tra Kieu, Pleistocene terraces covered with dune sand were scattered, and remains of the Sa Huynh culture, which was a pre-Champa iron culture, as well as remains showing the influence of the subsequent Sinicization and Indianization were also found. The Sa Huynh sites and the Champa sites around Hoi An are located in an area where coastal dunes and fluvial deposits from upstream overlap, suggesting that they were topographically stable. In the Da Nang area in the north, Champa sites were distributed along the minor rivers in the lowlands between terraces.

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KEYWORDS: Kingdom, Sa Huynh culture, Vietnam, Thu Bon River, sand dunes

Volcanogenic coastal modifications and human adaptation strategies: 2400-year geoarchaeological records in the Campi Flegrei caldera (Southern Italy)

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Campi Felgrei caldera, which is one of the most dangerous volcanos of the Mediterranean area, is currently undergoing volcanic unrest accompanied by seismic activity due to a phase of uplift started in August 2023. This study aimed to assess the coastal changes related to past and present ground deformations in this volcanic area that has been densely inhabited since the Greek-Roman time.
To evaluate the historical volcano tectonic activity, a several archeo-stratigraphic records were analysed along with data from direct and indirect surveys of the main underwater archaeological sites scattered along the whole coastal area and the reinterpretation of bibliographic sources. A first phase of measurements was carried out before the recent caldera unrest and corrected with respect to data provided by the INGV report in May 2023. Clear evidence of a differential volcano-tectonic behaviour led us to divide the study area into three coastal stretches with homogeneous ground deformation trends during historical time. In each sector, a new relative sea level (RSL) curve was reconstructed, by interpreting our geoarchaeological constraints in terms of SL markers. Data cover a timespan from the first Roman urbanization to May 2023, wider than the previous studies. The comparison between RSL curves and GIA models allowed calculating the ground deformation related to the unrest phases occurred during historical time along the coast. We measured an overall subsiding trend that brought the RSL from -12 m (4th century BC) to 7 m during three different episodes between 5th and 15th centuries, which was interrupted by short-lived falls of RSL. Finally, a new analysis has been applying to the main geoarchaeological constraints scattered along the whole coastal sector from West to Est in order to also evaluate the effects of the ongoing caldera unrest in terms of coastal changes and variable uplift rates.

KEYWORDS: coastal changes, vertical ground movements, sea level changes, Volcanic area

Landscapes and seascapes of the lagoon of Venice in antiquity

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Lagoons are hotspots of geo- and biodiversity at the intersection of different environments. Their resources have long been exploited by human communities for hunting, fishing and mollusk gathering, as well as for economic activities such as salt production and fish and shell farming. With the development of seafaring, lagoons have offered shelter and harbour for coastal navigation along otherwise unprotected, low sandy coasts. The lagoon of Venice in northern Italy is a paradigmatic case study of long-lasting colonization and exploitation of such coastal wetlands, since the Bronze Age at the least, and with increasing anthropic impact on the natural system since Roman times (Beltrame et al., 2023). Geomorphic processes have been shaping this vast barrier-and-lagoon system, leading to pronounced changes in the lagoon palaeogeography (Primon and Mozzi, 2023).

Our interdisciplinary research project encompasses historical, archaeological, geomorphological, palaeoecological, and palaeoclimatic investigations, with focus on the intricate relationship between environmental changes and cultural responses during the late Holocene in the lagoon of Venice and other lagoons. Here, we present preliminary results of remote sensing, sediment coring, geophysical survey and targeted underwater archaeological excavations that are currently underway at key sites in the northern Venice lagoon and in the harbour of the Iron Age and Roman city of Altinum. Palynological (pollen, dinocysts and other Non Pollen Palynomorphs-NPP) and carpological analyses from archaeological deposits and natural sediments are giving insights into environmental changes and cultural practices. Foraminifers and dinocysts provide evidence on lagoon palaeohydrology and connections with the sea. Collectively, investigations are offering new perspectives into how the Venice lagoon system responded to relative sea-level rise, migration of tidal channels and inlets, and coastline modifications. As well, they allow new understanding on settlement dynamics in antiquity, shedding light on human adaptation and resource exploitation.

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KEYWORDS: geoarchaeology, underwater archaeology, palynology, Roman times, coastal geomorphology

Late Quaternary seismic stratigraphy and morphology of the shelf-incised Krka River valley (Eastern Adriatic coast)

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During the Last Glacial Maximum, karst rivers along the eastern Adriatic coast (EAC) incised channels or valleys into the now submerged part of the shelf. However, there is a lack of studies along the EAC that indicate the submerged paleovalleys morphology, flow path, and sediment infill. Thus, we investigated the late Quaternary seafloor morphology, seismic stratigraphy, and depositional history of the submerged parts of the Krka River incised karst valley (central Dalmatia) using geophysical data (bathymetry and seismic profiles), and core sediments. The study aims to establish the morphology, flow pathways, and the infill of the paleovalley and to determine the controlling factors on the formation of the incised valley. Seismic analysis and sediment data reveal that the Krka incised valley experienced several episodes of erosion and drowning of the shelf area, forming a depositional sequence consisting of lowstand, transgressive, and highstand deposits. During a sea-level lowstand, most of the shelf area was exposed to subaerial conditions, resulting in a paleochannel incision on an alluvial plain. The alluvial environment is characterized by sediment bypass, whereas deltaic deposition of clinoforms occurs on the eastern slope of the Middle Adriatic Depression. Following the subsequent transgression, the shelf flooded, and the sediments filled the paleochannels, transitioning from brackish to estuarine and marine deposits. As the transgression continued, the near-surface sediments were reworked and redistributed by shelf erosion, resulting in a thin transgressive sand sheet covering most of the shelf area. The formation of the Krka River incised valley was strongly controlled by high-amplitude sea-level changes and local factors such as low sediment supply and inherited geology that highly influenced the river pathway and the amount of valley incision and its infill.

This work was supported by the Croatian Science Foundation Project "Sediments between source and sink during a late Quaternary eustatic cycle: the Krka River and the Mid Adriatic Deep System" (QMAD) (HRZZ IP-04-2019-8505).

KEYWORDS: shelf-incised valley, geophysics, karst shelf, sea-level change, Croatia

Coastal caves and human-environment interactions: insights into Late Quaternary sea-level and paleo-landscape evolution in Cilento (Southern Italy)

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Sea level indicators are crucial for paleo-reconstructions, offering insights into past climate conditions, coastal dynamics, and long-term environmental changes. These reconstructions contextualize present trends, such as sea level rise, and improve predictive models for future coastal evolution. Understanding past sea levels enhances our ability to assess natural and anthropogenic impacts on global and regional scales.

This study analyzes former sea-level markers and additional indicators that provide insights into paleogeographic reconstructions and climatic oscillations along the Cilento coast (Southern Tyrrhenian Sea), a tectonically stable sector where indicators from MIS 5 remain undisturbed. To achieve this, we developed "PALEOScape", a geodatabase structured according to international sea-level studies standards, integrating bibliographic data with new field observations.

Numerous surveys were carried out along the coastal stretch between Capo Palinuro and Infreschi Coast. Our methodology combined direct geological and geomorphological surveys, with indirect methods including drone-based surveys, seismic investigations, and remote sensing analyses. Notably, we focused our analysis on the numerous coastal caves scattered along the study area since these landforms typically form at specific elevations relative to the sea level at the time of their development and often preserve sedimentary deposits correlated with distinct climatic stages. In addition, most of these caves have been inhabited in the last millennia and can therefore provide relevant information on the interactions between humans and landscape modifications. This approach allowed an accurate characterization of coastal morphologies, as well as the detection of the main traces of past sea levels in the area. At Marina di Camerota, a cave with a well-preserved tidal notch at approximately 6 m above sea level was documented, associated with Lithophaga boreholes, alongside two other series of boreholes reaching about +9 and +4 m MSL. A monogenetic breccia containing lamellibranch fragments was identified within the tidal notch.

Furthermore, in another cave not studied till now, a small atrium leads to an internal erosive surface (partially buried by terrigenous deposits) located at approximately +1.20 m MSL; deeper within, signs of subsequent ancient human occupation were detected. Moreover, at Cala d'Arconte, a beach deposit was observed at about +3.28 m MSL with a thickness of roughly 80 cm, which appears to correlate with earlier tidal notches noted along the Capo Palinuro promontory. In another cave, a wave-cut platform situated between +4.5 and +5 m MSL preserves in situ marine remains inside a pothole, along with lithic industries.

Cluster analysis identified three major sea-level stands around 5.3±0.2, 2.2±0.10, and 4.8±0.5 m MSL, consistent with sea-level stands well-documented in the bibliography. These clusters were correlated with cave entrance elevations, supporting their positive relationship with sea-level fluctuations.

In conclusion, by integrating geomorphological, paleoenvironmental, and paleontological data, this study strongly highlights the twofold significance of coastal caves for a comprehensive view of long-term coastal evolution in paleo-landscape reconstructions: periods of sea level rise forced prehistoric inhabitants to abandon inundated caves meanwhile modelled by the sea, whereas phases of sea-level stability or regression exposed coastal areas, providing new opportunities for habitation, resource exploitation, and mobility.

KEYWORDS: coastal caves, paleo-landscape, human adaptation, sea-level change, geodatabase

Significance of geodynamic processes in the development of medieval town: a case study of geoarchaeological research in Toruń on the Vistula River (Poland)

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The geoarchaeological investigations aimed to reconstruct geodynamic processes in the lower Vistula Valley, within the medieval Toruń in central Poland, with particular emphasis on the interactions between natural and anthropogenic factors that shaped the landscape. The research area, situated near the river channel and partially encompassing the Benedictine convent complex and the Church of the Holy Spirit, was influenced by fluvial and denudation processes, including floods and landslides. These processes influenced the formation and development of the medieval town.
Toruń's location on a low floodplain terrace adjacent to the riverbank provided convenient access to water resources but also rendered the settlement vulnerable to frequent flooding, particularly those caused by ice jams, which were a common in the region.
Geomorphological, lithofacies, and sedimentological analyses were conducted in an archaeological excavation linked to road construction along the Vistula Boulevard, uncovering retaining wall foundations and monastic structures.
Sedimentological analysis identified eleven deposit types, dominated by sandy and silty fractions. Accessory clay and gravel fractions, derived from Neogene clays and moraine tills, indicate redeposition due to landslides and fluvial activity. Lithofacies characteristics suggest most deposits resulted from human activity (artificial embankments) or floods. These consisted of massive diamictons with artifacts such as brick fragments and medieval ceramics. Flood events produced rhythmic sediment sequences, with coarser layers forming during rising waters and finer layers during recession.
Radiocarbon dating of wooden fragments revealed that sedimentation on the floodplain terrace began approximately 1,000 years ago, coinciding with deforestation of the valley in the early Middle Ages. Meanwhile, dating of ceramics found within embankments indicates their formation during the establishment of Toruń in the 13th century. They contained Neogene clays displaced downslope due to mass movements. Additionally, Bronze Age and Roman-period artifacts discovered in the base of floodplain alluvium were likely redeposited from nearby settlements.
The study identified sediment layers corresponding to major medieval and early modern floods that deposited alluvial layers in the form of flood rhythmites, often mixed with anthropogenic materials such as coal dust, brick fragments, and architectural and domestic ceramics.
The Benedictine convent and the Church of the Holy Spirit were impacted by geodynamic processes, with floods and landslides causing repeated disruptions. Wooden structures and brick rubble indicate multiple cycles of destruction and reconstruction. Initially a religious site, it also served a defensive role from the 17th century onward.
The findings highlight the significant influence of natural processes, particularly floods and landslides, in shaping medieval settlement patterns in Toruń. The interplay between fluvial dynamics and mass movements on valley slopes created challenging conditions for both the monastic complex and broader urban development. The study

underscores the importance of understanding geodynamic processes in historical geoarchaeological research, as they provide crucial insights into human-environment interactions. Further research is necessary to correlate specific sediment layers with documented flood events and to examine the long-term cultural and environmental impacts of these processes on the region's history.

KEYWORDS: geodynamic processes, sedimentology, geoarchaeology, medieval town development

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Geomorphology and archaeology of the coastal town of Pisaurum and surrounding areas (Marche Region, Italy)

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The geomorphological analysis of historically urbanised areas enhances our understanding of how geomorphological factors have influenced urbanization and allows for comparisons with the modern urban environment. This research focuses on a historic urban site, the city of Pisaurum (now Pesaro), whose growth was shaped by specific geomorphological and environmental conditions that have evolved over the centuries.
The study examines the evolution of the coastline and related geomorphological variables, including riverbed migration and the positions of river mouths. These factors are crucial for the development of a city linked to maritime activities, both as elements of defence and as preferred routes for communication.
In 184 BC, the first colony of Pisaurum emerged on the site of an ancient Roman settlement, owing to its advantageous location near the harbor of the Foglia River. The morphology of the Pesaro coastal plain, characterized by a gentle slope, facilitated the formation of wide river meanders and the accumulation of alluvial sediments, including contributions from secondary watercourses such as the Genica Stream. The Roman city was strategically situated on an alluvial terrace, about 5 meters above the Foglia River—an intentional choice to avoid the risks associated with the river's instability. This terraced surface has a straight escarpment towards the sea, representing the morphological evidence of the advance of the Pesaro plain and constituting the coastline at the time of the Roman settlement.
The evolution of the river network enables the reconstruction of the shifts in the mouth of the Foglia River and the changes in the port over time. During the Middle Ages, the instability of the river intensified due to climatic changes; during the Renaissance, the city expanded, and the river mouth was relocated north of the new city walls. After the Renaissance period, sediment buildup led to the abandonment of the harbor, while the river mouth stabilized in a position similar to its current one, becoming separated from the harbor only after the Unification of Italy.
Pisaurum functioned as a significant road junction along the Via Flaminia, situated between Fanum Fortunae and Ariminum. Due to its strategic position, the city managed both local and more intense traffic flows, necessitating careful management of connectivity between urban and extra-urban routes. Although surrounded by hills, the Foglia plain allowed for the development of a wide suburban area, which may have facilitated traffic management, particularly for long-distance journeys that could bypass the city center. A roadway linking the primary roads outside the city likely enabled carts to circumvent Pisaurum, thus expediting transit.
The forum area, which served as the political and social heart of the city, was located at what is now Piazza del Popolo. It was situated at the intersection of the decumanus maximus, the urban segment of the Via Flaminia, and the cardo maximus. Excavations in Piazza Matteotti have revealed a domus from the 1st century AD, which showed evidence of agricultural activity. The presence of a driveway suggests that the decumanus was accessible to limited local traffic, likely restricted to serving the nearby residences.

KEYWORDS: urban geomorphology, archaeology, historical coastal towns, Italy

THEMATIC SESSION 11

GEOMORPHOLOGY AND SOCIETY

(co-organized by the IAG-International Geographical Union, Geomorphology and Society WG/Commission)

Chairpersons:

Jiun-Chuan Lin, Yasuhiro Suzuki, Anita Bernatek-Jakiel

Geohistorical analysis of landscape dynamics trajectories since the mid-20th century through diachronic cartography of Jessour on the Dahar plateau (Southeastern Tunisia)

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Located in Southeastern Tunisia, the Dahar plateau is characterized by a monocline structure (cuesta) culminating at Kef Ennsoura (713 meters) and forming a distinctive landscape dominated by abrupt ridges (Ben Fraj, 2012a, b; Reynard et al., 2018, 2022; Ben Fraj et al., 2019). The surface of the plateau is dissected by several seasonal wadis, which play a crucial role for the water supply in the area, characterized by arid climate with scarce precipitation.
Local populations have used, for centuries, the Jessour system, an ancient hydro-agricultural technique, to adapt to harsh climate conditions. These small dams, built across wadis and ravines, capture runoff water and sediment, creating cultivable terraces while preventing soil erosion. This method efficiently manages water resources, enabling sustainable agriculture in arid environments (Bonvallot, 1979, 1986; Ben Ouezdou, 2001; Ben Fraj et al., 2016, 2019; Blond et al., 2019; Fallot et al., 2019; Calianno et al., 2020, 2023; Reynard, 2024).
A scientific research project was developed through a collaboration between the CGMED Laboratory at the University of Tunis and the Institute of Geography and Sustainability (IGD) at the University of Lausanne. It aims to explore the hydrological, geomorphological and cultural aspects of Jessour as well as their spatiotemporal evolution. This study addresses the latter objective and proposes a geohistorical analysis (Jacob-Rousseau, 2009) of landscape dynamics trajectories through diachronic cartography (Baud and Reynard, 2015; Baud et al., 2015) of the Jessour system in a GIS environment (Franchomme and Schmidt, 2012; Ghram-Messedi et al., 2021). Two sectors have been selected: Zmertene, and El Hafsa/Bechgag area. The study is based on the analysis of historical maps (topographic maps of 1905 and 1941), aerial photographs of 1954 and 1967, and recent satellite images, covering a period from the mid-20th century to 2023 (Abdelkebir, 2025).
The results reveal the main phases of the Jessour evolution, highlight the dynamics of abandonment or development of these hydro-agricultural structures, related to socio-economic changes and migration, and helps to understand the factors that have influenced their sustainability. In El Hafsa and Bechgag watersheds, Jessour are affected by gullying. They have been abandoned upstream, in relation to the abandonment of the El Hafsa troglodytic village. They have developed downstream where lower slopes allow mechanization. In Zmertene, well-maintained jessour are growing continuously in relation to the expansion of the village.
This study provides an opportunity to consider the preservation of a valuable cultural and hydro-agricultural heritage. It offers the possibility of rediscovering a traditional technique in phase with current environmental issues, notably water resource management and sustainable agriculture in the context of climate change. It could also inspire decision makers on the importance of ancestral knowledge that allows maintaining geomorphological equilibrium in dynamic geomorphological contexts.

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KEYWORDS: Geomorphology, geohistory, GIS, Jessour, Dahar

Shaping the peaks: human-driven geomorphological transformations in high-elevation landscapes

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High-altitude landscapes are highly sensitive to human activities. In fact, anthropogenic interventions often modulate the intensity and rate of natural geomorphological processes, leading to significant and sometimes irreversible changes to landscapes and ecosystems.
This study examines the effects of human activities on the landscape in two distinctive areas affected by human agency at least since historical times: the Central Italian Alps (Cancano, Livigno and Passo dello Stelvio) and the Central Apennines. These regions showcase the effects of pastoralism, infrastructures, historical warfare and tourism. Our approach integrates remote-sensing analyses, investigation on archival records and field surveys to provide a comprehensive assessment of human impact on mountain regions.
At Cancano, the construction of dams for reservoirs modified natural hydrological and geomorphological systems, tuning water flow, altering sedimentary budgets and ultimately influencing the evolution of fluvial landforms.
In Livigno, the development of ski slopes, bike trails, and tourism infrastructure triggered a major change of local land cover, increased surface runoff, erosion, and slope instability. Analysis of historical aerial imagery reveals the expansion of erosion-prone zones, while archival photos highlight the stark contrast between past and present landscapes.
Passo dello Stelvio has been exploited for skiing since 1950s thus leaving a marked overprint on the landscape. Moreover, World War I trenches, bomb craters, and fortifications have disrupted natural landforms in an high-sensitive area, while tourism infrastructure and the construction of the road continue to affect slope stability and erosion.
In the Central Apennines, the introduction of pastoral land use centuries ago is the major anthropogenic forcing that shaped landscapes. The creation of numerous sheep tracks has contributed to soil loss, reduced water infiltration, and increased erosion. Additionally, the construction of dry-stone walls, terraces, corrals has significantly altered the geomorphology, modified surface hydrology and influencing slope stability.
This study, funded by Italian Ministry of University and Research through PRIN project "GEOTRes", underscores the diverse and enduring impacts of human activities on high-altitude geomorphological processes, also suggesting difference in their onset. Today, high-altitude ecosystems are particularly fragile to ongoing climate change and anthropogenic modifications of landscapes represent a further factor menacing the stability of surfaces and tuning geomorphic processes.

KEYWORDS: geomorphology, high-elevation areas, mountain ecosystem

Landslide databases in spatial planning – challenges for mountain communes in the Polish Carpathians

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Landslides are an important natural hazard that should be considered as a key element of risk management and an integral part of spatial planning, especially in mountainous areas. This study focuses on the problem of inappropriate land use for housing and economic development in landslide-prone areas of the Polish Carpathians. The analysis included a detailed study of 14 selected communes, which due to their geological conditions and relief have a high susceptibility to landslides. The study used a variety of data sources, including the vector landslide databases (the Landslide Counteracting System, SOPO Polish acronym), (Ministry of Development and Central Statistical Office of Poland), location of existing buildings (Database of Topographic Objects), and range and purpose of local spatial development plan (LSDP; Geo-System). The results indicate that between 1% and 23% of the area of the surveyed communes is landslide-prone, and in some cases up to 11% of the areas designated for development in the LSDP are located in landslide-prone areas. The study highlights the need to integrate landslide data into the spatial planning process and to raise awareness of the risks among local communities.

KEYWORDS: landslides, spatial planning, local development plan, Polish Carpathians

Implications of relief changes in the Anthropocene - case study of the post-mining area in Central Poland

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Strong anthropopressure makes open-pit mining area during the exploitation and subsequent reclamation a model for research on the landform transformation in the Anthropocene and as well as identifying the social perception of changes and determining their impact on the functioning of the local community. The presented study is based on observation carried out in the post-mining area of the lignite mine (Adamów Lignite Mine) located in lowland part of Central Poland. Geomorphologically the area lies within Warta River valley. Lignite deposits are of Miocene age and form horizons with a maximum thickness of up to 11 m, between 21 and 47 m below ground level. They are covered of Quaternary glacial, glaciofluvial and fluvial sediments.

The lignite was mined over sixty years between 1959-2021. Mining activities were carried out in a few opencasts with surface of individual unit no more than 45 km^2. Reclamation was undertaken immediately after the completion of works in individual fields. A determinant of the Anthropocene in the context of the reclamation of post-mining areas is the appearance, as a result of carefully planned activities, of new elements of landscape with a specific, artificial internal structure. The terrace surface was replaced by anthropogenic plain, which did not cause any significant physiographic changes. However, the newly created surface was devoid of natural features, such as swellings or concavities of various origins (e.g. fluvial, aeolian, biogenic) that make up the geomorphic diversity of natural plains. Shapes of convex forms created from dumps are far from natural. The shaping of artificial reservoirs in post-mining excavations and filling them with water led to the creation of an anthropogenic lake district with quite large and deep lakes with beaches built up next to them.

The studies are contribution to understanding the dynamics of anthropogeomorphological processes and new landforms, as well as identifying the social perception of changes and determining their impact on the functioning of the local community and predicting development directions. Transformations of the environment, from the river valley, through the anthropogenic desert during mining works, to the formation of the anthropogenic lake area, show the extent to which humans are able to drive geomorphological processes and have an important social dimension, as they occurred during the lifetime of one generation and had far-reaching effects for the entire local community.

The research is financed by the University of Lodz from IDUB funds under the research project no. 14/IGB/2025.

Comparison of guidelines and databases for the production of geomorphological maps with a social application: the cases of Italy and Spain

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Geomorphological maps are essential tools for effective land management. Their production typically involves four key steps: (i) expert-led geomorphological surveys based on established guidelines, (ii) data organization in structured geodatabases, (iii) digital mapping and GIS model development, and (iv) dissemination of results through infrastructures such as geoportals. Traditional guidelines provide surveyors with standardized nomenclature and symbology for morphotypes, as well as clear instructions on how to integrate related data into dedicated geodatabases. This standardization enhances data consistency, comparability, and interoperability across different studies and institutions. The structure of the data within geodatabases is fundamental to the development of the final cartographic product that can guarantee consistency, readability and interoperability in map production. On the other hand, the data contained in the map product are used to create GIS models that facilitate the analysis and presentation of geomorphological phenomena. Finally, data dissemination infrastructures - such as geoportals - are important to make the models available to the users who need them. The aim of this study is to carry out a comparative analysis of the production methods of geomorphological maps between the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), which follows the procedure described in "Quaderno 13", and the Instituto Geológico y Minero de España (IGME-CSIC), which follows the instructions contained in "Mapa geomorfológico de España escala 1:50000 Guía para su elaboración" and the "Normas de organización de la información del Mapa Geomorfológico Nacional digital". In fact, in a European context, this comparison will mainly focus on the differences in the classifications of the geomorphological guidelines, as well as the associated geodatabases (e.g., data sets, layers, attribute tables, etc.) and the derived GIS models. This comparative analysis, by highlighting both methodological convergences and divergences, could improve the usability of traditional mapping approaches within a digital representation, highlighting the potential of multiscale and multitemporal geomorphological data representation. Finally, improving the accessibility and readability of geomorphological data will have significant social applications, particularly in improving the evaluations of soil chemistry and regolith geotechnical features. It will also support the promotion and protection of geoheritage, directly benefiting decision-makers, local communities and non-specialist users. By providing clear and structured information, these data can contribute to more effective land-use planning, geomorphological risks management, environmental protection and sustainable resource management.

KEYWORDS: geomorphological mapping, geomorphological representation, GIS database, social application

Influence of human activity on the hydromorphological state of mountain rivers in the Polish and Romanian Carpathians

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The study includes an analysis of the hydromorphological condition of mountain rivers under contemporary conditions in the Polish and Romanian Carpathians. Four rivers - two from the foothills and Beskids of the Polish Carpathians and two from the Romanian Subcarpathians and Carpathians - were assessed. The hydromorphological condition of each reflects its habitat quality and depends on a number of natural and of natural and anthropogenic features. The research was based on a British method, the River Habitat Habitat Survey, which is in line with the EU Water Framework Directive. The Habitat Quality Assessment and Habitat Modification Score indices are used to determine the diversity of natural features and the degree of human transformation of the rivers studied. The research showed that the greatest changes in river hydromorphology and habitat conditions occurred in those parts of the characterised by intensive development of buildings and hydrotechnical infrastructure in both parts of the Polish and Romanian Carpathians.

KEYWORDS: human impact, river, hydromorphology, River Habitat Survey, mountain study

Local community perception of the Eurasian beaver (Castor fiber) in the Carpathians

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Beavers were once an integral part of the environment throughout Europe, Asia and North America. In the Carpathians, beavers disappeared at the end of the 16th century. The reintroduction in the Western Carpathians took place in Poland in 1980-1984 and then in 1999. These activities were aimed at increasing biodiversity and restoring proper water dynamics in an environment significantly altered by human activities. Beavers migrated from the Polish Carpathians to Slovakia. Due to rapid population growth, which has intensified both positive and negative interactions between humans and beavers, understanding societal attitudes towards reintroduced species is crucial to the success of this rewilding initiative. Public perception research was carried out in the Polish and Slovak Carpathians in 2023-2024. The research used a diagnostic survey method with a structured interview format. One of the most important factors influencing attitudes towards beavers was direct experience of damage. The most common types of damage mentioned by local people were undercutting of trees or shrubs, flooding of land, and geomorphological changes. Furthermore, the majority of respondents could not identify any benefits from the presence of beavers. The research showed that there is a need to focus on raising people's awareness of the benefits of beavers in order to improve human-wildlife coexistence.

KEYWORDS: wildlife, beaver, reintroduction, public perception, interviews, Carpathians

Geomorphological conditions of the situation of hillforts in Latvian part of Daugava River valley

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In Latvia, approximately 470 hillforts have been identified. Depending on their proximity to the river, around 60 sites have been documented within the 300 km long Latvian sector of Daugava River valley and its immediate surroundings. A significant proportion of these fortifications remain unexplored from both archaeological and geomorphological perspectives, despite their prominent presence in the landscape. They are typically dated from the Late Bronze Age (1100–500 BC) to the Middle Ages (1200–1500 AD). It is hypothesized that these fortifications were primarily associated with the utilization and control of the waterway, known in Middle Ages as the Daugava Trade Route. Establishing which of these hillforts were contemporaneously maintained is crucial for their historical classification and interpretation, and this requires accurate dating.

The fortifications along the Latvian Daugava River valley and their geomorphological context are the focus of the research project "Interdisciplinary Hillfort Studies at the Daugava River: Merging and Decoding Archaeological, Environmental, and Linguistic Data (INHILLDAUGAR)". This project seeks to advance Corpus-style studies by applying interdisciplinary methods to the analysis of fortification systems and landscapes aiming to address questions concerning chronology, functions, maintenance, demographic aspects, conflict potential, and the broader environmental context of studied hillforts. The research employs non-invasive and minimally invasive archaeological and geomorphological field techniques, integrating linguistic and toponymic studies as well. Archaeological trenches and test pits have been excavated to document the stratigraphic context, recover artefacts, and obtain samples for absolute dating. Trenching activities are complemented by coring, utilizing both motor drilling equipment and manual augering techniques. The geological and geomorphological context of the hillforts is explored through extensive field surveys, including augering and trenching. The chronology of the stratigraphic units, both archaeological and natural, is established through artefact typology, radiocarbon dating, optically stimulated luminescence (OSL) dating, and dendrochronology. All collected data are integrated into archival and contemporary topographic maps, aerial photographs, orthophotos, digital terrain models (DTM), and airborne laser scanning (ALS) data, supported by GIS-based spatial analyses. Between 2022 and 2024, fieldwork has been conducted at 18 fortified sites along the entire Latvian section of the Daugava River valley.

The geomorphological results indicate that hillforts were seldom located on the floor of the Daugava River valley or on fluvial and glaciofluvial terraces. Instead, they were predominantly situated along the valley edges or on the adjacent uplands. Concentrations of hillforts, and later castles, are particularly evident in the Upper Daugava spillway valley, within the river gorge zone between Pļaviņas and Aizkraukle, as well as in the region extending from Lielvārde to Rīga. These fortifications likely played a pivotal role in controlling the Daugava waterway, particularly in areas characterized by rapid river currents.

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KEYWORDS: geoarchaeology, GIS, hillforts

Geomorphology and society --- practical and application

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This paper mainly focuses on the application of geomorphological heritage to the society. Geo-heritage is a combination of geology and physical processes as well as the cultural characters. The awareness of the value of geo-heritage is getting more and more important in Taiwan after designation of geoparks. The methodology to conserve the geo-heritage is rather unclear before 1985 in Taiwan. However, through designation of geoparks, the conserving geo-heritage, in terms of landscape conservation, became clearer for local people to practice. Taiwan is also a hazardous country and needs to pay more attention on these issues on society. This study demonstrates some typical ways of conserving landscapes in Taiwan. First of all, through environmental education; second, through legislation; third, through local participation on geopark affairs; fourth, through guided tour by local interpreters. According to Environmental Education Law, everyone including all departments of different level of government workers and schools have to take 4 hours' environmental education course every year. It helps to enhance the awareness of environment conservation including conservation of geo-heritage. By Cultural Heritage Preservation Law, the designation of geoparks and natural monuments are the tools to conserve the landscapes. Through interpretation on the aesthetic/ scientific value by local licensed guides for visitors, it is a way to prevent further damage by human activities. This study demonstrates the such progresses or interaction with society in Taiwan.

KEYWORDS: geo-heritage, geo-conservation, environmental education, Taiwan geoparks

THEMATIC SESSION 12

GLACIAL GEOMORPHOLOGY AND CHRONOLOGY

Chairpersons:

Zsófia Ruszkiczay-Rüdiger, Marc Oliva, Cristina Balaban, Marcel Mîndrescu, Emil Gachev, Răzvan Popescu

Reconstructing Late Pleistocene glacier dynamics in the Southern Carpathians (Romania) with the Parallel Ice Sheet Model

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Reconstructing interactions between past glaciers, climate and topography over millennial timescales is crucial for predicting their dynamics under future climate change. Abrupt climate oscillations during the Last Glacial Maximum (~24 - 19 ka) and the Last Deglaciation (~19 - 11.7 ka) led to the growth, fluctuations and decay of large ice sheets and smaller mountain glaciers in Europe but the Southern Carpathians (Romania) have not been examined widely in this context.

Here, we present the first application of a palaeoclimate-driven, dynamic numerical ice model (Parallel Ice Sheet Model) to the Southern Carpathians. Focused on the Retezat-Godeanu mountain group, our aim is to simulate the extent, style, dynamics and climatic/topographic drivers of former glaciers in the region. Using a range of static and dynamically evolving simulations, we found that 1) the model could adequately grow plateau icefields and ice domes that match well with geomorphological evidence for ice extent in the region; 2) a significantly colder (-5°C…-8°C temperature deviations from the present) and drier (45%…15% of modern precipitation amounts) climate was required to grow palaeoglaciers to their maximum extents; 3) the model adds glaciological context to the geomorphological data by identifying where ice was slow- vs fast-moving, cold- vs warm-based, and aids interpretation of geological samples potentially containing inherited 10Be cosmogenic nuclides. Finally, by simulating a more muted response of glaciers to palaeoclimate during the Younger Dryas (12.9 - 11.7 ka), we find that it is possible that the Southern Carpathians could have supported limited ice at that time, suggesting where geological evidence for such ice could be sought.

KEYWORDS: glaciation, reconstruction, modelling, Carpathians, Romania

Current geomorphological processes in the middle mountain in Áliva

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Picos de Europa is a limestone and Atlantic massif where the rivers Deva, Cares, Dobra, Duje and Sella have an impact on deep and embedded gorges, this massif in turn is divided into three. In the Central Massif or Urrielles Massif we have the Áliva Ports that are located between the Peña Vieja group and the Eastern Massif or Andara, made up of a succession of black slates interspersed with limestone, limestone and sandstone conglomerates. The objective of this research is to know the current processes in Áliva and for this purpose a control of the different forms that we have in the study area has been carried out, slopes lobes, terracettes, ploughing blocks, badlands and slides, in addition, a monitoring of the soil temperature has been carried out to analyze its influence on the current geomorphological processes. The data analyzed and the measurements made cover the periods from 2008 to 2024.
The techniques used have been GPS-RTK, drone flights, photogrammetry, orthophoto analysis and thermometers installed at different points of interest in the area. For a better interpretation, the area was divided into several sectors, selecting elements and shapes that would allow us to monitor each of the years.
The thermal regime of the soil shows the absence of ice, so we propose that the current dynamics are associated with snow action. On the other hand, the geomatic data show us different displacements, some ploughing blocks with up to approximately 0.04 m/a and gully points with a displacement of approximately 0.16 m/a.

KEYWORDS: geomatic survey, periglacial, Picos de Europa, current processes

The hidden glacial landscape of the Monti della Laga (Central Apennines, Italy)

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The geological and geomorphological record of the Last Glaciation in the Apennines is extensively documented, except for the Monti della Laga sector, where limited indicators of glacier extension have been reported. This study presents field evidence of glacial deposits and landforms from two specific sites within the Monti della Laga Range: Monte Pelone and Tordino Valley head. Although limited, this evidence suggests glaciation within a structural and lithological setting that facilitated rapid slope evolution. The post-glaciation paraglacial processes in the area erased most glacial traces, but our geomorphological and stratigraphical investigations identified specific landforms of glacial origin. Notably, at Monte Pelone, a semi-circular depositional landform exhibiting a significant presence of coarse clasts and distinctive rotational features has been identified as a moraine. Additionally, a smaller moraine ridge with evidence of diamicton deposition was observed in the Tordino Valley head. These observations align with an Equilibrium Line Altitude estimated at 1750 m a.s.l. in the central Apennines in the Last Glacial Maximum and, considering the favourable topographic conditions of the area, significantly contribute to the understanding of glaciations within the central Apennines.

KEYWORDS: glacial geomorphology, Monti della Laga, Last glaciation, Central Apennines, Italy

The longest Pleistocene glaciers on the Balkan Peninsula: certain facts and open debates

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This study focuses on the issue about the maximum extent of Pleistocene glaciers in some mountain massifs throughout the Balkans that have been nominated to have had "the longest glacier" at a certain time in the past. Geomorphological evidence of extensive mountain glaciation was found in the Rila and Pirin Mountains (Bulgaria), Prokletije (Albania, Montenegro, Kosovo), Durmitor and Orjen (Montenegro). However, the absolute values of glacier expression (areas, lengths, ELA levels) have for long been a matter of debate among scientists. In Rila, where the 22 km long Beli Iskar glacier existed during the LGM, there is still an open issue if there was an older and more extensive glacial phase than the Late Wuermian. In Prokletije, various scientists determine the longest glaciers were between 10.5 and 36 km, more than three times difference. Debates exist also in the area of Durmitor massif and around (from valley and piedmont glaciers to a huge ice cap), and similar is the situation in the coastal massif of Orjen. Many more mountains were glaciated in the Pleistocene, but glaciers there were considerably smaller due to the limited extent of glacier accumulation areas in those mountains.
This article summarizes the presently existing views about maximum glacial extent in the mentioned mountains, and presents some original investigations of the author, aimed to contribute in finding solutions to those open debates.

KEYWORDS: glacier, moraine, ice cap, Pleistocene, evidence, ELA

Timing of maximal advances and post-LGM glacier withdrawal in the Parâng Mountain Group (Southern Carpathians, Romania)

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Geomorphological and chronological constraints for maximal glacier advance in the Southern Carpathians (Transylvanian Alps) are poorly documented in comparison with the Tatra Mountains and the Balkan Mountains. Most previous attempts with terrestrial cosmogenic nuclide (TCN) dating have concentrated on Late Glacial moraine sequences located above the tree line, whereas only single studies were conducted on maximal moraines hidden in densely forested areas. Additionally, the distribution and pattern of glacier recession from the maximal moraines were largely unstudied due to poor mapping documentation. Moreover, strong degradation of maximal moraines and possible contamination with blocks from rock slope failures are responsible for commonly too young ages of TCN-dated moraines. Therefore, most published LGM chronologies yield only the minimal age of a maximal glacier advance in the Southern Carpathians.

To fill this gap, we propose a new 10Be chronological constraint for maximal moraines in the Parâng Mountains. This range is the second-highest mountain massif in Romania (Parângul Mare, 2518 m asl), which exhibits well-developed glacial relief on granite and metamorphic lithology. Recently acquired high-resolution LiDAR data for western Romania provide for the first time an opportunity to map with high accuracy the extent and morphometry of glacial features in the Parâng Mountains. Using this data, we found a well-developed maximal moraine sequence in the Jieţ valley located on the northern slope of the massif. Prominent, multi-ridged (up to five) latero-frontal moraines mark the extent of the 8.5 km long valley glacier during the local last glacial maximum. Additionally, older, highly degraded moraine covers with several perched boulders were found up to ~ 1 km beyond LGM moraine walls. They are interpreted as the remnants of glacial landforms originating during earlier glacial periods. This is potentially the first recognition of pre-LGM moraines in the Southern Carpathians. Both LGM and pre-LGM moraines in the Jieţ valley are rich in large (3-6 m) surface granitic and gneiss boulders, which are suitable for dating using the 10Be method. A total amount of 12 rock samples were collected at the Jieţ moraine complex, representing pre-LGM, LGM and recessional moraine sites. This new 10Be glacier chronology for the Parâng Mountains enables the determination of the timing of maximal glacier advance as well as the duration of local LGM and the onset of deglaciation, thus contributing to the knowledge of the last glaciation chronology in the Southern Carpathians.

KEYWORDS: ^{10}Be exposure ages, LGM, pre-LGM moraines, Parâng Mountains, Southern Carpathians

Geomorphometric analysis of glacial curvilineations: a case study from the Komorze Lake, N-W Poland

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Glacial curvilineations (GCL) are postglacial landforms characterized by parallel, sinuous ridges separated by depressions, typically occurring in tunnel valleys. These features were identified relatively recently and are thought to result from subglacial processes, particularly rapid subglacial floods. Reconstructing the dynamics of ice sheets and understanding the processes that shaped postglacial landscapes require detailed studies of landform genesis, particularly through geomorphometric approaches. Despite growing research interest, GCLs remain insufficiently explored.

This study focuses on GCLs identified in the Komorze Lake trough within the Drawskie Lakeland, north-western Poland. The research applies geomorphometric methods to detect and characterize GCL swarms and their individual ridges and depressions. Automated mapping was conducted using a high-resolution digital terrain model (DTM) derived from LiDAR data. Methods such as the Topographic Position Index (TPI) and geomorphons were used to systematically analyze and classify the GCL assemblages, supporting the identification of both curvilinear patterns and associated topographic features.

This methodological approach provides a reproducible framework for both manual and automated analyses of subglacial landforms. By refining techniques for identifying and classifying GCLs, the study contributes to a better understanding of their origin and evolution in relation to ice-bed dynamics. The findings offer valuable insights into the geomorphometry of postglacial landscapes and the processes shaping them.

KEYWORDS: glacial curvilineations (GCL), tunnel valley, Topographic Position Index (TPI), geomorphons, Drawskie Lakeland

Scalloped cliffs in the outcrops of north pole of Mars

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The North Polar Layered Deposits (NPLD) of the Planum Boreum of Mars are stacked layers of water ice and dust deposited during the Amazonian period. The stratigraphy of the NPLD preserves the geological records of the climate history through cyclic episodes of accumulation and erosion. Alternate periods of past accumulation and erosion of the NPLD layers can result in unconformities. These features are sometimes exposed at the surface by troughs and scarps and these outcrops provide significant information about the surface and subsurface geomorphology. Our study aims to catalogue locations of outcropping cliffs and the unique surface morphology of "scalloped cliffs" that are associated with unconformities in various ways. We identify and map 98 scalloped cliffs across the NPLD, and most of the cliff formations are immediately associated with a stratigraphic unconformity. We observe using imagery from the High-Resolution Imaging Experiment (HiRISE) and Context Camera (CTX). Most cliffs are found in the Gemini Scopuli region of the Planum Boreum, where there is an extensive history of multiple periods of erosion that created unconformities. These cliffs often express scalloping or waviness with varying wavelengths. Some cliffs have block falls on their cliff faces and this happen because of the sublimation of the ice in northern summer, deposited during the northern spring. The structure of a cliff consists of three main sections: the cliff top, the cliff face, and the cliff bed/bench and this classification provides a better understanding of the geomorphological features and processes associated with cliff formation and erosion. All identified scalloped cliff locations are compiled in a catalogue with image details, coordinates and elevation and then categorized into types of cliffs according to the association with unconformities. Additionally, we present two distinct hypotheses behind their formation. For the formation of the cliffs, we hypothesize that an erosion-resistant layer must overly an erosion-prone layer, and the differential erosion of layers and through mass wasting, inducing block falls and steepening. Most scalloped cliffs are associated with an unconformity but in a few low relief cliffs, we suspect an unconformity is unresolvable from the orbit or could be a disconformity. we hypothesize that the scalloped cliffs form when dust-rich lag deposits, at unconformities, are between more resistant water ice layers and that their unique wavy appearance is due to wind scouring.

KEYWORDS: Mars, polar geology, layered deposits, scalloped cliffs

^{10}Be data from Făgăraș and Retezat Massifs set the timeframe of the last glacial activity in Southern Carpathians during Younger Dryas and Early Holocene

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Past glaciations extent and chronology in the Romanian Carpathians have been disputed along most of the 20th century. Despite the recent studies presenting numerical age datings of the glacial deposits and erosion surfaces, the view on the latest glacial activity remained in debate due to results from Retezat Massif (one of the high and best studied massifs from Southern Carpathians), where authors found no evidences of Younger Dryas glaciers. In this context, we bring in the discussion new data from Retezat but even more from the Făgăraș Massif, which is the highest and largest massif from Southern Carpathians but less studied in relation to the Pleistocene glaciations with only a handful of numerical ages obtained so far. The new ^{10}Be exposure ages collected from the highest moraines, fit the Younger Dryas - Early Holocene interval, in good agreement with European records, suggesting the glaciers reformation and advance during the Younger Dryas. It appears that some of the Younger Dryas glaciers survived in the first two millennia of the Early Holocene or reformed during Pre-Boreal Oscillation when cool and humid conditions have been present over Europe. Finally, we modeled the presence of Younger Dryas glaciers for the whole Făgăraș massif using the topographic and microclimatic characteristics of the glacial cirques which hosted new glaciers (proven by numerical ages) and found that ca 90 glaciers restricted to cirques formed during Younger Dryas in the Făgăraș massif.

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KEYWORDS: ^{10}Be dating, geochronology, Younger Dryas, Southern Carpathians

Glacial imprint on quartz grains from Pleistocene glaciers of different ages in Tatra Mts. (Carpathians) regardless of glaciers' parameters

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Sets of certain microtextures on the sand-size quartz grains can imply their depositional environments. Grains derived from glacial tills exhibit microtextures connected to abrasion (grinding and attrition) and crushing (fracturing) processes considered most powerful in subglacial settings. It has been assumed that the frequency of these features differs between the thin and thick ice and depends on transport length and basal shear stress. Yet, boundary conditions required to change quartz grains' morphology in glacial settings are still insufficiently recognized. Here we challenge these assumptions and promote the opposite view that the comminution of quartz grains in subglacial conditions is not related to glaciers' parameters. To confirm this hypothesis we collected samples from different-age glacial tills (pre-LGM, LGM, and post-LGM) from five Pleistocene glacial systems in the Tatra Mts. (Western Carpathians). Their length ranges from 2.3 km to 13.4 km and their maximum thickness is between 100 m and 420 m. We found grains with glacially-induced microtextures at all studied sites. The number of grains with abrasion/crushing microtextures does not correlate with the size of the glaciers, neither with their shear stress factor ranging from 73 to 151 kPa. Our results demonstrate that a high abundance of these features is not restricted to large glacial systems, in fact, even in small valley glaciers, up to 70 % of the grains can obtain glacial microrelief. Our findings suggest that the occurrence of abrasion/crushing microtextures in a glacial environment is likely the combination of substratum lithology, sediment texture, and till origin. We also hypothesize that at least two glacial stages can be distinguished based on the relative freshness of microtextures within a single sample. Our findings are reinforced by field geomorphological data, which, for the first time, confirm the presence of pre-LGM glacial deposits in the Western Tatra Mountains.

KEYWORDS: scanning electron microscopy, quartz, glacier, Carpathians

ZOSSM – zone of superimposed subaqueous megadunes in the vicinity of Serwy Lake, NE Poland

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The Zone Of Superimposed Subaqueous Megadunes (ZOSSM) near Lake Serwy is the next subject of the investigations of bedforms resulting from glacial lake outburst floods (GLOFs) from the Weichselian glaciation, after the discovery of the Suwałki Glacial Megaflood Landsystem in the western part of the Augustów Plain (outwash) in northeastern Poland. The study's main objective was to investigate the swarm of huge subaqueous bedforms by creating a database consisting of geomorphometric parameters (lengths, heights and slope gradients) and indices (steepness and asymmetry). The results were compared with well-known examples of GLOF-related bedforms worldwide (Missoula, Altai, British Columbia, NE Poland).

The study integrates 1x1 m resolution LiDAR-based digital elevation models to identify and measure the geomorphometric parameters of 254 large-scale subaqueous dunes. The results show the variability of dunes morphology, with lengths ranging from 23.6 to 241.8 metres and mean heights from 0.6 to 5.4 metres. This morphological diversity creates a continuum that reflects the characteristics of subaqueous dunes associated with GLOFs in other regions. Notably, many of the dunes exhibit symmetry, suggesting that they likely formed as antidunes and Froude supercritical floodwater outflow in unconfined setting.

The significance of this research lies in its contribution to the understanding of bedform development and recognition of floodwater outflow direction and regime, which sheds new light on the development of valley system in European Lowland. The discovery of ZOSSM is crucial in advancing knowledge of GLOF effects on outwash plain origin, which have long been under-researched in this context. The study also highlights the importance of using GIS tools and high-resolution LiDAR data to identify previously unrecognised landforms, thereby improving our understanding of outwash hydrodynamics and sedimentation patterns.

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KEYWORDS: glacial lake-outburst floods, outwash, geomorphometry, subaqueous megadunes, Weichselian glaciation

Late-Quaternary glacial history in the Milang Watershed, Lahaul Himalaya, Western Himalayas

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Glacial and Geological studies investigate the pieces of evidence to understand the timing and extent of glaciation of the late Quaternary period. Studying past glacial records can also be helpful in reconstructing the effects of environmental change in the region. The study of the Quaternary glaciation in the Himalayan and Tibetan regions has remained the focal point of several scientific research. The palaeo-glacial and palaeo-climatic reconstruction of the Milang watershed (MLW) has been done with the help of using geomorphic mapping and cosmogenic 10Be surface exposure, and Optically Stimulated Luminescence (OSL) dating. The MLW is a sub-basin of the Chenab basin in the Lahaul region of the Western Himalayas. It lies in the zone of transition between the arid regions of Spiti, Ladakh, and Tibet and the monsoon-influenced regions south of the Pir Panjal in Himachal Pradesh. This study reports the first ^{10}Be dates for the MLW watershed and tries to co-relate the results with a regional framework for palaeo-glaciation in the Lahaul Himalaya as given. Based on the Landform Mapping, ^{10}Be exposure and OSL ages the palaeo-glacial extent of the MLW has been reconstructed. Three major palaeo-glacial stages, namely, Chandra (~81.5 ±3.94 ka), Darcha (12 ka to 15.5 ka) and Mulika (~8 ±1.47 ka) have been identified. The Chandra stage of glaciation refers to a massive valley glaciation influenced by the Monsoon. The glaciers occupied the Chandra and Bhaga valleys. The Darcha stage represents a valley-wide glacier extended in the main Milang valley. It coincides with the regional glacial stages of SWHTS (Semi-arid Western Himalayan-Tibetan Stage) 2A, SWHTS 2B, and SWHTS 2C influenced by Westerlies. The Mulkila stage was a major glacial advance stage that occurred during the early Holocene. It is represented by well-preserved glacial trimlines and sharp-crested moraine ridges. During this stage the South Asian Monsoon moisture was dominant and glaciers were more sensitive to precipitation.

KEYWORDS: Himalaya, geochronology, glaciers, climate change, Palaeo-climate

Cirques and glaciation in the Balkans – a new piece of the mosaic: the cirques of Rila and Pirin Mts

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In the mountains of the Balkan Peninsula and the Southern Carpathians rising above 1500 meters, cirques are abundant. Their location and characteristics are related to the paleoclimate of the glacial periods and to the topographic and geological settings. The two main parameters to characterise the cirques are the cirque floor elevation and the median axis aspect. Cirques can be found in the Southern Carpathians and the Balkans between 1350 and 2700 m asl. The cirque floor elevation usually increases from west to east and from north to south. The dominant aspect is generally to the north, northeast or northwest. These parameters are determined primarily by climatic effects, but are also influenced by the pre-glacial topography (existence of plateaus and direction of the ridges) and the lithological features (e.g. glaciokarst processes). Although lots of data are available for a large part of the Balkans, a detailed morphometric analysis of all cirques in the Rila and Pirin Mountains (Bulgaria) has not yet been carried out. In our presentation, we compare the literature data for previously glaciated mountains in Southeast Europe with our data obtained during the study of Rila and Pirin cirques. According to our findings, the cirque floor elevations in the Rila and Pirin are among the highest in the in Southeast Europe that indicates more continentality and limited amount of precipitation compared to both the South Carpathians and the Dinarides. The distribution of cirques according to the aspect shows a clear concentration, in the case of Pirin towards the NE, in the case of Rila towards the N, which can be attributed to the main NW-SE and W-E strike of the ridges in the two ranges, respectively. Rila cirques are generally shallower and less developed, likely due to the presence of extensive pre-Quaternary planation surfaces. In contrast, the Pirin cirques, particularly those formed on marble bedrock, are more incised. Thus, paleoclimatic, topographic and geologic influences are all recognizable in Rila and Pirin cirque development, similarly to other high mountains in Southeast Europe.
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KEYWORDS: cirque, Balkans, morphometry, glacial, Rila

West-East asymmetry of the main crest of Făgăraș and Rila Massifs documents the polycyclic glacial shaping

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We present here the key morphometric parameters of the main ridge in two massifs located in south-eastern Europe, along with those of the adjacent rock walls and glacial cirques, in order to assess the west-east morphometric asymmetry within these massifs. The selected massifs are Rila and Făgăraș, which, in addition to being the highest in the Carpathians and North-Balkan Mountains, share the most extensive west–east development among all mountain ranges in southeastern Europe. We hypothesize that this morphometric asymmetry primarily stems from differences in the glaciation efficiency, with the western part benefiting from more humid conditions (i.e. higher snowfalls), which fostered the growth of larger glaciers and, in turn, led to more intensive erosion on the massif. The morphometric analysis was conducted in GIS environment using a 5-m resolution raster. It incorporated a set of parameters that collectively estimate the glaciation effectiveness: development of glacial cirques (e.g. relative depth, presence of lakes), width of the main crest, slope declivity of peaks, and both the width and mean slope of the rock walls adjacent to the main crest. By combining the west-east asymmetry in morphometric data with different proposed rates of glacial erosion, we aim to determine how many major glacial phases have shaped the current alpine level in these massifs, and whether the parameters exhibit similarities in both massifs.

KEYWORDS: glacial, erosion, morphometry, Rila, Făgăraș

Unique subglacial landsystems in northern Poland as a record of catastrophic meltwater flows

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An abrupt release of large volumes of meltwater from glacial lakes at the southern periphery of the Scandinavian Ice Sheet resulted in the formation of extensive glacial megaflood landscapes in northern Poland at the end of the last glaciation (Weckwerth et al., 2019). These landscapes include unique subglacial landsystems in the Dobrzyń and Suwałki Lakelands, consisting of first- and second-order subglacial features (Weckwerth and Wysota, 2024; Wysota et al., 2024).

The first-order landforms comprise extensive erosional areas up to 10 km wide and over 20 km long. They exhibit a remarkable diversity of morphologies, consisting predominantly of large compound tunnel valleys accompanied by widespread erosional levels. The erosional features dissect the moraine upland to a depth of tens to around 90 meters. Tunnel valleys and erosional levels contain numerous second-order erosional forms, including glacial curvilineations, erosional remnants, potholes and meltwater scours, and narrow channels, most of which occur at several topographic levels. Compound tunnel valleys also contain depositional landforms such as kames and eskers, which are often superimposed on the second-order erosional features.

The distinctive characteristics of these erosional forms demonstrate that catastrophic meltwater floods created unique subglacial landscapes in the study areas. The scale of erosion suggests broad, tens of metres deep meltwater flows, resulting in widespread unconformities. Landforms occurring at several topographical levels indicate a multi-stage carving of the substratum by subglacial meltwater flows, most likely in multiple discharge events. Following the erosional event, ice stagnation and subsequent sediment deposition occurred in supraglacial crevasses and channels. It has been hypothesised that meltwater stored in subglacial or potentially supraglacial reservoirs may have been a contributing factor to the catastrophic floods. In the case of the Suwałki megafloods, the most likely source of water was a hypothetical subglacial lake situated within a substantial depression in south-western Lithuania. However, the possibility that this glacial flood was also fed by supraglacial lakes cannot be discounted. In the case of the Dobrzyń megafloods, it is suggested that supraglacial lakes were feeding the floods.

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KEYWORDS: subglacial relief, glacial megafloods, last glaciation, northern Poland

Linking glacier area loss and temperature rise in the Chhombo Chhu watershed of Tista basin, Sikkim Himalaya

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Glaciers in the Tista Basin, especially those in the Chhombo Chhu Watershed (CCW), are vital water sources for local mountain communities and the larger populations downstream. This study examines both glacier area reductions and changes in surface temperatures from 1975 to 2018 in the CCW, using remote sensing data from Hexagon KH-9 (1975), Landsat 5 TM (1989, 2010), Landsat 7 ETM+ (2000), and Sentinel 2A (2018). The CCW contains 74 glaciers, with an average area of 0.61 km^2. In 1975, the total glacier area was 62.6 ± 0.7 km^2, which decreased to 44.8 ± 1.5 km^2 by 2018, corresponding to a significant loss of 17.9 ± 1.7 km^2 (0.42 ± 0.04 km^2 annually). Debris-free glaciers experienced the largest area reduction (11.8 ± 1.2 km^2 or 0.27 ± 0.03 km^2 per year), followed by partially debris-covered glaciers (5.0 ± 0.4 km^2 or 0.12 ± 0.01 km^2 per year), and debris-covered glaciers, which showed minimal change (1.0 ± 0.1 km^2 or –0.02 ± 0.002 km^2 per year). The rate of glacier recession accelerated from 0.62 ± 0.5 km^2 per year during 2000–2010 to 0.77 ± 0.6 km^2 per year in the subsequent 2010–2018 period. Surface temperature analysis using Landsat TM-5 (1988) and Landsat OLI/TIRS-8 (2017) revealed a notable warming trend of +3.6°C across the glaciers, with increases in both minimum (+0.4°C) and maximum (+6.2°C) temperatures. These temperature increases were spatially variable, influenced by local topography, aspect, and the interplay between glacier albedo and insulation. This thermal warming coincides with the observed glacier shrinkage, indicating a direct connection between rising temperatures and accelerated glacier retreat. Together, these findings provide crucial insights into the climatic drivers of glacier dynamics in the Sikkim Himalaya, contributing valuable data for hydrological assessments and water resource management in the region.

KEYWORDS: glacier retreat, temperature trends, satellite imagery, Chhombo Chhu watershed, Sikkim Himalaya

A peculiar style of valley-type glaciation during the Alpine LGM: insights from the Seckauer Tauern, Austria

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Recent studies increasingly focus on numerical modelling of the expansive Last Glacial Maximum (LGM) glacier network of the Alps, using ice flow dynamics and climate forcing. Isolated local mountain glaciers, disconnected from the main glacier network, are particularly important to calibrate numerical models. They preserve key information about local mass balance and paleoclimate conditions, which can be analyzed through equilibrium line altitude (ELA) studies. In the easternmost part of the Eastern Alps, numerous small mountain glaciers were isolated from the main glacial network. A notable example is the Seckauer Tauern massif, located in the eastern part of the Lower Tauern Mountains (German: Niedere Tauern). The massif is built with crystalline lithology and stands out for its well-preserved geomorphological imprints of valley glaciation. This study presents a new reconstruction of LGM glacier extents and 3D surface geometry in the massif, based on geomorphological evidence from field and DEM observations, along with ELA calculations, offering new insights into local glaciation patterns and climate conditions during the LGM. The area hosted 51 small glaciers, which covered a total surface of 180 km^2. The largest glacier was 14 km long, covered 33 km^2 of area, and was about 340 m thick which makes it comparable to the largest Carpathian glaciers during the LGM. The glacial relief in the broad U-shaped N-S oriented Pölstal valley delimits the massif to the west, and is particularly interesting because here, two glaciers from tributaries reached the valley floor, forming fan-shaped latero-frontal moraines with dead-ice mounds and undulating terrain. Those prominent landforms contrast with the subdued relief of the valley and illustrate small piedmont-type glaciers during the LGM, highlighting their limited development compared to earlier glaciations that shaped the U-shaped valley. The glacier ELA across the massif averaged between 1600 and 1700 m during the LGM and increased slightly from east to west. This contrasts with the regional trend observed in Central Europe, where the ELA generally rises eastward into the continent's interior. The glacier ELA across the massif averaged between 1600 and 1700 m during the LGM and increased slightly from east to west. This contrasts with the regional trend observed in Central Europe, where the ELA generally rises eastward into the continent's interior. This local trend most likely results from orographic-induced precipitation which generated moisture starvation and ELA rising trend toward the interior of the Alps. The influence of western moisture advection was minimal in this region due to the significant topographic shielding by the Alps and their ice cover to the west. This finding aligns with similar conclusions about local ELA variability of satellite glaciers along the southern edge of the Alpine ice cover, highlighting the very localized nature of climatic conditions and precipitation distribution during the LGM in the Alps.

KEYWORDS: LGM, moraines, glacier reconstruction, ELA, Eastern Alps

THEMATIC SESSION 13

KARST GEOMORPHOLOGY: A MODERN PERSPECTIVE

Chairpersons:

Maria-Laura Tîrlă, Nenad Buzjak, Francisco Gutiérrez, Christos Pennos, Rannveig Skoglund

Revealing coastal subsidence by Quaternary faults through karst vadose records

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Traditionally, karst studies along carbonate coastlines have focused on reconstructing Quaternary coastal uplift and sea-level fluctuations. However, their potential for investigating coastal subsidence and extensive faults remains largely unexplored, particularly in regions with limited sedimentary records. Our study examines the utility of karst research in the identification of Quaternary faults within the paleogeographic evolution of the Granada coast in southern Spain—an area where records of recent tectonic movements are scarce. Existing data, coupled with a lack of evidence for uplift, led to the hypothesis that the Granada Coast may be experiencing subsidence, though this remained unverified. While submerged marine terraces were previously attributed solely to sea-level oscillations, our multidisciplinary approach—integrating karst vadose features, biostratigraphy, and the dating of 22 speleothems—provided new insights into the regional tectonic history. Our findings indicate that the Granada coast emerged between 3.5/2.4 Ma and 650 ka ago, predating similar uplift events in adjacent coastal areas to the west and east, which occurred within the last 200–180 ka. This temporal disparity suggests that sea-level changes alone cannot explain the observed patterns, highlighting the role of tectonic activity in shaping the coastline. We identified extensional faults as the primary drivers of coastal subsidence, aligning with previous studies in nearby regions. However, their specific impact on the Granada Coast has not been comprehensively assessed until now. Our research demonstrates a novel application of classical karst studies in understanding coastal subsidence and active extensional tectonics. By comparing vadose cave ages with established chronologies in adjacent coastal areas, our approach provides new perspectives on the complex tectonic evolution of coastal regions.

KEYWORDS: karst, coast, subsidence, Quaternary fault

Asymmetric dolines in the Central Styrian Karst: a periglacial imprint?

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The formation of dolines in carbonate karst terrains typically spans long timescales, often exceeding 10,000 or even 100,000 years. Over such extended periods, climatic conditions can vary substantially, meaning that many dolines in today's temperate environments were primarily shaped under significantly different climatic regimes. In central Europe, these were the colder conditions during the Pleistocene. This study focuses on a specific type of dolines in the Central Styrian Karst (CSK), located near the eastern margin of the Alps. During the colder periods of the Pleistocene, this area experienced periglacial conditions but remained unglaciated, unlike the alpine regions further west, which were affected by Pleistocene glacial denudation. Given the absence of glacial erosion karst landforms are presumed to have persisted for a long period of time. Consequently, the CSK is a suitable area to investigate landscape evolution in a non-glaciated Alpine environment where karstifiable rocks were also affected by periglacial processes. Additionally, the CSK contains numerous planation surfaces grouped into several levels, dating back to several million years. Recent analyses using airborne laser scanning have revealed previously undocumented asymmetries in many dolines within the CSK. These dolines exhibit a consistent NW-SE elongation, with steeper slopes facing S-SE. While asymmetric dolines in other regions have been linked to tectonic influences or to the dip of strata, this explanation appears insufficient for the CSK, as no correlation exists between doline asymmetry and proximity to major fault systems. Furthermore, dolines distant from faults exhibit clear asymmetries, suggesting an alternative controlling factor. The occurrence of asymmetric dolines within an elevation range of 540 to 780 m asl. implies multiple formation phases, contradicting a syngenetic origin and instead pointing to a reshaping of the originally circular features to elongated geometries. Similar asymmetries have been documented in the Northern Calcareous Alps, where they have been attributed to snow patch dynamics – specifically, wind-driven snow accumulation in the lee of doline rims. This process is characteristic of nival karst, which develops in the absence of glacial erosion but requires permafrost conditions to restrict subsurface drainage. According to paleo-climatic reconstructions, the CSK would have met these conditions during colder phases of the Pleistocene. We hypothesize that the asymmetric morphology of dolines in the CSK might reflect a periglacial influence, preserving evidence of past periglacial processes and climate conditions.

KEYWORDS: dolines, sinkholes, asymmetry, periglacial origin, nival karst

Geomorphological and microclimatic evidence of periglacial processes in caves – the case of Samograd and Budina ledenica caves (Croatia)

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The impact of accelerated climatic change is becoming increasingly evident in subterranean environments, particularly in caves and pits where snow and ice used to persist for extended periods. In Croatia, over the past decade, an unprecedented retreat or complete disappearance of these ice deposits has been observed in numerous caves and pits, underscoring the importance of additional research into cave microclimate and geomorphological characteristics.

The aim of this study is to demonstrate how systematic measurements of seasonal variations in air temperature and CO_2 concentration, combined with geomorphological analyses of caves, enable the reconstruction of past geomorphic processes. In Samograd Cave, a dynamic convection cell was identified: in summer, it facilitates CO_2 accumulation, while in winter, cold air markedly reduces CO_2 levels, leading to significant cooling of the cave interior. A similar situation was recorded in Budina ledenica, where morphology and temperature fluctuations mirror the processes observed in Samograd Cave. Experiences from Scărișoara Cave (Romania) and Eisriesenwelt (Austria) further indicate that such microclimatic conditions in the past could have supported the formation of permanent ice deposits. Geomorphological evidence of former ice accumulations has been mapped in the two caves in various denudational forms on rocks and speleothems, as well as in cryogenic sediments. By applying geomorphological mapping, using present-day analogues and combining current microclimatic measurements with geomorphological markers, we can reconstruct ancient freezing processes and understand how past climatic conditions shaped the subterranean environment. This research enhances our understanding of the interplay between microclimate and geomorphology and can serve as a basis for further multidisciplinary studies on cave system evolution in an era of global warming.

This work has been supported by the Croatian Science Foundation under the project Dynamics and distribution of CO_2 in karst vadose and epiphreatic zone (CARDIKARST) IPS -2022-02-2260.

KEYWORDS: ice cave, geomorphological marker, microclimate, CO_2

Dolines as fire refuges: the example of the Kras Plateau and the 2022 wildfire event, Slovenia

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Climate change contributes increase the frequency of natural hazards worldwide, and Slovenia is no exception to this trend. In the summer of 2022, a prolonged drought resulted in the largest recorded wildfire in the country's history, affecting the Kras/Carso Plateau on the border between Slovenia and Italy. The total area encompassed by the fire in Slovenia was 3,707 ha, of which 2,902 ha were forests (78% of the total fire area). However, it is frequently observed that certain areas remain unburnt by chance or due to lower flammability. Such patches are termed "refugia" and can be distinguished as either natural or anthropogenic in origin. In landscapes, specific landforms and/or landscape elements (e.g., water bodies, rocky cliffs) may exhibit no, fewer or less severe fires. Field examination of the area following the 2022 fire in the Kras Plateau was conducted in the scope of the European project Karst FireWall 5.0, where some dolines were identified as unburnt or less burnt. In previous studies (Bátori et al. 2019; Čarni et al. 2022) dolines were recognised as refugia for cool-adapted vegetation species on karst plateaus. In these depressions the microclimate conditions differ significantly from the surrounding (macro)climate of the extensive and generally flat plateau. For example, cooler air and thicker soil accumulate at their bottoms, leading to higher humidity and lower temperatures than in the surrounding area. Such conditions can prevent fire from entering the dolines.

Therefore, in this study we focused on the dolines in the burnt area and analysed how their geomorphological characteristics affected the burn severity of the forests. In the first step, we classified the dolines into four clusters based on 15 different geomorphological characteristics (i.e., area, perimeter, volume, depth, width, length, elongation, slope, aspect TPI, VRM, TWI, curvature, negative and positive openness). Then, we linked these clusters to the burn severity of the forests (estimated by Slovenia Forest Service). We presented the dolines in a multidimensional space of detrended correspondence analysis (DCA) with a passive projection of the burn severity of the forests (estimated by four categories). After correlation and regression analysis, we established that smaller and shallower dolines are more severely burnt than larger and deeper ones.

Landforms that act as fire refuges present a unique opportunity for biodiversity conservation and the reduction of potential fire risk to people and infrastructure. Consequently, the identification of such refuges may assist land managers in including these areas in relevant conservation strategies.

KEYWORDS: landforms, geomorphology, karst, refugia, natural hazards

Role of dissolution in the formation of “pseudokarst” relief in the Stołowe Mts (SW Poland)

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The Stołowe Mts, constituting a part of the Sudety Mts and situated in SW Poland, are an example of sandstone tableland, abounding in rock outcrops with numerous corridors, caves and roofed slots. The top and marginal parts of the tableland on a significant area support ruiniform relief, consisting of isolated bedrock compartments separated by joint-aligned corridors. Unveiling its genesis and controls is challenging, since sandstone counterparts thought to be subject to the most intense decay are usually no longer existent, being replaced by the corridors and slots. The formation of relief features in the Stołowe Mts has usually been described as “pseudokarst”. Investigation of a small cave and roofed slots in the Stołowe Mts allowed us to tackle the problem. We demonstrate that chemical dissolution of cement plays an important role in the formation of slots and corridors constituting ruiniform and the process is controlled by both the geological and environmental factors. The former includes thick sandstone beds with subhorizontal attitude, well-developed vertical jointing and coarse grain size, all accounting for preferential groundwater drainage and the susceptibility to mechanical removal of mass. The dominance of quartz and kaolinite in mineral composition, together with the present-day temperate climate and the dense vegetation cover, result in the development of permeable and very acidic soils. Such soils allow efficient rainwater percolation, produce chemically aggressive acidic solutions and create room for the dominance of fungi among soil microorganisms. The development of the corridors of ruiniform relief is associated with structure-controlled topographic lows upon the plateau surface, which act as sinks. There, the throughput of acidic water enriched with microorganisms is the highest and over prolonged period of time causes dissolution of clay minerals and quartz, increasing rock porosity and deteriorating making sandstone deteriorated en masse. Subsequently, such an arenized portion of rock is subject to grain-by-grain removal. The cavity below the enclosed depressions propagates upwards until the emergence of an unroofed corridor. The remaining bedrock compartments, case-hardened by reprecipitated minerals and colonies of microorganisms, are also subject to dissolution, but at a slower pace.

KEYWORDS: pseudokarst, ruiniform, arenization, dissolution

Environmental and landscape meaning of the tufa deposits in a cultural context: the case of Añana Salt Valley (Álava. Spain)

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Tufa buildups are geomorphological elements of significant environmental interest. They are excellent indicators of the landscape changes of the territory and authentic paleoenvironmental archives. Furthermore, the beauty and spectacular nature of certain tufa landscapes provide them with important natural heritage values strongly intertwined with cultural heritage.

Añana Salt Valley is situated in the High Ebro basin, occupying the southern slopes of the Cantabrian and Basque mountain ranges, within sub-Atlantic transition zone. Geologically, Añana Salt Valley is located on a diapiric structure over Triassic (Keuper facies). This structure overlies more than 5,000 metres of Mesozoic and Cenozoic lithologies, mainly calcareous, and several aquifers. The salty waters emerge from four springs located in the contact between the Jurassic limestones and the clayey materials of the Keuper, springs of highly saline water are located. These saline springs are the origin of salt exploitation in the valley, dating back to the Neolithic period, around 7000 BP, making this one of the oldest documented salt exploitations.

In Añana Salt Valley, Holocene-aged barrage fluvial tufa fills the main valley. Two tufa sedimentation stages, separated by an incision phase, have been identified. The oldest stage, associated with the Atlantic period, is characterized by a 7 m thick valley fill deposit in which biogenic tuffaceous levels alternate with other detrital ones, along with other levels of clear anthropogenic influence, linked to the ancient salt mining activity. The most recent tufa cascade, in association with macrophyte hummocks, is located in a lateral freshwater upwelling.

The intensification of salt exploitation activities led to an intense alteration of the environment that caused the incision of the main tufa buildup, leaving terraces hanging up to 5 m on both sides of the valley riverbed. This stage is coherent with the model established for the Upper Ebro, in the Millennium of Change (between the Subboreal and the Sub-Atlantic). The incision occurred as human impact intensified, exceeding a critical threshold that shifted the dynamics from tuffaceous valley-fill sedimentation toward incision This idea is consistent with the evidence for a decline in tuffaceous growth in Europe in the recent Holocene.

Subsequently, tufa precipitation processes resumed and continue to this day, which can be interpreted as a rebalancing response of the geosystem.

The study of tufa in Añana has provided initial insights that allow to establish a first approximation to the recent landscape history. The alternating periods of strong natural protagonism in which the tufa buildups are shaped, with periods of human protagonism, defined by intense salt exploitation, control the evolution of the landscape and give full meaning to the notion of cultural landscape.

KEYWORDS: Tufa buildups, Añana Salt Valley, Holocene, landscape evolution

Tectonic and diapiric geomorphology in the Jahani salt extrusion, Zagros Mountains, Iran

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The Zagros Mountains in Iran constitute the best natural laboratory for the investigation of active salt extrusions worldwide. In fact, the salt domes and glaciers (namakiers) of the Zagros Fold and Thrust Belt have been selected as a IUGS Geological Heritage Site, and have also been identified as a potential UNESCO World Heritage Site because of their remarkable salt karst developed on a mobile salt bedrock. As part of the DIAPERNO project, funded by the Spanish Government, a multidisciplinary investigation has been conducted at the Jahani salt extrusion. This is an active salt fountain with a well-defined summit dome and radially spreading namakiers associated with the active right-lateral strike-slip Kareh Bas Fault in western Fars Arc of the Simply Folded Belt. The northern namakier of Jahani interacts with the Shur River, which has carved a salt escarpment, which is probably the largest on Earth. The following issues are addressed in the investigation of this world-class salt diapir and strike-slip fault system: (1) neotectonics and paleoseismology associated with the Kareh Bas Fault and its role on the emergence and development of the Jahani salt extrusion; (2) maximum extent of the salt fountain in the past; (3) damming of the Shur River in the past by a salt glacier and the development of an upstream lake; (4) current activity of the salt fountain based on DInSAR data; (5) characteristics and evolution of sinkholes developed on continuously spelling and flowing salt; (6) development of unique large polje-like salt karst depressions; and (7) occurrence of unique ephemeral halite rimstones.

KEYWORDS: salt diapir, diapiric deformation, salt karst, namakier, paleolake

Using cave surveys to unravel speleogenetic conditions. The Lefka Ori karst massif on Crete Island, Greece

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Cave levels represent distinct horizontal passages confined within narrow vertical ranges. While the term "cave level" specifically refers to passages influenced by external baselevels, "tier" or "storey" describes passages controlled by structural or stratigraphical factors. This distinction is crucial for understanding cave morphology and development. The Lefka Ori (White Mountains) region of Crete is an area of extensive cave development. The geological composition, dominated by carbonate rocks, combined with intense tectonic activity and substantial precipitation, creates optimal conditions for speleogenesis. The region hosts an impressive network of over 1000 documented caves, including Greece's two deepest cave systems: Gourgouthakas and Lion caves. These cave systems form integral components of a larger hydrogeological network that serves as the primary recharge zone for the Koiliaris drainage basin. Through detailed analysis of cave geometries within the largest systems, our research reveals a significant cave tier consistently occurring at approximately 1500 m asl. This appears to be directly related to the unique stratigraphic sequence of the Lefka Ori massif. Field observations and geological analysis suggest that this prominent tier development is primarily controlled by the presence of an impermeable layer. The stratigraphy exhibits specific horizons that are more susceptible to dissolution, creating preferential zones for horizontal cave development. This pattern of development differs from typical cave levels, which are often controlled by past or present water table positions. Understanding these speleogenetic controls has important implications for predicting cave distributions, assessing aquifer characteristics, and managing water resources in the region. The findings also contribute to our broader understanding of how stratigraphic factors influence cave development in similar geological settings worldwide.

KEYWORDS: cave level, cave tier, Crete Island, Greece

Morphometry and evolution of salt karren using multi-temporal photogrammetry

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The Cardona salt diapir, located in the northeastern sector of the Ebro Cenozoic Basin (NE Spain), is an emergent salt extrusion formed by the late Eocene Cardona Saline Formation, mainly composed of halite and K-Mg chlorides. The emergence of the salt was initiated in the late Quaternary by the entrenchment of the Cardener River. Active salt rise is driven by the combined effect of two differential loading mechanisms related to greater overburden load in the synclines and at valley margins. The main salt exposure occurs on the steep slopes of a large, internally drained karstic depression known as the Bofia Gran, which displays a remarkable diversity of karren. This work focuses on the morphometry and evolution of various types of karren features (flutes, bevels, pits, pedestals) using multi-temporal high-resolution 3D point clouds generated by Structure from Motion (SfM) Photogrammetry using photographs taken with a full-frame hand-held camera. Solution pits are mostly found in low-gradient areas, typically at ridge crests, and exhibit elongated shapes with peculiar characteristics, including openings in most of the measured pits that often connect to solution flutes. These elongated pits are deeper than wide and have average depths of up to 43 mm. Solution flutes dominate the salt outcrops, mainly occurring on slopes with gradients higher than 30º. They show parabolic cross profiles, ranging from 6 to 59 mm in depth and from 15 to 54 mm in width. These flutes tend to be wider than deep, with an average width-to-depth ratio of 1.45. Solution bevels are decimetre-scale planar surfaces located below the solution flutes with a sharp slope break at their boundary. The bevels are typically wider than long, with slopes between 3° and 32°, and local irregularities such as abrupt changes in the slope gradient. The analysed karren show marked differences with those in carbonate rocks. Rainpits in salt are more elongated and, on average, 1.5-2 times longer, 4.5-8 times deeper, and with a higher depth-to-length ratio attributed to the rapid dissolution kinetics of halite. Average values indicate that solution flutes in salt are wider (30 vs. 16.9 mm) and about 5 times deeper (22.7 vs. 4.4), suggesting that the high solubility of the salt favours the rapid enlargement of the furrows. Solution flutes show a complex spatial-temporal evolution not consistent with the commonly proposed models of parallel-retreat and rill persistence. They tend to experience a cyclic evolution involving: (1) rill deepening and widening accompanied by the narrowing of the intervening ridges; (2) ridge destruction and rill coalescence, leading to new broad flutes; (3) flute splitting through the development of new intra-rill ridges. The solution bevels locally display the inception and expansion of new solution flutes.

KEYWORDS: salt, karren, rillenkarren, morphometry, photogrammetry

Glacial controls on cave development and landscape evolution - lessons from Stortuvhola, Northern Norway

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Cave morphology, among other features, reflects former water levels and is extensively used as a proxy to decode landscape evolution through time and to understand different drivers that affect the geomorphological development of a given area. Geomorphological and speleogenetic research has advanced with high-resolution DEMs, new cave survey techniques and spatial analysis. Here, we combine cave research with geomorphological analysis of the surface topography to expand our understanding on the evolution of the karst system and fjord landscape in Northern Norway. Stortuvhola (or Aspfjordgrotta, 67°29'N 15°38'E) is situated on a small hill in a tributary valley to the Sørfolda fjord. The cave is developed in marble stripe karst, and the orientation of the bedrock controls both the valley and the cave geometry/pattern. The longitudinal valley profile has multiple steps typical of glacial erosion. The influence of both glacial and fluvial processes is visible in the surface and subsurface morphology. The cave pattern, phreatic tubes and sediment accumulations display several phases of glacial hydrological regimes, while the keyhole morphologies reveal phases of invasion by subaerial streams. We link differences in dimensions of the two keyhole passages to invasion by streams with different catchment areas and, thus, changes in valley morphology at the surface. A corroded flowstone dates to the upper range of the U-Th dating method and seemed to grow in MIS 11 and MIS 9. This suggests that the speleogenesis of the upper phreatic levels cannot be younger than MIS 11. The cave system preserves a detailed record of multiple glacial cycles in Northern Norway, containing evidence of past ice regimes, shifting base levels, and datable deposits. This archive provides unprecedented insights into the region's long-term landscape evolution.

KEYWORDS: speleogenesis, landscape development, marble karst, cave, flowstone dating

Implications of geomorphic connectivity for the depositional context of caves: an example from Trascău Mountains, Western Romania

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Isolated or discontinuous uplifted karst massifs were more exposed to Quaternary climate changes than their continuous or lowland counterparts and consequently have to potential of recording a wider range of paleoenvironmental signals. Cave morphology and sedimentary infills are important underground components of such massifs. Caves normally act as sediment traps, and may record a specific stage in the evolution of karst topography. The topmost caves or cave levels are of high interest since they could preserve the oldest geomorphological evidence on regional landscape evolution. In such a context, studying the geologic and geomorphic framework of karstification is crucial for understanding the complexity of caves from a paleoenvironmental perspective.

Here, we investigate the geomorphic connectivity between the perched caves and the exokarstic landforms in the Ciumerna Plateau (Trascău Mountains, Eastern Apuseni Mountains), to better understand the depositional context of cave sediments and their paleontological content. Our research focused on Bisericuța Cave, located slightly below the topographic surface of a karst plateau at ~1200 m a.s.l. The methods used are: structural analysis of bedrock fracturing, geomorphological mapping, morphometric and spatial analysis of dolines, cave survey, and general description of sediment layers. Field measurements and surface analysis of LiDAR-derived DEM highlight the distribution of two generations of dolines within a larger karst depression (uvala) at the top of the plateau. The doline strings indicate the orientations of the local fractures or faults. Bisericuța is a small cave truncated by erosion and slope retreat. It is ~150 m in length and displays two levels. The upper level forms the main passage that interconnects several chambers, whereas the lower level consists only of chambers connected with the main passage by two narrow descending subsidiary passages. The Bears Chamber from the lower level (-10 m) functioned as a true sediment trap and hosts a thick deposit (>2 m), sourced from the upper level and possibly from another now inaccessible passage. The upper level also hosts significant deposits, but preliminary assessment shows a different sedimentation regime. The cave geomorphology and the layering of sediment piles suggest that the two main passages of Bisericuța Cave developed and evolved independently. The common processes that controlled landform initiation and evolution in the study area were mountain uplift, valley incision, karstification, and slope retreat. The results allow to clarify the depositional context of cave sediments in the Ciumerna Plateau during the Pleistocene, and to provide information for further paleoenvironmental reconstructions.

KEYWORDS: karst, cave, doline, geomorphic connectivity, landscape evolution, Pleistocene

The karst landscape of the Dhofar Mountains (Sultanate of Oman). Landforms and human exploitation at the edge of the Indian Ocean Monsoon

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The Dhofar Mountains (southern Sultanate of Oman) are a system of Late Cretaceous to Neogene limestone strata gently rolling to the north and intersected by a system of transtensional faults, which have contributed to the uplift of the plateau and the formation of a stepped escarpment up to ~850 m asl. The massif is dissected by a dendritic system of valleys carved into the bedrock, which are active in the monsoon season (May to September) and are often blocked by massive calcareous tufa dams that have formed since the Middle Pleistocene along knickpoints of structural origin. The surface of the Dhofar Mountains is characterized by widespread rock outcrops due to intense denudation processes that, likely since the last millennia of the Holocene, have removed the superficial soils. These outcrops exhibit evidence of karst dissolution at small to medium scales, including the presence of common flat-bottomed solution dolines, often used for livestock enclosures or, due to their ability to retain soil, for rain-fed cultivation. Elsewhere, collapse sinkholes connect the plateau surface to the underground karst system, which has only been partially explored. Field surveys of the Dhofar Mountains' surface have revealed the extensive complexity of the geomorphological processes affecting the area. The evolution of the dendritic hydrographic system, consisting of deep canyons, is closely linked to the presence of faults and connected to the deep karst system, likely evolving through collapse and exhumation processes of the cave system. Evidence of this includes the presence of sinkholes at valley bends, inland notches and rock-shelters opening at different elevations along the valleys, and the identification of riverbeds showing relief inversion in association with faults and sinkholes. The karst landscape of the region has been exploited since the early Holocene and especially in recent millennia. Human activity has significantly influenced the dynamics of surface processes, together with the monsoon rains from the Indian Ocean, which are the primary agents shaping the appearance of the plateau surface.

KEYWORDS: karst landscape, Sultanate of Oman, denudation, tufa dam, human exploitation

THEMATIC SESSION 14

LANDSLIDES IN CLIMATE CHANGE CIRCUMSTANCES

(co-organized IAG-International Consortium on Landslides- International Geographical Union, Commission on Hazard and Risk)

Chairpersons:

Zeljko Arbanas, Veronica Tofani, Alessandro Mondini, Mihai Micu

Accurate landslide dating using Sentinel-1 and Sentinel-2 data in Google Earth Engine

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Landslides are movements of earth, rock, or debris across a slope, triggered by natural factors such as intense rainfall, earthquakes, or erosion processes, as well as human activities like deforestation or land use changes. Monitoring landslides is crucial for assessing their magnitude and frequency, and for early detection of potential landslide activity. New methods for landslide monitoring rely on satellite remote sensing, enabling continuous observation of large areas and tracking changes in vegetation, soil, and terrain through optical and radar imagery, enabling efficient, cost-effective, and timely detection and analysis of landslides.

A key aspect of landslide monitoring is determining the trigger moment of a landslide. This information is essential for developing predictive models, identifying vulnerable areas, and improving risk management strategies. However, satellite-based landslide dating faces challenges, especially cloud cover, which can limit optical imagery and reduce the number of usable images, complicating landscape monitoring and analysis. This limitation can be overcome by using satellite radar imagery, which penetrates cloud cover and complements optical satellite monitoring.

In this work, we propose an innovative approach for accurately determining the trigger moment of a landslide by combining optical (Sentinel-2) and radar (Sentinel-1) data, processed using Google Earth Engine (GEE). GEE is an advanced cloud-based platform for processing and analyzing large amounts of satellite imagery.

Analysing Sentinel-2 images allows for the identification of sudden vegetation loss or changes in soil structure, which can be linked to landslide triggers. Abrupt changes in vegetation indices help to identify the time window during which the landslide occurred. Sentinel-1 radar sensors detect variations in backscattering, which help refine the time window and improve the accuracy of landslide dating.

The effectiveness of integrating Sentinel-2 and Sentinel-1 satellite data within the GEE environment is tested using a database of known landslides. Applying the proposed procedure demonstrates improved accuracy in landslide dating, providing more precise time windows for events. By combining Sentinel-2 and Sentinel-1 data, the method significantly reduces dating errors.

This approach not only enhances the precision of determining the time window of landslide events but also opens new perspectives for continuous monitoring and risk management in remote or hard-to-reach areas. Conducting large-scale analyses in vulnerable and poorly monitored regions represents a significant step toward more timely and efficient landslide management.

Furthermore, GEE's shared scripting environment allows the creation of reproducible workflows, enabling other researchers to replicate and build upon the analysis, further advancing the use of satellite-based landslide monitoring.

KEYWORDS: Landslide, dating, Google Earth Engine, Sentinel-2, Sentinel-1

Mapping landslide susceptibility under different rainfall scenarios

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Extreme rainfall events represent one of the main triggers of landslides. Notably, their frequency and intensity are increasing due to climate change, amplifying landslide occurrences. This study analyzes the relationship between landslide susceptibility and extreme rainfall events through a "glass-box" machine learning algorithm, namely Explainable Boosting Machines. These models are defined as "glass-box" due to their direct interpretability and full transparency. As a consequence, the incorporation of these models within studies dealing with landslide occurrence and extreme rainfall events raises considerable interest. In light of these considerations, this contribution focuses on landslides triggered by a heavy rainfall event on September 15, 2022, in the Misa River Basin (Marche region, Central Italy). To explore the interaction between landslide occurrence and the event, a novel rainfall variable is introduced among the set of predictors. This variable is meant to capture the event's intensity relative to historical rainfall patterns. Specifically, the rainfall variable is expressed as the percentage of precipitation attributed to the event in relation to the mean annual rainfall. The outcomes highlight the critical role of the rainfall variable as the most important predictor. Moreover, the novel rainfall variable introduces a dynamic component to the modeling, as it may vary at every future rainfall event. As a result, by combining the dynamic nature of such a variable and the exact intelligibility of the model, landslide susceptibility is mapped under different rainfall scenarios with respect to the event of September, 2022.

KEYWORDS: landslides; landslide susceptibility; glass-box machine learning; extreme rainfall events

Post dynamics of storm-triggered landslides after their initial failure – observations and current challenges from Granitztal (Carinthia, Austria)

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Landslides represent a significant natural hazard worldwide, with their frequency and intensity increasing as a result of the ongoing global and climate changes. Particularly, rainfall-induced landslides exhibit complex kinematics and often develop morphological features of progressive deformation after the first landslide initiation. A key question lies in understanding the behaviour of destabilized masses following the initial failure. Therefore, reconstructing the spatio-temporal evolution of surface features is essential for interpreting failure mechanics from initial failure to potential future displacements.

This study presents preliminary findings from the monitoring of a complex earth-slide system in Granitztal (Carinthia, SW Austria). In August 2023, extreme rainfall associated with the "Zacharias" storm caused widespread flooding and triggered hundreds of landslides in the federal state of Carinthia, as well as in neighbouring regions in southern Austria. The intense precipitation led to the occurrence of multiple earth-slides and mudflows, causing significant damage to local properties and infrastructure. However, some of these slope instabilities have not fully failed, posing an ongoing hazard for residents and threatening households and transportation networks.

Our research aims to characterize post-failure landslide dynamics through multi-temporal analysis, with a particular focus on surface deformation features critical for hazard assessment. This study integrates close-range remote sensing, using a commercial DJI Mavic Pro 2, with field mapping across an area of 2.6 hectares. UAV imagery is processed using a standard Structure from Motion (SfM) workflow to generate a high-resolution 3D point cloud, georeferenced using ground control points (GCPs), equally distributed across the study area and surveyed with a high-precision GNSS device. A subset of the GCPs was used as checkpoints to evaluate the accuracy of the georeferentiation process.

This study identifies and maps spatio-temporal changes in distinct morphological features, such as surface fractures, while the integration of multi-temporal DEMs and orthoimages enables a quantitative assessment of deformation patterns. These findings enhance our understanding of landslide evolution after initial failure and contribute to hazard assessment, supporting mitigation efforts at the local scale.

KEYWORDS: rainfall-triggered landslides, post-failure dynamics, landslide monitoring, UAV surveys, Structure from Motion

Integrating pixel and slope units for spatial prediction of tropical storm-induced landslides in El Salvador

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In landslide susceptibility mapping, the selection of terrain partitioning units critically influences susceptibility zonation and the spatial distribution of predicted landslide-prone areas. Two primary approaches are commonly employed: pixel-based units and slope units. Pixel-based mapping, derived from high-resolution digital elevation models (DEMs), captures detailed local variability of environmental predictors such as slope, curvature, and elevation. However, this method often lacks the spatial continuity and geomorphological context necessary to fully represent the processes driving landslide occurrences. Conversely, slope units provide a coherent geomorphological framework that reflects the overall dynamics of slope stability. Despite their relevance, slope units may oversimplify local variations by averaging out critical details, potentially leading to less precise predictions.

To address these limitations, this research proposes an integrated methodological approach that combines the strengths of both pixel- and slope-units. Environmental variables are extracted from high-resolution Digital Elevation Model (DEM) and available thematic maps. Predictor values are computed at the pixel level, while key statistical descriptors (e.g., mean, standard deviation, quantiles) are aggregated within corresponding slope units. This dual-level analysis captures fine-scale heterogeneities alongside broader geomorphological trends, enhancing the predictive performance of landslide susceptibility assessments.

The methodology is applied to a study area in El Salvador, significantly impacted by tropical storms—such as Hurricane IDA in 2009, Amanda and Cristobal in 2020, and Julia in 2022—that have caused extensive flooding and triggered thousands of landslides. Preliminary results indicate that the integrated mapping strategy improves model accuracy and provides insights into how different terrain partitioning schemes influence susceptibility assessments. This approach serves as a robust tool for disaster risk management and land-use planning.

This research was developed within the framework of the project "Establish and develop a degree program in Earth Sciences at the University of El Salvador" (CASTES), funded by the Italian Agency for Development Cooperation.

KEYWORDS: landslide susceptibility, pixel-based units, slope units, tropical storms, El Salvador

A dense concentration of landslides with permafrost molards in Alaska

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Landslides in permafrost areas are becoming more commonplace with global climate change, and we focus our attention on those in discontinuous mountain permafrost. Conical debris mounds within landslide deposits (called permafrost molards) indicate that ice-cemented ground was mobilised by a landslide. We catalogue a remarkably dense concentration of molard-hosting landslides in the Talkeetna Mountain Range in southcentral Alaska using remote sensing data. We document their morphology, ages, geological, climatological and geomorphic settings with a view to understanding their particularly high concentration in this part of the world. We find that molard-hosting landslides mainly originate in mechanically weak bedrock of various origins, and can sometimes also moblilise non-consolidated deposits. The non-consolidated deposits are usually in the form of rock glaciers. The majority of the precisely dated landslides occur during the winter season, without easily identifiable triggers such as intense rainfall/snowmelt or seismic shaking. This argues for a more complex and perhaps progressive path to failure by warming the permafrost, including perhaps long-term changes in the slope-hydrology and/or a seasonal/decadal lag in the thawing of pre-existing frozen planes of weakness. We present key case studies where we have tight constraints on their timing, we explore the different materials mobilised and dynamics of these landslides. We use seismic inversion and field investigations to explore their dynamics. Finally, we discuss how interactions with the local community have enriched our scientific investigation and are providing impetus for future research.

KEYWORDS: landslide, molards, permafrost, community engagement, climate change

The influence of geomorphological terrain characteristics on snow cover dynamics as preparatory process for landslides

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Snow cover spatio-temporal variability is a relevant indicator of climate effects on slope instability in mountainous and hilly regions, complementing other climatic parameters such as rainfall and temperature. Snow loading and seasonal melting can change the soil stress field, with the latter that can increase pore water pressure, reducing the available shear strength and compromising the slope stability. This influence is time-dependent and cyclic throughout the year. In mid-latitude regions of northern hemisphere snow typically begins to accumulate in late autumn, peaks in late winter, and melts from spring to summer, leading to water infiltration and soil strength reduction. In the Italian Apennines, snow dynamics often exhibit greater complexity, including intraseasonal transitions between accumulation and melting, and complete melt-out events even in mid-winter. Moreover, landslide triggers, such as earthquakes or heavy rainfall, can interact with varying levels of snowpack-induced soil weakness, resulting in distinct landslide scenarios.

While snow accumulation and melting are widely recognized as triggers for landslides, particularly shallow ones, their role as dynamic preparatory processes is less frequently explored.

This research, conducted within the framework of Italy's National Recovery and Resilience Plan (PNRR), funded by Next Generation EU, extended partnership RETURN (multi Risk sciEnce for resilienT commUnities under a changing climate), aims to evaluate the role of snow cover in preparing landslides, focusing on the spatial and temporal variability of snow accumulation and melting. The study area is in the Italian Apennines, characterized by significant, yet highly variable, annual snowfall and a comprehensive landslide inventory. The analysis was conducted in two steps. Firstly, IT-SNOW snow accumulation data (Avanzi et al., 2023) was examined using a Bayesian ensemble algorithm for change-point detection and time series decomposition (BEAST; Zhao et al., 2019). This approach identified abrupt changepoints in snow height (HS) seasonality and trend for each grid cell in the study area, allowing for the delineation of time windows associated with snow accumulation or melting. Secondly, HS data were grouped by these time windows and correlated with geomorphometric parameters (e.g., slope, aspect and curvature) to identify spatio-temporal relationships between terrain characteristics and snow cover, enhancing understanding of snow preparatory role in landslide processes.

Preliminary results are encouraging, underscoring the potential of this approach to model future landslide scenarios and enhance hazard prediction. Notably, BEAST proves to be an effective tool for distinguishing trend and seasonal signals in IT-SNOW snow depth data. Additionally, early findings related to snow cover and morphometric parameters are promising, further supporting the prospect of modelling landslide scenarios with greater accuracy.

KEYWORDS: landslide susceptibility, snow cover dynamics, preparatory processes, Bayesian estimation, Molise Region (Southern Apennines)

Morphometric analysis using multi-temporal LiDAR DTMs: the Ca' Lita landslide case (northern Apennines, Italy)

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The Northern Apennines experienced extreme rainfall events between 2022 and 2023, leading to multiple landslide phenomena, many of these reactivations of previous landslides, already subject to monitoring and observation. This is the case of the Ca' Lita landslide (44.458657N, 10.626566E), in the Emilia-Romagna region, a complex landslide characterized by a roto-translational rockslide evolving in earthflow in its lower portion, for a total length of about 2.6 km and an area of nearly 0.9 km^2, which underwent two major reactivation phases in May 2022 and May 2023.
Considering historical reactivations, after several slope instability events throughout the 20th century, the landslide resumed its activity in 2002, and it underwent paroxysmal phases during the winter of 2003 and the spring of 2004. These reactivations affected the entire recognized landslide slope, which, based on geomorphological interpretations, is part of a prehistoric landslide. These events caused the mobilization of at least 10 million m^3 of mixed clay and boulders, with the landslide toe advancing about 400 m at peak speeds of 10 m/day into a previously undisturbed valley. This area was subsequently filled with landslide deposits ranging from 10 to about 40 m in thickness, along with significant retrogression of the main landslide scarp. At least three additional reactivation phases followed (2016, 2019, 2022-2023), which have been studied using direct and indirect instrumentation installed both within and outside the landslide perimeter.
With the aim of highlighting the areas affected by greater displacements and to understand the triggering causes of the landslide, a geotechnical and hydrological model and DTMs analysis (2009-2024 interval period) of the landslide were carried out. Previous studies (Corsini et al., 2009) comparing DTMs from 1973, 2004, 2005 and 2006 highlighted the downslope movement of clayey loose material without significant altimetric variations until 2004. Deep roto-translational phenomena affecting the upper part of the landslide began in 2004 and continued throughout 2005 with 40 m total depletions, while local collapses of the main scarp were observed in 2006, with a subsidence > 10 m and the deposition of material at the base of the scarp. The 2009, 2016, 2024 differential DTMs confirm previous long-term depletion and accumulation zones. A detailed analysis was conducted using new DTMs obtained from four 50cm-resolution UAV flights carried out between August 2023 and July 2024 realized by the Emilia-Romagna Regional Agency for Civil Protection. In detail, depletions up to 20 m affected the rotational head area, whilst the flow toe zone advanced up to 5 m. Movements appear mainly concentrated in the head area, with evident undercutting from the crown zone and continuous secondary slides in the main scarp area, boundary between the rockslide and the earthflow. The study showed that over time, due to intense and concentrated rainfall, Apennine complex landslides exhibit clear progressive movements which should be continuously monitored.

KEYWORDS: complex landslide, extreme rainfall, UAV surveys, Differential DTM, Emilia-Romagna

A complex landslide as a complex field laboratory: 30 years of Čeřeniště site research

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The České Středohoří volcanic mountain range in NW Bohemia is highly susceptible to slope deformations due to Quaternary incision of the Labe River, which carved deep valleys with steep slopes. Combined with the high clay content in weathered volcanic rocks, these conditions favour landsliding. Among the largest and most complex deep-seated gravitational slope deformations (DSGSD) is the Čeřeniště landslide. This extensive landslide in Tertiary volcanic tuffs and basalts features a 25 m high scarp, large basalt blocks controlled by tectonic structures, and deep-seated gravitational processes. The central area consists of smaller, occasionally back-tilted blocks, while the distal part exhibits lobe-like shallow flows, representing the most active section.

Research on the site dates back to the mid-20th century, with systematic monitoring and instrumentation beginning in the 1990s. Today, Čeřeniště is one of the best-equipped natural laboratories, managed by a multidisciplinary team within the SLOPENET monitoring network. This site provides valuable insights into landslide evolution, reactivations, and triggering mechanisms.

To monitor long-term activity, displacement measurements employ 3D extensometers (TM-71), wire and tape extensometers, time-lapse geodetic surveys (laser scanning, total stations), and a 30 m multiparametric inclinometer providing near real-time data on sliding plane activity, including inclinometric, piezometric, and thermal readings.

To investigate triggering factors, time-lapse electrical resistivity tomography (TL-ERT) has transitioned from monthly manual measurements to automated monitoring with 2-7 days interval. This improvement enhances understanding of subsurface water saturation dynamics and their influence on mass movement activation. Additionally, movement velocity monitoring via geodetic and geotechnical methods, coupled with local meteorological and pore-water pressure data, enables detailed analysis of precipitation-induced landslide reactivation. This comprehensive monitoring approach at Čeřeniště offers a unique opportunity to study landslide processes in natural conditions, advancing knowledge of slope stability and mass movement behaviour.

To understand the detailed structure of the DSGSD, a vast ERT surveying was performed across various parts of the landslide. During last 10 years, 12 profiles with total length of over 3700 m were measured on the site, aiming at various aspects of the research. The geophysical survey aside from manual (and later automatic, developed by the team) time-lapse ERT, included long and deep ERT profiles to assess the general features of the landslide and shorter, detailed surveys with special purposes, such as obtaining support data for dendrogeomorphologic research, formation of the side walls and structures of distal part lobes.

The above-described surveying, long-term monitoring and observation of the landslide aims to describe the long-term behaviour of the complex slope deformation, and to reveal links among predispositions in morphology, tectonics and lithology, triggering factors (extreme precipitations, soil humidity changes, long-term climatic oscillations, etc.) and landslide activity.

KEYWORDS: complex landslide, ERT survey, time-lapse, landslide monitoring, České Středohoří

Global distribution of landslide events as a function of climatic and anthropogenic factors

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One of the main factors that influence slope stability and landslide risk is climate, especially precipitation and temperature patterns. In recent decades, humans have significantly impacted and altered the natural environment during the Anthropocene. There is no doubt that climate change is having obvious effects on slope stability and on the typical patterns of landslide occurrence. While the topic of climate change and landslides has been a growing issue for some time, there are still very large regional differences in the number of related publications. Recently, interest in understanding the spatial and temporal distribution of landslides on a global scale has increased, fueled by the growing availability of global and open landslide inventories. However, only few existing studies provide a global perspective on the occurrence of landslide events in connection with current climate classification maps and a future outlook on the interplay between landslides and projected changes in climatic drivers.

This study presents an up-to-date and comprehensive compilation of the current global distribution of landslide events in relation to the identified climatic and anthropogenic drivers, excluding seismic and volcanic triggers. The global occurrence of landslides is analysed based on NASA's Global Landslide Catalog (GLC) in connection with the latest and high-resolution maps on climate classification and global precipitation pattern, susceptibility to landslides as well as on the human terrestrial footprint. Recent examples of landslides and their possible triggering factors are discussed for each climate zone. Variations between climatically and anthropogenically driven landslides are analysed and projected changes in climatic impact-drivers and their potential effects on landslides are highlighted.

The results of this study show that the majority of landslides occur in temperate and tropical environments associated with mountainous topography. Even if a large number of events can be attributed to natural/climatic factors (especially precipitation), the results show that the impact of anthropogenically triggered events should not be underestimated. There is a high probability that landslides will generally increase in frequency and magnitude worldwide as climate change progresses and human impacts further increase. With respect to urgently needed and effective mitigation strategies, a better understanding of the interactions and feedbacks between natural and anthropogenic factors related to ongoing climate change, increasing urbanisation and human pressures is essential.

KEYWORDS: landslides, global landslide catalog (GLC), climatic drivers, Anthropogenic drivers, climate change

Emilia-Romagna, Italy: could the landslide phenomena of May 2023 have been predicted?

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In May 2023, the Emilia-Romagna region (Italy) was hit by intense rainfall, causing significant economic damage (8.6 billion euros) and 17 fatalities. After a prolonged dry period, with only occasional light precipitation, two major rainfall events occurred on May 1st- 3rd and May 16th-17th, bringing cumulative precipitation exceeding 500 millimetres in various locations. The Emilia-Romagna Region reported 80,946 landslides triggered by these rainfall events, many of which damaged roads in approximately 2,000 cases and numerous houses. Among the fan of landslide typologies recognized, mud/earth/debris flows, which are the focus of this research, largely prevail on subordinated slides, mainly affecting Miocene sandy clay/sandstone alternations.
The main question of this research is: could these landslide phenomena have been predicted?
Focusing on the small basin of the Senio River (180 km^2), we first collected a pre-event and post-event inventory, identifying flow landslides through remote mapping from 2002 to 2022 (11,597 cases, seasonal rainfall trigger), and after May 2023 (8,323 cases, linked to extreme events). Using the Multivariate Adaptive Regression Splines (MARS) statistical method and a set of eleven predictor variables, we analysed the relationships between presence/absence of landslides and spatial distribution of the geo-environmental variables. In particular, two model-building procedures - the PRE_{2023} and $POST_{2023}$ models - were developed by calibrating with 75% of the pre/post-event inventory (a balanced subset of the main inventory), respectively. Four validation procedures were then performed: $SELF_{PRE2023}$ and $SELF_{POST2023}$, for which the above-mentioned models were validated using the remaining specific 25%, FRW (forward validation) where the $SELF_{PRE2023}$ model was used to predict the 25% of the post-2023 inventory, and BKW (backward validation) where the $SELF_{POST2023}$ model was used to predict the 25% of the pre-2023 inventory. Even if the PRE_{2023} model achieves exceptional results in predicting the coeval blinded 25% (AUC= 0.95, Sensitivity =0.89, Specificity = 0.89), its prediction skill significantly decreases in FRW validation (AUC= 0.8, Sensitivity= 0.56, Specificity =0.89), demonstrating a marked inability to predict the landslides triggered by the extreme events. On the other hand, the $POST_{2023}$ model delivers very good results both in predicting the coeval inventory (AUC= 0.87, Sensitivity= 0.71, Specificity= 0.88) and in BKW validation (AUC= 0.9, Sensitivity= 0.78, Specificity= 0.88). However, the slightly high sensitivity value of the $POST_{2023}$ model suggests that it is not particularly effective at discriminating landslides triggered by the extreme event (coeval), as evidenced by the increase in sensitivity in BKW validation. The results obtained led us to a detailed analysis of the variables used by the two models, as well as an extensive study of the precipitation trends before the 2023 events. The latter was conducted by examining the records from six rain gauges located within or near the basin, covering the period from 2006 to 2023. The results show that not only did the intensity of the 2023 events exceed that of any other extreme event recorded during the considered period, but also that the spatial distribution of these precipitations was anomalous, triggering areas of the basin that had historically been stable.
This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

KEYWORDS: climate change rainfall trigger, landslides, susceptibility, Emilia Romagna 2023

A hybrid deep learning framework for analysis and prediction of reservoir landslide displacements

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Reservoir landslide displacements exhibit step-like deformation patterns influenced, which poses a great challenge for prediction. This study proposes a hybrid spatio-temporal deep learning framework for analyzing and predicting these displacements. Complementary Ensemble Empirical Mode Decomposition with Adaptive Noise (CEEMDAN) and Pearson correlation coefficient (PCC) are employed to deeply mine reservoir landslide displacements triggers factors. CNN, BiLSTM, and Attention mechanisms are combined to capture high-dimensional spatial features, long-term temporal dependencies, and key influencing factors, respectively. A nonlinear weighted Huber loss function (NLWHL) is proposed to evaluate the reservoir landslide step-like displacement. Additionally, Shapley Additive exPlanation (SHAP) is applied to interpret the different positional displacement triggers from a model transparency perspective. The results show that front-edge displacements are primarily driven by reservoir water level fluctuations, with the "Change in reservoir water level during the current month (L5)" identified as the dominant factor. While middle-edge displacements are mainly influenced by short-term intense rainfall events. The proposed CNN-BiLSTM-Attention framework achieves the lowest prediction error for periodic displacements in testing phases. For the total displacements, it achieves high accuracy in predicting displacement during mutation phases, with NLWHL values of 1.11 and 1.84 for Z85 and Z86, respectively, outperforming conventional models. This framework provides valuable insights into the stepwise deformation behavior, instability mechanisms, and geomorphological evolution of slow-moving reservoir landslides. It offers a foundation for mitigating similar geomorphological disasters worldwide.

KEYWORDS: Deep Learning, Nonlinear Weighted Huber Loss Function, Reservoir landslide triggers

A hybrid deep learning network for landslide susceptibility assessment

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Landslides occur frequently and pose a major threat to human life and property. The landslide susceptibility mapping is an important and effective tool in predicting landslides. This research proposed a novel deep learning framework for landslide susceptibility assessment using an improved deep belief networks (Laplace's function sparse regularized continuous deep belief network, LSCDBN) with two intelligent optimization algorithms (grey wolf optimization and whale optimization algorithm, GWO and WOA). This framework addresses the challenges of feature homogenization for continuous input variables for landslide condition factors, limited historical landslide samples, and local optima in the training process. To facilitate this investigation, a meticulous compilation of existing landslide occurrences was used to create a database comprising 18 landslide conditioning factors, including geomorphology, hydrological, geological, and climatic conditions. The information gain ratio method was used to assess the landslide conditioning factor. To compare the performance of the model, a set of statistical indicators were employed, including root mean square error (RMSE) and area under the receiver operating characteristic curve (AUC). The results demonstrate the superior performance of both the LSCDBN-GWO model (AUC = 0.952, RMSE = 0.182) and LSCDBN-WOA model (AUC = 0.964, RMSE = 0.174) when compared to the alone LSCDBN model (AUC = 0.913, RMSE = 0.291). This due to the global search of the optimization algorithm avoids local optimization. It is noteworthy that the performance of the LSCDBN model outperformed that of lone machine learning (SVM, BP, RF, and LR) and deep learning algorithms (RNN and CNN) due to the sparse regular terms to address feature homogenization. Furthermore, the LSCDBN-GWO and LSCDBN-WOA models emerged as the superior choices in a comparative analysis with alternative models incorporating CNN in conjunction with GWO and WOA algorithms. Therefore, it is evident that the proposed LSCDBN-WOA framework can generate models that are optimally suited for landslide susceptibility assessment.

KEYWORDS: Machine Learning, GIS, Greywolf Optimization Algorithm, Whale Optimization Algorithm

Landslide disaster risk reduction: geomorphic services and the modern challenges of global change

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Environmental risks represent a major issue to be tackled by scientists and by society in terms of disaster risk reduction. The Sendai Framework for Disaster Risk Reduction of the United Nations (SFDRR; 2015-2030) points out that, at a global level, the exposure of elements at risk has increased more rapidly than the vulnerability decrease, and the most visible effects are marked at the level of local communities. In the meantime, SFDRR emphasizes the urgent implementation of pre-disaster anticipation and planning strategies for effective societal recovery. Among natural hazards, landslides are acknowledged worldwide as being among the most important geomorphological processes in terms of potential impact on the natural and anthropic environment. Landslides occur in all environments and numerous predisposing, preparing, and triggering factors are conditioning a wide variety of processes and resulted forms; they either initiate or reactivate in various conditions, within a single or multi-hazard framework. In this way, environmental changes (especially long-term and short-term climate change) are conditioning multiple uncertainties in the spatial and multi-temporal distribution of landslides, with regional particularities that complicate the already complex risk assessment. Climate changes resulting in increased extreme precipitation events (leading to cascading effects), general warming in mountain regions (the most landslide-prone environments, increasingly affected by the transformation of snow and ice into fluid water), or the shifts in seasonal, latitudinal or altitudinal distributions of temperatures are challenging communities to adapt; meanwhile, not always local communities have the resources to develop and support a climate-resilient sustainable development, since delayed or long-distance effects may exceed natural, political and administrative borders. All these considerations are transforming the landslide disaster risk reduction framework into a highly complex endeavour, within which geomorphic services hold a consistent share. In this framework, it is the purpose of this presentation to offer a worldwide overview of geomorphic services in terms of landslide disaster risk reduction, outlining the importance of geomorphological expertise in developing a proper, fundamental scientific support and applying its characteristic systemic approach for the construction of modern modeling tools for hazard, exposure, vulnerability, and risk assessments. Through examples focusing on some of the world's most landslide-prone areas (temperate, tropical, or arid mountain environments), we will focus on the geomorphic expertise in landslide morphogenetic and dynamic spatio-temporal evaluation as the key elements for a systemic approach of hazard and risk; meanwhile, we will outline the important role played by geomorphologists in bridging science and society, contributing to an ethical, transparent and effective dialogue, and offering continuous links to a wide range of stakeholders, from processes inventory to risk governance.

KEYWORDS: landslides, DRR, geomorphic service, global change

Insights into the relationship between extreme rainfall and slope instabilities in the Apennines Mountain chain, Italy

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In recent years in Italy, an average change in precipitation is underway, and many extreme rainfall events are clearly related to physical processes different from those that govern long-term means. Such extremes have occurred due to a combination of several preconditions, including maximised potential moisture transport into the region, high temperatures or large temperature gradients, and significant atmospheric instability. These events have had very harmful effects on the ground, causing geo-hydrological hazards that were often unexpected, as they evolved in ways and timelines different from what current knowledge of the territory and its mean climate condition could predict.
In this study, we examine the effects on the slope stabilities in two areas of the northern Apennines Mountain chain (Italy) that were affected by extreme weather conditions in 2022 and 2023. Despite differing meteorological origins, these events were highly impactful. In 2022, the Marche region was affected by an intense self-regenerating storm system that remained in the inland areas for several hours, causing heavy precipitation up to exceptional peaks of over 400 mm. In 2023, the Emilia-Romagna region was affected by two sequential events in less than twenty days, with cumulative monthly precipitation exceeding 450 mm in various locations. The latter two cases were produced by an occluded meteorological front of Atlantic origin, in turn, fed by a Mediterranean cyclone. In both cases, some climatic causes were identified as factors amplifying the land disruption (mainly, long previous drought periods). These areas are well known for their landslide propensity, and, for this reason, susceptibility studies and detailed landslide mapping have been realized over time for public utility. Following freely available post-events inventories, it was possible to observe that, in both affected areas, the landslides induced by the extreme events moved from those already mapped only in a small percentage and not always with the same kinematics, indicating the absence of continuity of the dynamics of motion or real reactivation. This led to a series of spatial and typological analyses of new events compared with existing mapped ones, subsequently making also correlations of these with other aspects of the territory such as lithology, slope orientation and land use to be assessed together with precipitation distribution. Such connection analyses allowed us to observe the different controls they had in developing different types of events. Finally, some morphometric parameters characterizing the planimetric geometry of the occurred landslides were calculated and correlated for various typologies of events in order to complete the comprehension of the slope evolution under unusual and extreme rainfall and, overall, assess the reliability of existing mapping for such conditions.

KEYWORDS: extreme rainfall events, post-event inventories, landslides, GIS analyses, Italy

Failed volcanic tableland: why does arid Patagonia host some of Earth's largest landslide terrains?

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Volcanic and sedimentary tablelands are known for hosting large landslides, yet their causes, chronology, and kinematic modes remain poorly understood. This study summarizes our long-term research on landslides affecting hundreds of kilometers of volcanic tablelands in eastern, extra-Andean Patagonia. We employed a multidisciplinary approach, using a GIS-based landslide inventory derived from high-resolution DEMs and optical satellite imagery, radiometric dating (OSL, ^{36}Cl, ^{14}C, ^{40}Ar/^{39}Ar), and InSAR for recent movements. Our inventory, covering over 500,000 km^2, reveals that landslides in eastern Patagonia cover approximately 30,000 km^2—about a fifth of the Patagonian escarpments—with the largest areas exceeding 1,000 km^2. The most common landslide types are rotational slides and lateral spreads, with some flow-type landslides (rock avalanches, earthflows) exceeding 10 km in runout, particularly in the humid, steep western part, which was deglaciated during the late Pleistocene-Holocene transition. Dating results show that the Patagonian tablelands include landslides older than 4 Ma, as well as Late Quaternary (Holocene) failures. However, significant (~cm/yr) displacements in the last decade were detected in only a small fraction of the landslide area, particularly in lateral spreads along the eastern part of the tableland, near the Atlantic coast. We conclude that: 1) the morphological footprint of landslides in the Patagonian tablelands has persisted for millions of years due to the preservative effect of the arid climate, 2) the vast landslide-affected areas result from weak sub-caprock lithologies and the long-term evolution of escarpments through multiphase reactivation and retrogressive retreat, and 3) rather than climate change, Late Cenozoic landslide activity has been driven by the coupling (and de-coupling) of escarpments with river channels, fluctuating lakes, and glaciers.

KEYWORDS: landslides, volcanic tableland, spatial distribution, dating, Late Cenozoic

Glacier retreat and recent landslides in Patagonia: a post-Little Ice Age inventory

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The Patagonian Andes, characterized by large scale ice fields, have undergone some of the fastest recent glacier retreats globally. Research in this region is extensive, with a number of studies analysing glacier retreat. Several reconstructions provide information on the historical extent of glaciers and their retreat from the Little Ice Age (LIA) to the present. The glacier area loss during this period exceeds 15%. However, the relationship between deglaciation and landslide activity remains understudied in this region. Previous studies have focused on individual landslides, but a regional inventory of landslides associated with deglaciation across Patagonian Andes has been lacking until now. This study presents an inventory of landslides on deglaciated slopes that resulted from glacial retreat following the Little Ice Age in the Patagonian Andes. More than 5000 landslides have been mapped and classified using high-resolution satellite imagery from Google Earth™ and ArcGIS World Imagery. Shallow landslides, such as debris slides, debris flows, and landslide-erosion complexes on moraines, predominate in the study area. Rockslides and slope deformations are less frequent. This dataset provides insights into the spatial distribution, frequency, and characteristics of landslides in previously glaciated areas. We also analysed the influence of environmental factors, including glacier retreat rates, ice thickness, geological conditions, permafrost zonation, climatic variables and recent uplift, on landslide distribution. The inventory will be used for multitemporal analyses such as determining horizontal and vertical displacement rates of selected landslides.

KEYWORDS: landslides, glacier retreat, Little Ice Age, Patagonia

Investigating the response of slow-moving landslides to climate change: a case study from the Modena Apennines (Northern Italy)

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Extreme weather events can significantly enhance landslide activity, and their frequency and intensity are increasing in relation to climate change. The Emilia-Romagna region (Northern Italy) has been severely affected by extreme rainfall events in the past few years, such as between 15 and 17 May 2023, when the amount of precipitation surpassed historical records, leading to the activation of more than 80,000 landslides, resulting in significant losses. More recently, between 19 and 20 October 2024, another extreme rainfall event struck the region, leading not only to severe flooding but also widespread landsliding. Understanding how slope dynamics responds to changing rainfall patterns is an urgent task for improving landslide risk assessment and developing mitigation and adaptation strategies.

This paper concerns a study aimed at deciphering the response of slope dynamics under climate change in a pilot area of the Modena Apennines where the Gaiato historical landslide is located. The latter is an intermittent slow-moving landslide primarily controlled by a complex structural setting characterised by lithologies with contrasting geomechanical behaviours, i.e., clayey terrains overlain by fractured sandstones. The sandstone cliffs are affected by rock falls evolving into block slides downslope, while the clayey terrains are mainly affected by earth and debris flows. Slope instability is also favoured by the high-water availability due to the presence of springs emerging at the contact between sandstones and clays, and the absence of drainages for running water. As a consequence, the Gaiato landslide can be subject to reactivation, particularly in response to intense precipitation, making it a key study site for understanding slope dynamics in relation to the changing climate. Historical records document multiple significant reactivation phases, particularly during the first half of the 18th century and between 1900 and 1904, which considerably impacted local communities. However, based on data from other sites in the Emilia Apennines, it can be inferred that the activity of the Gaiato landslide dates back to at least the Late Pleistocene. Additionally, the landslide repeatedly interacted with fluvial morphodynamics at times damming the Scoltenna stream. In order to investigate landslide dynamics, detailed geomorphological mapping was performed based on field surveys and analyses of data obtained from literature, landslide inventories and remote sensing. The use of a high-resolution DEM, derived from LiDAR data acquired through UAV surveys, allowed to enhance the accuracy of geomorphological mapping. Additionally, InSAR displacement data were used to support the identification of the most active landslide sectors. To further support the investigation, a weather station was installed near the landslide crown area, ensuring the acquisition of site-specific data. In mountain areas, the high variability of weather conditions, partly due to morpho-topographic situations, makes it challenging to collect representative meteorological data.

The integration of these techniques has proven to be an effective approach for the study of surface deformations, particularly in the context of slow-moving landslides. These investigations are currently in progress and will be extended over a longer period to monitor the evolution of slope dynamics, improving our understanding of slope instability processes under changing meteo-climatic conditions.

KEYWORDS: slope instability, climate change, Northern Apennines, Italy

THEMATIC SESSION 15

METHODS AND TOOLS FOR MONITORING AND MODELLING SEDIMENT FLUXES IN MOUNTAIN ENVIRONMENTS

Chairpersons:

Olimpiu Pop, Armelle Decaulne, Katja Laute, Achim Beylich

Analysis of chemical and mechanical denudation rates in a cold-climate mountain environment in central Norway (upper Driva drainage basin)

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The upper Driva drainage basin system in central Norway (Oppdal) is situated in a cold-climate and mountainous environment and ranges with a total drainage basin area of 1630 km^2 from 220 to 2286 m a.s.l. The mean annual air temperature at Oppdal (545 m a.s.l.) is 4.3°C, and mean annual precipitation at Oppdal amounts to 532 mm. The lithology in the drainage basin is complex and varied, and is clearly dominated by metamorphic rocks (mostly gneisses and schists). Vegetation cover varies between tundra vegetation in the high and rather flat areas of the uppermost drainage basin area, situated at elevations around 900-1200 m a.s.l., tree vegetation (mostly birch and pine) in the lower parts of the incised tributary valleys of the Driva main river and grasslands in the agriculturally used areas close to the lower sections of the main river Driva. Relevant geomorphological processes include chemical and mechanical weathering, rockfalls, snow avalanches, debris flows, slides, wash processes, fluvial erosion, fluvial streambank erosion and down-cutting, and fluvial solute, suspended sediment and bedload transport. This ongoing GFL research on environmental drivers, quantitative rates and future trends of chemical and mechanical denudation includes detailed field and remotely sensed geomorphological mapping, permafrost mapping, and computing of morphometric catchment parameters. This work is combined with the detailed statistical analysis of high-resolution meteorological and ground temperature data, and the continuous observation and year-round monitoring of sediment transfers, runoff and fluvial solute and sediment transport using a range of different techniques. Specific focus is on six selected tributary systems (Svone, Kaldvella, Stølåa, Tronda, Vinstra, Ålma) of the upper Driva drainage basin system. Stationary hydrological stations are monitoring continuously and year-round runoff, fluvial solute and suspended sediment transport. The analysis of fluvial bedload transport includes the application of different tracer techniques together with underwater video filming and Helley Smith and impact sensor measurements. Discharge in the upper Driva drainage basin occurs year-round with a nival runoff regime and a mean annual runoff of 576 mm. The temporal variability of sediment transfers, runoff and fluvial transport are largely controlled by thermally and/or pluvially determined events. The selected tributary systems display varying solute and sediment yields which are explained by different lithologies, valley morphometries and sediment availabilities. The activation of sediment sources and mechanical denudation are strongly determined by thermally and/or pluvially induced events. The highest share of annual sediment transport occurs during the snowmelt period in spring. Altogether, drainage-basin wide chemical denudation dominates over drainage-basin wide mechanical fluvial denudation. It is expected that global warming and the connected shifts in the ratio of snow and rain, the increased frequency of heavy rainfall events, and the continued thawing of permafrost will have complex effects on denudation, with an increasing importance of pluvially induced denudational events, a decreasing importance of snowmelt induced denudation processes, and an increasing dominance of chemical denudation over mechanical denudation.

KEYWORDS: sediment transfers, fluvial transport, monitoring techniques, denudation, central Norway

What do we learn on the dynamic of an subarctic slope from multiproxy signatures (Raspberry site, Clearwater lake, Nunavik, Canada)?

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This contribution describes a preliminary study of slope dynamics in the Nunavik region (northern Québec), specifically on a northern slope of Lepage Island, at Clearwater lake. This area, characterized by a subarctic climate, features active slope dynamics as well as clear signs of weak geomorphologic recent activity: the active process on slope have limited effect on the reworking of the slope at present-time, while the slope have an obvious post-glacial evolution. The aim of this study is to document the evolution of the slope at different timescales, as it consists of a coarse debris talus in the apical zone, followed by a forested slope below a flat area. Fieldwork includes topographical profiles of the slope, an inventory of the morphometric properties of the rock debris, and visual estimation of the vegetal cover on the clasts. Dendrochronology methods were also used to observe disturbances in black spruce growth, suggesting recurrent surface instabilities since 1790. An automatic camera documents snow-avalanche activity over the past seven winters (2018-2025). The results show that the upper part of the slope is dominated by large and coarse boulders with continuous vegetation cover, indicating little recent geomorphological activity on the majority of the slope. In contrast, the lower part shows signs of destabilization in tree rings, notably after 1980. The results indicate that current geomorphological processes, such as snow avalanches, rockfall or landslides, are limited, although there are signs of past readjustments (<1790 CE) and recent disturbances (<1980 CE).

KEYWORDS: avalanche, landslide, clast morphometry, tree rings, timescales

Sediment fingerprinting for river basin applications: latest developments of the FingerPro Model

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Reliable identification of sediment sources in river catchments is essential for managing soil erosion, assessing reservoir siltation, mitigating river pollution, and supporting sustainable land-use planning. These processes directly impact water quality and soil sustainability. Sediment fingerprinting has emerged as a powerful tool to address these challenges and in this context, we present the updated version of the FingerPro model, an R package that offers a comprehensive, reproducible, and user-friendly tool for sediment source apportionment. FingerPro provides a fully reproducible workflow to i) characterise sediment sources and evaluate tracer correlations ii) select optimal tracers, iii) unmix sediment samples using a linear multivariate mixing model, and iv) generate clear and informative graphical outputs for result interpretation. Recent developments integrated into FingerPro address long-standing methodological issues in the field, particularly tracer selection and source variability. These innovations aim to address key challenges in sediment fingerprinting, particularly those related to tracer reliability and source heterogeneity. To improve the identification of non-conservative or inconsistent tracers, FingerPro incorporates a consensus-based approach that integrates individual tracer predictions. In parallel, a conservativeness analysis is used to quantitatively assess the robustness of each tracer. Additionally, a new method has been developed to mitigate potential biases in source apportionment caused by dominant or non-contributing sources and high variability among source materials. Together, these advances enhance the precision and interpretability of fingerprinting results, especially in complex catchments, and further consolidate FingerPro as a reliable framework for geomorphological research and environmental decision-making.

KEYWORDS: source apportions, tracer selection, unmixing model

Assessment of fluvial transport dynamics in high-mountain environments using OSL properties

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As sediment fluxes in mountain environments are intensively changing as a result of global warming, the investigation of bedload dynamics is crucial to understand catchment scale responses to climate change. However, assessing bedload transport and erosion rates within larger river systems, especially in high-mountain environments, is complicated and time-consuming when using traditional sediment monitoring methods.
The aim of this research is to test a new method based on OSL (Optically Stimulated Luminescence) along the 250 km long Zaravshan Valley in the Western Tian Shan, Tajikistan. The investigated catchment is elongated and has a relatively homogeneous geological background. Due to spatially variable uplift rates along the river, erosion potential changes significantly downstream, making the site excellent for testing the applicability of OSL properties in determining sediment virtual velocity.
Samples were collected from lateral bars of the river every 20–30 kilometers. The 212–300 µm fraction of the samples was used for the analyses, from which K-feldspar grains were separated using a heavy liquid procedure. Measurements were performed using a single-grain pIRIR (post-infrared infrared stimulated luminescence) protocol. Optical stimulation was conducted at different temperatures. The measurements aimed to determine the residual doses remaining in the grains, which refers to the velocity of sediment grains. High residual doses indicate erosion and fast sediment transport, whereas low values indicate repeated sediment cycles and slow movement.
Based on the results, the analysed samples exhibited very similar luminescence properties, allowing for the establishment of a standardised growth curve applicable to the entire valley. Results have shown that the measured residual doses vary significantly along the river and influenced by various geomorphological factors. In general, the tested method has a great potential in the assessment of sediment virtual velocity in mountain areas.

KEYWORDS: OSL, residual dose, sediment transport rate, mountain catchments, pIRIR

Exploring weathering processes at rockwalls in steep Norwegian mountain valleys based on a ten-year record of rock temperatures

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Permafrost and seasonal frost regimes are expected to react differently to current and projected climate changes, which will have different effects on mechanical weathering and the associated rockfall supply at rockwalls. Most existing studies on rockwall frost regimes and frost weathering at rockwalls focus on permafrost-affected rockwalls. However, a high share of current rockwall surface areas in Norway and in many other cold-climate environments is actually free of permafrost. It is therefore of interest how these permafrost-free rockwall systems will respond to future changes in air and rock temperatures. In this study, we report field measurements conducted at rockwalls beneath the current permafrost limit and investigate thermal regimes at rockwalls that include both rockwall areas with and without permafrost. Rock temperature measurements play a pivotal role in assessing the thermal regime of rockwalls. It is therefore crucial to supplement the existing measurements of rockwall temperatures, both in terms of spatial distribution and longer-term data. We present a unique dataset of up to ten years of rockwall temperature measurements from ten temperature sensors installed in two mountain valleys in western Norway, covering different elevation ranges, rockwall aspects and slope inclinations. Based on this dataset, we provide an analysis of the different rockwall thermal regimes with respect to rock weathering and associated rockfall supply for both, permafrost-affected rockwalls and rockwalls without permafrost. Our results indicate a strong interplay of elevation- and aspect-dependent weathering regimes of rockfall source areas. The highest intensity of recent rockwall weathering including determined rockwall retreat rates and associated rockfall supply is detected for northeast-facing rockwalls followed by south-facing rockwalls in our study area. Frost cracking activity seems to be an important factor particularly for the high weathering intensity on northeast-facing rockwalls whereas solar radiation-induced thermal stress is assumed to play a relevant role in the moderate weathering intensity on south- and southwest-facing rockwalls. Rising air temperatures will most likely lead to more frequent interruptions of longer seasonal frost phases, whereby the resulting higher number of shorter frost phases should be less relevant for frost weathering than the previous lower number of longer lasting frost phases, especially on rockwalls without permafrost. At the same time, increased permafrost degradation/thawing is expected, which will lead to greater thawing depth on the rockwalls affected by permafrost and increased rockfall activity on these rock surfaces.

KEYWORDS: temperature monitoring, Rockwall thermal regime, Rockfall, Rockwall retreat, Norway

Sediment mediated elemental transfer from forests and agricultural slopes to Phewa Lake, Nepal

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Accelerated erosion due to human activities poses a significant global challenge, leading to widespread land degradation and adverse impacts on water bodies. The transfer of fine sediment and associated contaminants through the sediment cascade is particularly challenging for ecosystem health. Highly sediment-productive areas in high mountains under monsoon climates currently present a risk in Nepal, where lakes in populated areas at the foot of the Himalayas are experiencing rapid siltation and eutrophication. The Phewa Lake catchment, with an altitudinal range between 759 and 2,481 m a.s.l., receives an average annual rainfall of approximately 4,000 mm, reaching over 5,000 mm at higher elevations. Over recent decades, the catchment has undergone various activities on its steep slopes, including unplanned development, construction projects (such as roads, sediment dams, and quarry exploitation), and inappropriate agricultural practices. These, along with intensified rainfall events during the monsoon season, contribute to increased sediment loads into the tributaries of the Harpan River, which flows into the lake near the city of Pokhara. The lake's surface area has decreased by 60% over the past seven decades. Despite interventions for land and water conservation by national and international agencies, high sedimentation and water pollution levels have persisted. A field survey expedition funded by the INT5156 IAEA project was conducted to identify the main landforms and land uses contributing fine sediments to the hydrological network. The Phewa catchment's sides differ in land use and geomorphic features, with forest dominating the northern side and cropland the southern side. Samples were taken from landslides, riverbanks, road cuts, forests, and croplands to determine elemental composition (29 stable elements and 6 radionuclides) and compare them with existing levels in fine riverbed sediments at the outlets of the Andheri and Harpan subcatchments, as well as along the Harpan River and its outflow into Phewa Lake. Silt and sand fractions predominated while clay content was less than 2%. After the confluence of the two headwater tributaries, silt content was high (67%) and correlated with peak levels of most stable elements and radionuclides. Differences in the geochemical contents of riverbed sediments at the headwaters appear to be related to lithology. The phyllite-dominated, agricultural-intensive Andheri catchment showed higher levels of major elements (Al, Fe, Ca, Mg and Ti) as well as trace elements (Zn, As, Mn, S, Cr and Co), compared to the quartzite-dominated, forested Harpan catchment. At the river's outflow into the lake, several elemental contents increased, coinciding with higher sediment yield from the agricultural southern slopes, where silt-sized particles predominated. The most notable enrichments were observed for As, Ca, Fe and Mg. However, riverbed C and N contents were much lower than in sediment sources, whereas P levels were higher, especially in midstream and at the outflow. Assessing the transfer of particle-bound elements and nutrients through fine sediments is essential for understanding spatial and temporal patterns of compositional variation, as well as identifying the key environmental and anthropogenic factors driving these changes. Such knowledge is crucial for informing targeted and effective strategies for land and water resource management.

KEYWORDS: catchment erosion, fine riverbed sediment, geochemical tracers, nutrient fluxes, lake siltation

Identifying predominant exogenic processes in a small high-mountain catchment using supervised learning

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Systematizing the set of exogenic processes and their spatial distribution is a critical component of studying sediment budgets in small catchments. This is particularly important in mountainous regions, where significant elevation gradients and variations in slope steepness create high spatial heterogeneity of exogenic processes. Standard methods for mapping predominant exogenic processes include fieldworks, aerial surveys, and visual interpretation. However, manually generated results can be used as training data to automate the mapping of these processes. While the accuracy of this approach may be limited, automatically generated maps can provide a basis for subsequent refinement. An experiment to map predominant exogenic processes was conducted for two small catchments in the central sector of the Greater Caucasus Mountains: the Lake Donguz-Orun catchment and the Djankuat Stream catchment. Both are located on the northern slope of the Main Divide Range near the Russia-Georgia border. They are characterized by similar elevation ranges but differ in overall geomorphic characteristics. For the Lake Donguz-Orun catchment (A = 13 km^2), a map of predominant exogenic processes was created (approach: each point corresponds only to the most active process). Key process groups include glacial erosion, fluvial erosion, various types of creep (fine-grained and coarse debris), rockfalls, sheetwash, gully erosion, and stream erosion. A Random Forest model was trained on 80% of the catchment area, with model accuracy evaluated on a 20% test subset and independently validated via 5-fold cross-validation. Predictors included elevation, TPI (radius = 100 m), slope, topographic wetness index, and Haralick texture metrics derived from RGB orthomosaic channels. Accuracy estimates ranged from 80% to 84%, exceeding baseline (random guessing) by 7–7.5 times. The trained model was applied to the Jankuat Stream catchment (A = 10 km^2), located 20 km away. Model results indicate the most widespread processes are fine-grained material creep (3.1 km^2), coarse debris creep (1.5 km^2), rockfalls (1.6 km^2), glacial and fluvioglacial erosion (1.3 km^2), gully erosion (0.9 km^2), and stable surfaces takes 1.3 km^2. Future work will validate the semi-automated mapping approach against manually generated reference maps for the second catchment. This work was supported by the grant of The Government of the Russian Federation (Agreement №075-15-2024-614 date 13.06.2024).

KEYWORDS: erosion processes, Created Caucasus, random forest, mapping, sediment budget

THEMATIC SESSION 16

NEW APPROACHES IN VIRTUAL FIELDTRIPS IN GEOMORPHOLOGY

(organized by the IAG WG Virtual trips in Geomorphology)

Chairpersons:

Anna Karkani, Mihaela Verga, Arjen Stroeven, Derek McDougall

A digital odyssey: exploring glaciokarst and endangered flora in the Dinaric Karst via virtual reality

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The cross-border area of the Snežnik (Slovenia) and Gorski kotar (Croatia) high karst plateaus in the northern Dinaric Mountains was subject to various phases of glaciation. Its remnants are still visible in the landscape, directly in the great variety of landforms and indirectly in the vegetation patterns, which largely reflect the geodiversity. The complex mountainous and rugged topography can restrict or limit the ability of many people to visit the area, and many landforms are difficult or impossible for the average mountaineer to access and see in the field. In addition, certain landforms which are both very rare and exceptional, necessitate their preservation, thus they should not be exposed to large numbers of visitors. Therefore, it is useful to complement a visit to the area with virtual presentations of individual sections of the area that are too dangerous for visitors. The creation of a virtual tour is also useful for educational purposes and for interpreting the glacial karst heritage. As part of the transPlant project (Interreg Slovenia/Croatia), which focuses on the conservation of high mountain Natura 2000 plant species threatened by habitat loss due to climate change, a virtual excursion has been developed based on the real field trip. It follows peaks, ridges, slopes, and glacial moraines, descending into deep and steep konte dolines, that are the climatic refuges of many endangered plants. The creation of a virtual educational excursion through the current landscape, interpreting the glacial karst and its geoheritage with biodiversity protection and conservation, was achieved by utilising state-of-the-art 3D representations and animations of the real landscape. These were captured during field research with different sensors on drones (Lidar, thermal and multispectral camera), a handheld 3D laser scanner, and the processing and visualization of in-situ monitoring data in konte dolines, using existing high-resolution terrain data. Additionally, by incorporating historical maps and aerial photographs, we have taken the virtual excursion temporally backwards, which is not possible when visiting the area itself.

KEYWORDS: glacial karst, paleoenvironment, 3D model, geoheritage interpretation, Dinaric Mountains

Virtual fieldtrips in geomorphology

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Fieldtrips are a pivotal component of geoscience, as they facilitate the visualization and comprehension of geological processes. Geomorphological mapping, an integral component of geomorphological research, necessitates fieldwork as a fundamental prerequisite. Furthermore, field trips represent an indispensable component of an integrated geomorphology education. Nevertheless, there are several drawbacks associated with them, the most common being the high cost and time needed to conduct them, and the effort required to organise them. This, in turn, acts as a deterrent to student participation, as well as to the organisation of such events by geoscience classes. Virtual fieldtrips (VFTs) represent a cost-effective solution, offering universal accessibility from any location (e.g. classroom, home). The accessibility of VFTs ensures that individuals can explore any location, including remote or inaccessible areas. VFTs can be utilized as a valuable preparatory tool for physical fieldtrips. The efficacy of VFTs is particularly pronounced in the field of geomorphology, given its capacity to encompass a diverse array of environments, which often necessitate extensive travel.

Here, we present some of the tools we have developed to help you take part in a VFT yourself. The first is a web platform, geovirtualfieldtrips, containing links to story maps and Google Earth-based VFTs on various locations and environments. The second tool is the GeoVT application, which contains 360° photographs and videos from various locations and aspects of geomorphology, offering the unique experience of using VR goggles to provide the impression of actually being there. The Virtual Trips in Geomorphology Working Group, of the International Association of Geomorphologists, aims to demonstrate the importance of virtual trips in geomorphology. Specifically, we highlight the benefits of VFTs in geomorphological research, emphasizing their role in facilitating fieldwork preparations. The potential contributions of VFTs to the promotion of geomorphology are also demonstrated, as are their exemplification of diverse environmental contexts and their interactions with human activities. Furthermore, we present how beneficial VFTs can be in geomorphology education.

KEYWORDS: geomorphology, virtual fieldtrips, education, awareness raising, environment

A synthetic world for virtual field trips and serious gaming

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One of the main aims of study programmes in geography and related subjects is to convey a deep understanding on earth surface processes. Practical constraints often force curriculum developers to stick to traditional learning formats, with limited options for the creations of innovative, exciting learning environments. We attempt to close this gap by creating a freely available physical geography environment that can be used for virtual field trips, for serious gaming, or even for the combination of both concepts. Bachelor students of geography and related subjects will be the target audience, but the environment will be flexible enough to be adapted to learners of different levels. it will be optimized for virtual reality experiences, but also useable with PCs, notebooks, and possibly mobile phones in order to increase reach and accessibility. The game is developed with Unreal Engine 5.

The scene of the game is an 80 km x 80 km synthetic landscape featuring all major geomorphic landforms and biomes in a logical arrangement, from the equator to high latitudes, and from high mountains to the deep sea. Terrain elevation is scaled by approx. 1:10–1:15, meaning that the highest mountains peak at some hundreds of metres asl. The environment consists of (i) the terrain, created in GIS; (ii) land cover, composed from materials, grass, and foliage available for Unreal Engine; (iii) oceans, rivers, and lakes; (iv) geomorphic processes (e.g., landslides, volcanic eruptions); (v) movement of the excursion participants through trails, roads, railways, air and water transport; and (vi) atmospheric conditions.

For gaming applications, which can be integrated with virtual field trips, a well-coordinated set of tasks and rewards will be introduced. The player will move through the landscape and guided through the tasks. Tasks will be related to each other and will focus on gaining a deep understanding of earth surface processes in an exciting interactive way. Particular emphasis will be put on the understanding of spatial and functional relations between geomorphic processes of different types.

The proposed environment is still in the phase of prototype development. This prototype is intended to be exposed to the target audience, so that students are invited to add their own ideas. The environment should then be gradually enhanced and improved. It will be made available to the public when considered sufficiently mature.

KEYWORDS: serious games, synthetic landscape, virtual reality

Developing engaging virtual reality landslide experiences for museum audiences: lessons from a case study for the Wildalpen landslide (Austria)

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Despite the immediate impact of landslides (LS) on individuals and society, the public understanding of the underlying processes remains limited. Diverse manifestations and rare opportunities for in-situ, real-time observations present significant challenges for LS education. While simulations provide important insights in process dynamics, their outputs are too abstract for non-experts. Immersive, interactive virtual reality experiences (VRE), enriched with gaming elements are a promising approach to enhance engagement and learning in science communication.

Our workflow builds on simulations performed with the open-source tool r.avaflow, processed in the 3D modelling software Blender and imported into the game engine Unreal Engine 5 (UE5). Leveraging our self-developed MassMoVR template for (UE5), we create the VRE from modular components for player setup, environment design, interactive objects, visual effects, soundscapes, and user interfaces. Realistic environments are built using free assets from the Fab platform.

Our case study features a VR experience of the prehistoric Wildalpen landslide (Styria, Austria), embedded in a museum exhibition at the visitor centre of the UNESCO Global Geopark Steirische Eisenwurzen. Prototypes were tested during supervised science events, but adapting for unsupervised museum use required addressing cost efficiency, usability, safety, and hygiene. To ensure accessibility, we chose a seated setup with minimal inputs and physical movement. The VRE comprises multiple scenes, each centred on specific learning objectives and featuring interactive tasks designed as quizzes. These tasks advance the storyline and trigger key events. Interactivity is facilitated through a user interface, divided into an information panel that provides instructions and an interaction panel for completing tasks, such as selecting locations on a map or identifying potential triggers. The educational goals cover the understanding of the landslide's timeline, location, triggers, and its impact on landscape evolution. Throughout the experience, users explore the virtual landslide terrain from carefully selected viewpoints, offering an overview of the study area to encourage real-life-style analysis of the terrain.

Future advancements for the VRE include enhancing immersion by enabling standing positions and free, multi-directional movement while ensuring safety and user-friendliness. Additionally, we are interested in evaluating the educational impact of our instructional design strategy. For this purpose, we intend to employ polls to assess learning outcomes and engagement.

We acknowledge that our work is part of the project "Moving mountains - landslides as geosystemservices in Austrian geoparks" (ESS22-24-MOVEMONT) funded through the Earth System Sciences programme of the Austrian Academy of Sciences.

KEYWORDS: landslides, virtual reality, game engines, science communication, geo-education

STEAM education in geosciences: the role of virtual field trips

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STEAM is an educational approach, derived from the terms: Science, Technology, Engineering, Arts and Mathematics. Its aim is to promote an interactive and engaging way of learning, combined with the development of critical thinking. The usage of augmented reality (AR) and virtual reality (VR) in Virtual field trips (VFTs) is a particularly effective, STEAM-based educational approach, which can offer students an integrated comprehension of natural processes, and how they interact with human activities. For this reason, they are very frequently used in geoscience education. Here, we present an innovative, STEAM-based approach, incorporating both augmented and virtual reality, focused on various geoscientific aspects. The AR platform features an inventor module for crafting digital scenes and a viewer app that allows users to visualize scenarios through smart devices, encouraging hands-on interaction with augmented artifacts. In addition, the VR tool offers immersive 360-degree geoscientific environments enhanced with audiovisual elements and 3D models. These VFTs deepen the understanding of intricate geological processes and spatial relationships, fostering creative thinking and engagement. Through simulations, educational games, and training resources, this technology-driven initiative aligns with global educational goals, addressing challenges in STEAM education and equipping teachers and students for a digitally interconnected world. This strategy underscores the transformative potential of AR and VR in making education inclusive, interactive, and prepared for the future.
ACKNOWLEDGEMENTS: This work was funded by the project "Training pupils on geosciences through Virtual Field Trips" (TRiPGiFT) under the Erasmus+ Program (Project ID: 2021-1-EL01-KA220-SCH-000032556).

KEYWORDS: emerging technologies, control structures and microprogramming, web technologies, virtual and augmented reality, TRiPGiFT

GeoVT: a virtual reality application to enhance geoeducation on geomorphology, geohazards and geoheritage

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Virtual reality has become very popular in Earth sciences, because it offers a variety of benefits to the users, such as virtually visiting remote, expensive or dangerous areas which they could not go to otherwise. Given that field trips are a necessary component of geoscience, virtual field trips are an excellent tool to help students comprehend their surrounding environment and the natural processes that have shaped the relief. Virtual reality can also be used to address geomorphological hazards, such as flooding, runoff erosion, landslides and coastal inundation, as well as to increase hazard awareness. Moreover, it is an excellent tool for familiarizing with the geo-cultural heritage. Here, we present a virtual reality application, created in the framework of the Erasmus+ GeoVT project, which is available to the public. One can use it to create their own virtual field trip, by uploading photos, videos, audio, as well as 360° photos and videos. The application is designed to help teachers and students comprehend the basic principles of geomorphology, geohazards and geoheritage. Through this application, we have created a series of virtual geomorphological field trips, addressing various aspects such as fluvial geomorphology, sea-level changes, marine terraces, karstic environments, glacial geomorphology, runoff erosion risk etc. These virtual field trips, as well as the application itself, are directly available to every potential user at the project's website: https://www.geovt.eu/.
ACKNOWLEDGEMENTS: This work was funded by the project "Training new generations on geomorphology, geohazards and geoheritage through Virtual Reality Technologies" (GeoVT) under the Erasmus+ Program (Project ID: 2021-1-SE01-KA220-HED-000032142).

KEYWORDS: virtual reality; geo-education; virtual field trips

Virtual field trips to address sea-level changes: West Naxos as a case study

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The western part of Naxos Island, Cyclades, Greece, is a unique region to address sea-level changes. The combination of local lithology, relief, coastal processes and vertical tectonic movements has led to the configuration of a unique coastal landscape, consisting of geomorphological sea-level indicators (e.g. beachrocks, tidal notches), as well as archaeological ones, such as submerged quarries. For this reason, it is an ideal location for geoscience students to comprehend what sea-level changes are, how they are induced, how they are affected by humans besides natural factors, and what their future impacts on coastal activities, communities and cultural heritage will be. By collecting a series of 360° photos from selected sites of western Naxos, and by utilizing a virtual reality platform, we have created a virtual field trip, which can be used by students, as well as tutors, both through a simple computer and through virtual reality goggles, thus giving users the impression of being actually in the field. The virtual field trip consists of various "stops", each one of which addresses a different site of Naxos and contains supporting audiovisual material. Thus, the virtual field trip can be used for various purposes, such as: (a) Students can use it for autodidacticism, in order to better comprehend sea-level changes and how they affect the coastal landscape; (b) Geoscience tutors can use it as a means of education, supplementary to other materials such as presentations and videos; (c) Potential future visitors of the island can use this virtual field trip in order to become familiar with the geomorphological regime of the island in advance, before actually visiting it. It is to be noted that this virtual field trip can also be used by people without previous expertise on geology or geomorphology, as it is structured in an easily comprehendible way.
ACKNOWLEDGEMENTS: This work was funded by the project "Tracing Climate Change" (TRACE) under the Erasmus+ Program (Project ID: KA220-HED-612216D9).

KEYWORDS: sea-level indicators, beachrocks, submerged quarries, coastal lagoons, virtual reality

A virtual geo-journey to Samaria Gorge

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Samaria Gorge is one of the most highly visited areas of western Crete Island, Greece, due to its natural beauty. At the same time, it is an ideal location for both geoscientists and the general public to comprehend landscape evolution, and how it is affected by endogenous (e.g. vertical tectonic uplift movements) and exogenous processes (predominantly surface water runoff and fluvial erosion, and to a lesser extent karstic processes). Many different features are present, each one of which can unravel a different perspective of the complex geological history of the gorge. This is the reason why the Samaria Gorge was selected as a case study to develop a virtual field trip, targeting mostly pupils, to train them on geomorphological processes and the evolution of the landscape. More specifically, through the means provided by the Erasmus+ TRiPGiFT project, we visited the area and collected 360° photographic material, which we used to create a virtual reality application. The A-Frame framework and the AutoCAD software (version 2023) were used to create this virtual field trip, and it can be accessed under this link: https://tripgift.eu/virtualReality/samaria/samaria_home.html. It can be directly accessed through a simple computer, but it can also be connected to virtual reality goggles. It consists of 11 stops, starting from the gorge's entrance and ending in its exit, to the sea. Depending on the stop, one can either view the gorge panoramically from above, or observe specific landforms from up close. Users can move from one stop to the next one, or choose the stop they would like to visit. They can also perform measurements, and they have the option to view the necessary information about each stop.

ACKNOWLEDGEMENTS: This work was funded by the project "Training pupils on geosciences through Virtual Field Trips" (TRiPGiFT) under the Erasmus+ Program (Project ID: 2021-1-EL01-KA220-SCH-000032556).

KEYWORDS: virtual reality application, endogenous processes, exogenous processes, landscape evolution, TRiPGiFT

Virtual tour and 3D reconstruction of volcanic landforms at the 1858 lava flow field of Somma-Vesuvius (Italy)

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Somma-Vesuvius in southern Italy is one of the most famous and visited volcanoes of the world. Noteworthy, geotourism at Somma-Vesuvius is mainly concentrated around the central crater while the rest of the volcano, which is part of the Vesuvius National Park, is largely unvisited.
The volcano's worldwide fame is largely linked to its explosive activity, most notably the famous eruption that destroyed the Roman towns of Pompeii and Herculaneum in 79 CE. Despite its explosive activity, the volcano had periods of effusive activity, as testified by examples of archetypal lava flows, including the 1858 lava flow field in which lava tubes formed. In this paper, we propose a geoitinerary through the 1858 lava flow field with the aim of exposing people to evidence of effusive activity produced by the stratovolcano. The geoitinerary includes five sites that allow visitors to discover volcanic features formed during effusive activity at Somma-Vesuvius. A 3D scan of the largest lava tube of the 1858 lava flow field has been carried out to allow a precise reconstruction of its geometry and to conserve a virtual copy of this fragile structure through time. A website has been also developed with the aim of favouring a virtual tour for people either not used to hiking or with physical impediment (https://sites.google.com/view/vesuvius-1858lavaflow/). The website includes panels with the description of volcanic landforms of the five sites and panoramic views from each site, including 360° photos of the interior of the lava tube. We are confident that the adopted approach may contribute to divert tourist traffic away from the central crater and raise awareness among the local population of volcanic processes such as lava flow emplacement and lava tube formation.

KEYWORDS: lava tube; geotourism; volcano tourism; 3D scan; virtual tour

Reaching the unreachable: virtual field trips for geoheritage enhancement and geotourism promotion

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The perception and understanding of landscape features and evolution are normally achieved through the physical exploration and appreciation of specific locations. Recent advancements in technology, including the increasing use of Virtual Reality (VR), are providing further means to visit sites of geological and geomorphological interest thanks to Virtual Field Trips (VFTs) based on 360-degree imaging and interactive digital contents. In recent years, the latter, have proved to be powerful tools for promoting the knowledge of geoheritage. VFTs have become an effective alternative to traditional field visits by enabling immersive experiences of remote or inaccessible sites, overcoming physical and financial limitations. Additionally, VFTs can be an excellent tool for visiting sites which can be severely affected by human presence and may contribute to maintaining the sites' integrity while still allowing visitors to 1experience and appreciate these locations. VFTs can also encourage people to explore lesser-known locations that however hold significant landscape, cultural, geological and environmental significance, and may play a role in redistributing tourism flows and help preventing overcrowding in popular destinations. This makes VFTs an inclusive and sustainable tool for appreciating natural and cultural heritage and disseminating geoscientific knowledge in an innovative and engaging way.

This study explores diverse applications of VFTs in geoheritage and geotourism enhancement in Europe. A series of VFTs was developed for various geomorphic environments, including mountain and coastal areas, characterized by valuable geological and landscape features showing also a cultural significance and an educational potential. These virtual experiences integrate interactive maps, 3D terrain models, and historical documents to provide users with a meaningful understanding of the scientific value of each site, beyond its aesthetic appreciation. This approach aligns with the principles of sustainable development by emphasizing the importance of geoscientific literacy in fostering resilient communities.

KEYWORDS: geoheritage, virtual reality technologies, geotourism

THEMATIC SESSION 17

PERMAFROST AND PERIGLACIAL PROCESSES IN CLIMATE CHANGES CONTEXT

(co-organized IAG-International Permafrost Association)

Chairpersons:

Gonçalo Vieira, Isabelle Gärtner-Roer, Petru Urdea, Alexandru Onaca

Changing permafrost features on Yamal as seen from space

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Ground temperatures are increasing across the Arctic in continuous permafrost as well as in its transition zones. The Yamal peninsula stretches north-south and thus spans a gradient of permafrost conditions, vegetation communities and geomorphological settings. The latter specifically comprises marine terraces and extensive floodplains. Typical permafrost landscape features such as thaw lakes, drained lake basins, thaw slumps and polygonal patterns are common. Remote sensing provides a wide range of options for their monitoring. The general climatic gradient can be documented for example through landcover such as the 10 m Circumarctic land surface units (CALU). Ground temperature timeseries available through ESA CCI Permafrost (based on modelling using satellite derived land surface temperature data) document continuous warming in the region and shift from continuous to discontinuous permafrost in the southern part. Lake drainage occurs frequently, leading to an increase of drained lake basins across the region with varying properties across the climatic gradient. Thaw subsidence occurs at varying magnitude across the landscape what can be documented regionally only with synthetic aperture radar data to date. A database of relevant satellite-based records has been set up for the entire Yamal peninsula for a comprehensive analysis of landscape change patterns considering the climatic gradient as well as different geomorphological landscape units. Results are presented and discussed with focus on changing permafrost.

KEYWORDS: permafrost, remote sensing, lake basins, subsidence

Beyond destabilization: rapid disintegration of an active rock glacier through mass wasting and headward channel incision, Livigno, Italy

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Recent studies in the Alps have shown that in response to climate warming active rock glaciers may become destabilized. That is, they may undergo an abrupt surge in velocity, which typically can last from seasons to years, followed by a phase of progressive recovery to "pre-crisis" rates of deformation. In this contribution we document the catastrophic evolution of Monte delle Mine rock glacier in Livigno (Sondrio), where metric annual velocity resulted in the rapid disintegration of this landform through a series of geomorphic feedback mechanisms. This general objective is pursued through: (1) visual interpretation of sequential aerial photos and satellite optical imagery (1998-2024); (2) field visits and UAV SfM surveys conducted over the summer and fall of 2024; and (3) DInSAR analysis performed on multiple sources of satellite SAR acquisitions (1992-2024). We show that the main rock glacier tongue began displaying widespread signs of destabilization as early as 2018: lateral levees underwent transverse downslope displacement and a thermokarst collapse feature at the front became apparent for the first time. This thermokarst feature, which hosts the spring of the main headwater stream draining the catchment, has remained about stable throughout 2022, while the rock glacier tongue continued to displace in a destabilized, chaotic fashion. In early September 2023, we detected on satellite imagery the distinct scar of a rotational slide on the rock glacier surface, approximately at the root of the main tongue, between the upper ends of the two lateral levees By early July 2024, we observed that the rotational slide had grown larger and that simultaneously headward stream migration had connected the thermokarst feature at the front with the main slide scar, thereby triggering a rapid phase of vertical incision and sediment evacuation via fluvial transport and fine-grained debris flows. Preliminary analysis of sequential UAV SfM surveys indicates that between August and October 2024 about 28,000 m^3 of material was evacuated from the rock glacier. Part of this material (~10,000 m^3) was redeposited to form a debris fan that is currently prograding downslope of the rock glacier front, while the rest reached the confluence with the Rio Spol in the drainage network of the Livigno valley. Today, the formerly creeping rock glacier has become an active source of debris flows, with immediate practical implications for geohazard potential, as well as for the water quality of Rio Spol, which flows permanently muddy. Ongoing work aims to reconstruct the pre-2023 rock glacier kinematics, through DInSAR and digital image correlation analysis, to better constrain and understand this unexpected, climate-driven style of landscape evolution.

KEYWORDS: rock glacier, climate warming, destabilization, mass wasting, remote sensing

Refining long-lying snow

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We present a rationalisation and simplification of the existing nomenclature and terminology for long-lying snow (snowpatches), advocating wider cross-disciplinary adoption of the word snowpatch, longevity as the most effective means to discriminate snowpatches of different types and use of the established qualifiers seasonal, semi-perennial and perennial. Novel definitions are presented for each longevity type, providing a clearer discrimination between them, permitting their better quantification, and tracking over time, enabling greater insights into potential future changes in snowpatch dependent vegetation communities, nivation processes and local hydrology. Snowpatch longevity has been observed to be declining in locations as diverse as Norway, Alaska, Canada, Australia and Scotland, with once perennial snowpatches now ablating prior to the next winter's snowpack. This reduction in snowpatch longevity has significant implications for snowpatch dependent plant communities, local hydrology and nivation processes in alpine and high latitude environments.

Tracking changes in snowpatch types has been stymied by ill-defined, conflicting and inconsistent definitions for seasonal, semi-perennial and perennial snowpatches, and between nival and glacial ice. Revised definitions are presented, enabling changes in snowpatch type over time to be more accurately tracked, and for snowpatches to be more clearly separated from glaciers and small ice bodies such as glacierets. When the revised definitions are applied to Sentinel and Landsat satellite imagery of snowpatches from the northern and southern hemispheres, the change in snowpatch type from perennial to semi-perennial, and from semi-perennial to seasonal, can be effectively tracked.

To analyse the factors influencing snowpatch longevity and it's defined type, a random forest machine learning model was trained on a diverse set of climatic and environmental features across 52 snowpatches in Australia's three alpine zones. The model leveraged ensemble learning to optimize predictive accuracy, capturing complex nonlinear relationships between input variables and snowpatch dynamics. This analysis has shown that topographic variables (e.g., latitude and elevation) and local climate variables (e.g., snow depth) are of high variable importance (i.e., improved the accuracy of predictions of snowpatch longevity), while regional (e.g., El Niño–Southern Oscillation (ENSO)) and global (e.g., global CO2 concentration) climate drivers were of intermediate importance in predicting snowpatch longevity.

KEYWORDS: snowpatch, glacieret, machine learning

Temperatures trends in Picos de Europa ice caves (Northern Spain)

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In the current context of Global Change, the cryosphere is diminishing at all levels, with the increase in temperatures as one of the main factors. Continuous monitoring records of change patterns in both cryogeomorphological processes and morphologies, as well as their climatic reasons, is essential for understanding the evolution and accelerated processes that have been observed in recent decades as causes of the ice mass reduction and disappearance of some of the most representative elements of cold environments. It also occurs with the least recognized cryological element: ice caves.

As a consequence of being the cryospheric topic that has been received the least the least attention in the literature in the specific scientific literature, there is a significant lack of long-term records of the main endoclimatic factors in ice caves. For the most part, only in the last three decades has a continuous monitoring corpus been formed, but in just a dozen cavities around the world, and mainly in those most accessible in the mid-latitudes of Europe.

This study presents the reconstruction of temperature trends inside three high mountain ice caves in the Picos de Europa: Castil, Verónica and Altaiz ice caves, monitored since 2010 continuously. The implications for their respective mass balances and future projections in different warming scenarios are highlighted. This evolution is compared with thermal records of air temperature obtained from several meteorological stations of the Spanish national parks network, and with the surface temperature provided by the ERA5-Land model.

Ice caves, as the ultimate representatives of paleoenvironmental records in completely deglaciated areas such as the Picos de Europa, urgently need continuity in this type of endoclimatic monitoring before their complete disappearance.

KEYWORDS: ice caves, temperatures monitoring, endoclimate cave evolution, Picos de Europa, Spain

Time-lapse joint inversion of seismic refraction and electrical resistivity monitoring data for more reliable estimates of ground ice content changes

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Geophysical monitoring has become more and more popular in permafrost environments due to its remarkable success to detect permafrost thawing and associated spatio-temporal changes in the ground ice content. However, the quantification of absolute ground ice volumes, and especially of their temporal changes are still challenging tasks. Recent advancements in the petrophysical joint inversion of seismic refraction and electrical resistivity monitoring data now allow for a time-lapse application of the petrophysical joint inversion approach published by Wagner et al. (2019, https://doi.org/10.1093/gji/ggz402). While the petrophysical coupling enables the direct estimation of pore-filling constituents honoring petrophysical relations and physical plausibility (i.e. volumetric constraints), the temporal coupling enables the differentiation between parameters that are assumed to be invariant with time (e.g., porosity) and those parameters, which are expected to exhibit a dynamic behaviour (e.g., ice and liquid water contents). This new time-lapse petrophysical joint inversion (TL-PJI) approach therefore ensures a time-consistent porosity distribution and improves the reliability of predicted ice content changes.
We demonstrate the potential of TL-PJI approach based on repeated geoelectrical and refraction seismic data from different mountain permafrost sites that have been subject to substantial change over the past decades.
Our results show, that the TL-PJI approach is applicable to permafrost field sites with different ice content characteristics and that the temporal regularization avoids changes in the porosity, which in turn leads to more realistic results for the ice, water and air contents and their temporal changes. By this, the TL-PJI helps to solve the rock-ice ambiguity and to compensate for the poorly constrained ice content in the currently used petrophysical relations.

KEYWORDS: Petrophysical Joint Inversion, ice content, permafrost

Deciphering seasonal kinematics of rock glaciers: insights from the Swiss Alps

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Rock glaciers are ubiquitous debris landforms in periglacial environments worldwide. A combination of the creep of the frozen body and the concentrated deformation in the shear horizon at about 20 m depth shapes the distinctive morphology of rock glaciers, and their characteristic kinematic behavior indicates important climatic controls over time scales.

In this study, we focus on the seasonal pattern of rock glacier kinematics and the observed relationship with several meteorological-related factors, such as snow cover regime, precipitation, and ground thawing/freezing index. We present the seasonal kinematic pattern as revealed by permanent GNSS data and other repetitive geodetic surveys on the surface of more than ten rock glaciers with a wide range of velocities (from 0.1 m/day to 0.1 m/year) in the Swiss Alps during the last decade and beyond.

We have proved that rock glaciers in the Swiss Alps typically repeat a site-specific seasonal cycle – a general acceleration phase from the onset of snowmelt/zero-curtain until the end of the thawing season, then usually (but not always) decelerating during the freezing season and reaching their velocity minima in late winter/early spring. The amplitude of the seasonal variation ranges approximately between one-fifth and ten times of the mean velocity. We investigate the climatic control by analyzing the responses of rock glaciers in their thermal, hydrological, and kinematic changes detected by a series of new borehole measurements (i.e., ground temperature, cross-borehole ERT, piezometer and inclinometer measurements) on Schafberg and Muragl rock glaciers since 2020/2024. We highlight the thermal control, collectively influenced by air temperature, snow cover, and ground water, in adjusting the timing and amplitude of the seasonal kinematic variations.

KEYWORDS: rock glacier dynamics, permafrost creep, GNSS, borehole measurements

COLDSPOTS: low temperatures of ground in the Sudetes (Bohemian Massif)

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The project was carried out in the Sudetes, the highest massif of which is the Karkonosze Mts on the Polish-Czech border. The Central European mountains of medium altitude are not usually the place for permafrost research. Nevertheless, low or even negative ground temperatures can persist here all year round in special terrain situations. I call these exceptional places COLDSPOTS. They are closed depressions (cold-air pools), coarse-grained sediments at high altitudes, rock crevices, and caves into which cold air flows. Although their thermal conditions have been observed by many researchers, such reports come mainly from the past and are often not based on longer measurement series. This research project brings specific data from a reference borehole 15 m deep placed in the Karkonosze mountain range and a network of thermistors installed in selected locations with a cold microclimate. The field reconnaissance is supplemented by geophysical measurements using the electrical resistivity tomography (ERT) of the bedrock in search of anomalies that could indicate the survival of relict permafrost in the highest areas of the Sudetes. The premise for this is the patches of long-standing snow in glacial cirques and the low average annual temperatures observed in these places 100 years ago.

The climate is warming rapidly, and in the OBSz1 research borehole on Mt. Szrenica (1.365 m a.s.l., 50.79° N) at a depth of 15 m, the ground temperature (solid granite) is maintained at 4.4–4.9 °C with the lowest average (4,5 °C) observed at a depth of 11 m (readings in the hydrological year 2023–2024). Data from thermistors distributed in the typed COLDSPOTs show a large temperature variation but have averages above 0 °C. However, the results of geophysical measurements in the highest parts of the Karkonosze Mts should be discussed. Above one of the glacial cirques, under a section of the slope covered with rock debris (approx. 1500 m a.s.l.), extremely high electrical resistivities of granite were measured at a depth of approx. 50 m. At this location, they cannot be explained by differences in the geological structure. According to the proposed thesis, this is a low-temperature rock body that has survived since the last glaciation of this area – relict permafrost. It may be facilitated by the lack of fissure waters, as shown by nearby drilling. A similar situation was not found on Śnieżka, the highest peak of the Karkonosze Mountains, or in any other geophysical site. Several topographic premises indicate that the proposed thesis may be true, although, under current climatic conditions, it would be a phenomenon on a scale of the Bohemian Massif.

KEYWORDS: coldspots, relict permafrost, seasonally frozen ground, Sudetes

The shape matters! Variability of ground temperature and permafrost at a symmetrical mountain summit in the Eastern Alps in the period 2018–2024

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Thermal ground conditions in mountainous areas are influenced by slope orientation and inclination, local topoclimatic conditions including snow-related effects, and thermal properties of rock material. Minor differences in any of these factors can have significant effects on ground thermal regimes, weathering, and permafrost occurrence. The aim of this study is to improve the understanding of complex ground temperature conditions on individual mountain summits by analysing six years (2018–2024) of data compiled at a triangular (plan view) and moderately steep pyramidal peak. In summer 2018, we instrumented 17 ground temperature monitoring sites with 23 sensors near the summit of Innerer Knorrkogel (47,102°N, 12,420°E; Venediger Mountains, Hohe Tauern Range, Austria), a 2882 m high mountain peak characterised by autochthonous coarse-debris material and bedrock outcrops. In detail, three different mountain ridges (east, northwest and southwest orientations) and flanks (northeast, west and south orientations) were instrumented with single-channel data loggers at two different elevations (2840 and 2860 m asl). In addition, three bedrock temperature monitoring sites with shallow boreholes (40 cm) were installed at an altitude of 2870 m asl on each mountainside. Finally, two locations were installed in the summit area. The results show remarkable differences in the mean annual ground temperature (MAGT) between the 23 different sensors despite the small spatial extent of the study area (0.023 km^2) and minor difference in altitude (around 46 m). On average across all 23 sensors, MAGT varied from highly negative (-0.96°C in 2020/21) to clearly positive (0.55°C in 2023/24) values with a total value range of 1.5 °C in the 6-year observation period. The lowest MAGT values were calculated for either the northeast-facing flank, the summit area itself, or the northwest-facing ridge. In contrast, the highest MAGT values were always on the southern flank. Temperature differences are only partially related to the slope orientation and the associated solar radiation, as shown by a correlation coefficient of r=0.60 between the averaged MAGT and the annual potential shortwave radiation. The values indicate permafrost-free conditions on the southern flank and at some ridge locations. The correlation between the average MAGT and the duration of the winter snow cover derived from the ground temperature data resulted in a coefficient of 0.41. This means that the longer the seasonal snow covers the surface, the warmer is the observation site, which is due to thermal decoupling of a thicker seasonal snowpack during periods of very low temperatures. Despite the short data series, a slight warming trend can be seen for the locations with little snow. Our study shows that the thermal regime at the studied triangular pyramidal mountain peak is highly variable between different aspects, landforms and monitoring years. Due to high intersite and interannual variabilities, temperature-related processes such as frost weathering can vary greatly between neighbouring locations. Therefore, thermal conditions of mountain peaks, even if they are symmetrical and rather simple in shape are not straightforward to quantify by monitoring and subsequently difficult to model. We conclude that there is a need for systematic and long-term ground temperature monitoring in alpine terrain to improve the understanding of small- to medium-scale temperature variabilities in permafrost-influenced areas.

KEYWORDS: permafrost monitoring, thermal regime, complex mountain topography, frost-related processes

Paraglacial dynamics and hydro-geomorphic responses to global change in Mediterranean mountain catchment: the Pineta Valley (Southern Pyrenees)

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The effects of global change on water and sediment transfer at catchment scales, as well as on hydrological and geomorphic activity at reach scales, are widely studied. However, few studies focus on how climate change and land use changes influence erosion processes in headwaters and its water and sediment transfer downstream, particularly in Mediterranean mountain areas. The Pyrenean range presents a valuable study area for examining these processes due to its unique physical and climatic characteristics, including glacial, periglacial, and headwater-fluvial landforms. A key research gap remains in linking proglacial geomorphology with fluvial dynamics, despite the significant impacts of glacier retreat and snow dynamics on downstream hydrology, sediment transport, and ecosystem functioning. Addressing this gap is crucial for understanding mountain ecosystems and managing water resources in downstream areas. Given these perspectives, several questions should be answered: How sediment source areas in periglacial zones of headwaters streams are eroded and evolve through time? How and when is this sediment transferred downstream? What are the consequences of this (dis)connectivity between source areas and alluvial channels?
To address these questions, we have applied a methodological approach at multiple temporal and spatial scales based on remote sensing techniques. The study area encompasses the high-mountain headwaters of the southern Pyrenean range, with a particular focus on the Pineta Valley (Cinca River) during the period 1957–2024. First, we characterize the climatic trends of the study area using historical hydrometeorological records. Then, through the analysis of archival aerial imagery and its processing with historical Structure-from-Motion (SfM) photogrammetry, we assess land use and cover changes at the catchment scale, as well as identify the main sediment sources, erosional features, and mass-wasting processes. Additionally, structural water and sediment connectivity models were developed. At the river-corridor scale, we analyzed the evolution of active channel width and key geomorphic processes using the same techniques (i.e., SfM). Furthermore, between 2010 and 2024, we monitored an experimental area in the uppermost part of the catchment at high spatial resolution using annual high-resolution topography obtained from SfM techniques using drone-platforms. This area, a recently deglaciated zone, contains a large volume of readily available sediment with a high erosion potential.
Preliminary results showed how during the 1955-2021 period the Cinca River exhibited a stabilization of the active channel width, coinciding with minimal high-magnitude land use and land cover (LULC) changes due to rural abandonment in this high mountain environment. However, after 2021, a renewed fluvial dynamic has been observed, despite the persistence of the LULC trend. This shift appears to be driven by an increased frequency and intensity of meteorological events, suggesting the mobilization of previously disconnected sediment stored since glacier retreat. The findings raise questions about the role of paraglacial processes in sediment availability, particularly the influence of ice melting in these high-altitude landscapes.

KEYWORDS: headwater streams, deglaciation, sediment availability, high-resolution topography, land use changes

Distribution, morphology and processes of sorted patterned ground: a global perspective

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Climatic and geological controls on periglacial sorted patterned ground (SPG) are overviewed based on literature and field surveys. Data on the location, morphology, dimensions, climate and soil/rock conditions, and if available, soil movements (frost heave/creep) are collected from worldwide 63 locations where active SPGs are observed. In terms of the spacing of stripes or diameters of circles the SPGs are broadly classified into three size classes, S (<0.3 m), M (0.3-2 m) and L (>2 m). The S-class features that prevail in tropical to mid-latitude high mountains and subantarctic islands can be associated with particle sorting by needle ice. The M-class features, occurring widely from mid-latitude high mountains to subpolar low mountains, are mainly ascribed to differential frost heave in the upper seasonally frozen soil. The L-class features are mostly confined in high-arctic lowlands and can be attributed to buoyancy-induced soil convection in the whole active layer. Geologically, the SPGs are preferred by rocks producing loamy soils (e.g., mudstone, limestone and schist), glacial tills and aeolian covers. The pattern spacing (or diameter) is on average 3.6 times greater than the sorting depth, which implies that larger forms require thicker fine soils. The sizes of surface clasts also contribute to the occurrence and regularity of SPGs. In S-class sorted stripes, for instance, typical diameters of stones in the coarse stripes (~3 cm) are about one tenth of the spacing (~30 cm) and stones larger than 5-10 cm in diameter tend to disturb the regularity of fine stripes. These situations indicate that needle ice can heave and transport stones up to about 3 cm in diameter efficiently, while the abundance of stones larger than 5-10 cm in diameter significantly constrains the formation and preservation of stripes.

KEYWORDS: periglacial, patterned ground, frost sorting, frost heave

Temperature, hydrogeochemical and isotopic study of alpine springs in the Southern Carpathians, Romania

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Rock glaciers are creeping formations of permafrost, consisting of a mix of rock and ice, characterized by a distinctive topography of ridges and furrows. The hydrology of these rock glaciers is a complex and underexplored field, with uncertainties surrounding water flow patterns and the uneven distribution of frozen materials, which highlights the importance of hydrogeochemical and isotopic studies to better understand the origins, movement, and interactions of water within these periglacial environments. In order to understand these, we have developed an observation program at several rock-glaciers located in Southern Carpathians (Romania) that included observations and measurements of spring water temperature, chemical parameters and the stable isotopic composition of water. We present here the results of observations over a four-year period (2021 to 2024) across several glacial valleys in the Southern Carpathians.

The measurement of spring water temperature in late summer (SWTS) was used to determine the distribution of permafrost in alpine regions, with a temperature below 2°C being considered an indicator of the presence of underground ice. The stable isotopic composition of water (expressed as $\delta^{18}O$ and $\delta^{2}H$) was used as indicator of water source (more negative values indicating melt water from rock-glaciers and higher values indicating ice-free aquifers). Spot measurements of water temperatures were made at every spring studied using a Testo 110 instrument with a resolution of 0.1°C and an accuracy of ±0.2°C. Several springs were equipped with data loggers, logging water temperature at 1-hour intervals, with a resolution of 0.01°C and an accuracy of ±0.5°C. Stable isotope analysis will be performed on samples collected from springs and rivers using a Picarro L2130-I, with a precision better than 0.16‰ for $\delta^{18}O$ and 0.7‰ for $\delta^{2}H$, respectively.

Our data shows that springs fed by intact rock glaciers have a distinctive isotopic signal, with δ values lower than those discharging "normal" aquifers. Further, the rock-glacier isotopic signal is dominant along the river, suggesting that these are preferentially recharged by ice melt from these glaciers. Our measurements indicate that late summer spring water temperatures range from 0.7 – 9.2°C, serving as evidence of ground ice presence. Our data show that rivers downstream of rock glaciers are preferentially recharged by snow and ice melt, suggesting a heightened risk of drying if ice from these underground glaciers is lost due to ongoing climate warming.

This study emphasizes the need for continued investigation into the hydrological and isotopic characteristics of rock glaciers, as it contributes to a deeper understanding of permafrost dynamics, water flow behavior, and climate-related processes in alpine regions, particularly in the Southern Carpathians.

KEYWORDS: rock glaciers, mountain hydrology, SWTS, stable isotopes, permafrost

On the influence of ground surface temperature on rock glacier velocity

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Rock glaciers are debris landforms generated by the creep of perennially frozen ground (permafrost) and are found in most mountain ranges worldwide. Active rock glaciers (i.e. exhibiting signs of movement) are distinct landforms, whose dynamics is controlled by a combination of environmental (i.e. internal structure and composition, geometry, topography, geologic context, debris loading) and climatic (i.e. air temperature and precipitation) factors. Studies have shown that regardless of site-specific characteristics, relative changes in the creep rates of many rock glaciers follow a similar regional evolution at interannual to multidecadal time scales, which mostly fits with the evolution of ground temperature and by extension climate change. For this reason, Rock Glacier Velocity (RGV) was defined as an associated parameter to the Essential Climate Variable (ECV) Permafrost in 2022.

However, the physical processes controlling rock glacier dynamics as well as the relation with climate forcing are not yet fully understood. Earlier studies show that surface displacements of rock glaciers result from the combined effect of both the internal deformation within the crystalline structure of the frozen ground (creep stricto sensu) and the shearing in one or more ground layers (shear horizon(s)). The combination of scarce direct observations of permafrost temperature in rock glaciers with modelling approaches highlighted a relation between the evolution of the surface velocity and the variation of ground temperature and liquid water content between the permafrost table and the shear horizon at depth.

In this contribution we aim to better understand the relation between permafrost temperature and rock glacier velocity by a statistical analysis of field time series of up to 20 years on more than 15 landforms in the Swiss Alps. We use ground surface temperature (GST) to compute an index representing the permafrost temperature at the depth of the shear horizon (~15–30 m depth) and compare it to surface velocities obtained at different points on each rock glacier. Results show that a statistically significant exponential relation is found between the 2-year running mean of GST and the annual velocity at most sites. Regression coefficients as well as residuals will be examined in this contribution to assess the variability and factors influencing the relation between velocity and temperature.

KEYWORDS: permafrost, rock glacier, ground surface temperature, ECV, climate change

Modelling the thermo-hydrological dynamics of permafrost in fractured rock walls

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It is acknowledged for more than 20 years that degradation of mountain permafrost destabilises rock walls, which are systems that are particularly sensitive to temperature increase. Therefore, the current global climate change accelerates the frequency and intensity of rock wall failures which represent a threat for people and infrastructures in mountain environments. Hence, studying the thermal dynamics of rock wall permafrost is crucial to understand how rock wall failures are triggered, and ultimately to anticipate such hazards. In that scope, previous studies were carried out to understand the thermal dynamics of rock wall permafrost through numerical modelling.

The presence of fractures plays an important role in the thermal dynamics and hydrogeology of rock walls – and thus ultimately on their stability. Ice filling fractures cements them, strengthening rock walls; but water (from precipitation, snow or ice melting) flowing within fractures could enhance permafrost degradation at depth due to thermal erosion. The higher thermal conductivity of ice compared to rock also enhances conductive heat transfer within rock walls. Moreover, high hydrostatic pressure associated with groundwater may be a potential trigger factor for rock wall instabilities.

However, understanding the hydrogeology of fractured rock walls is a challenge in permafrost modelling studies. Rock walls represent dynamic multiphase systems composed of rock, air, water and ice. As the ratio water/ice within rock walls changes over time – with the temperature zonation notably – the hydraulic conductivity also varies. Due to the complexity of modelling these processes and their interactions, the exact role of fractures was largely ignored in rock wall permafrost studies, and rock walls are commonly considered having a homogeneous porosity in modelling studies.

To address this knowledge gap, we are conducting the first systematic modelling study aiming at understanding the role of fractures in the thermal dynamics and hydrogeology of rock wall permafrost. As a first effort, we don't investigate a specific study site, but rather adopt a theoretical approach. We use the commercial software FEFLOW, which uses the finite-element method in order to model heat transfer and groundwater flow within two-dimensional geometries.

We constructed synthetic temperature time series to be used as boundary conditions for a synthetical summit geometry. At this primary stage, the goal of the study is to investigate the effect of several fracturing configurations, by varying four parameters: length of fractures, orientation of fractures, density of the fracture network, connectivity of the fracture network.

KEYWORDS: permafrost, fracturing, heat transfer modelling, water flow modelling

Rock glacier and permafrost degradation in the Pyrenees: recent fast changes

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Rock glaciers are the best indicators of permafrost in the Pyrenees. They are placed in the high mountains among the environments with discontinuous and continuous permafrost, above 2,700 m a.s.l. Nowadays, the cryosphere of the Pyrenees is quickly becoming degrading involving changes in the snowpack, the fast retreat of glaciers, including their disappearance, and the deterioration of permafrost environments. The aim of this work is to understand the changes in the dynamics of rock glaciers, their response to atmospheric thermal changes and the recent rates of permafrost degradation.

This work is based on the geomatic monitoring of the surface dynamics of four rock glaciers (Argualas, years 1991-2000; Posets, years 2000-2011; Maladeta, years 2008-2023; and La Paúl, years 2013-2023) by means of Total Station, GNSS and UAV photogrammetry. Displacement velocities and vertical variations have been correlated with thermal anomalies for the months of July, August and September with respect to the period 1950-2023, estimated in the high mountains of the Pyrenees by reanalysis with Era-land.

The flow variations show that rock glaciers have not significantly increased in extent but indicate an increase in deformation and deterioration of the fronts. This coincides with the periods of strongest thermal anomalies. There is a rapid response of rock glacier behaviour to changes in atmospheric temperatures and a recent increase in the degradation of frozen bodies and therefore of permafrost in the Pyrenees.

KEYWORDS: cryosphere, permafrost, rock glaciers, Pyrenees

Use of remote sensing for multi-hazard assessment along Arctic permafrost coasts and settlements

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As the Arctic region warms, the vulnerability of Arctic coastal settlements is increasing due to coastal erosion and thawing permafrost, threatening both livelihoods and infrastructure stability. Automated remote sensing techniques have enabled the detection of infrastructure, recent coastal dynamics, and permafrost ground temperature trends. When combined, these observations spatially highlight both recent and future exposure of Arctic coastal settlements to coastal erosion, marine submersion, and subsidence hazards. In this study, we introduce a new semi-automatic approach to detect changes in permafrost coastlines over the period 2000–2019. Along erosive sections, coastline positions were extrapolated for short-, mid-, and long-term periods, allowing the identification of infrastructure and settlements at potential risk. Additionally, regional sea-level rise projections for 2100 were analysed along Arctic coasts. Permafrost ground temperature and active layer thickness trends were also investigated across coastal permafrost regions. The results indicate that by 2030, approximately 18% of Arctic coastal settlements will be affected by coastal erosion, while 45% will be impacted by sea-level rise. During the study period, permafrost ground temperature increased by 0.8°C per decade, and the active layer thickness by 6 cm per decade, in average. These changes in surface permafrost properties contribute significantly to subsidence and infrastructure instability. Furthermore, new insights on radar interferometry techniques (InSAR) for detecting vertical land motion and potential impacts on infrastructures in Canada and Greenland are presented.

KEYWORDS: permafrost, coastal changes, subsidence, infrastructure

30 years-trend towards a warming cryosphere: changing patterns and implications for the periglacial system in the Central Andes

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This study integrates observations collected over the last 30 years in the Vallecitos Stream basin (Central Andes of Argentina), focusing on thermal, hydrological, ecological, and geomorphic data, which allow for the direct and indirect inference of permafrost degradation processes. Permafrost is a challenging thermal/temporal phenomenon in terms of its recognition and quantification in mountainous areas. It is also a key component of the cryosphere and an essential climate variable due to its role in coupled atmosphere-surface processes. Numerous studies are warning about the problems associated with permafrost degradation: changes in hydrological processes, ecological balances, energy exchange, and the carbon cycle, as well as an increase in natural and engineering risks in cold environments. Since the 1990s, a warming trend has been observed in the region. This is reflected in statistical permafrost prediction models and measurements of ground temperature in the active layer of rock glaciers. The increase in temperatures and the degradation of areas with permanent freezing favour the altitudinal expansion and survival of vegetation in wetlands, a process that influences carbon capture. Considering the climatic trends for the Central Andes, which foresee drastic water shortages in the next decades, the hydrological/hydrogeological system might experience significant changes. For instance, the spatial-temporal evolution of the water's chemical quality may lead to adaptation strategies by the local population.
This study aims to contribute to a deeper understanding of the current state of knowledge of the periglacial system of the Vallecitos basin, including the research needs in terms of natural hazards related to permafrost degradation and its effects on growing population and industry.

KEYWORDS: Central Andes, permafrost, degradation

Slope destabilization and sediment movement in Snežna Cave (Slovenia): impact of extreme weather events

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Snežna Cave (Cave Register No. 1254) is located on the south-eastern slope of Mount Raduha (N Slovenia) at an elevation of 1504 m. The cave system extends 1327 m in length and reaches a depth of 75 m (Cave Register, 2025). Sediment analyses indicate that the cave is at least 5 million years old (Häuselmann et al., 2015).

In the entrance chamber, known as the "Ice Hall," a permanent ice body has formed due to the specific exchange of cold air. This ice body reaches a depth of up to 10 m and has a volume of approximately 4000 m^3 (Mihevc, 2018). Since the cave's discovery in 1981, a gradual decrease in ice volume has been observed. In 2020 alone, the ice surface level dropped by 20–40 cm (Blatnik et al., 2022). Climate change is accelerating underground ice melting, with ice caves worldwide losing at least 15% of their ice over the past century (Kern & Perşoiu, 2013). Temperature measurements in Alpine ice caves indicate a rising trend of 0.2°C per decade (Obleitner et al., 2024). This warming also affects geomorphological processes in these relatively stable cave environments.

An extreme precipitation event in August 2023 caused extensive flooding and landslides in the Upper Savinja Valley. At the Luče weather station (4,8 km to the south), 320 mm of rainfall was recorded over four days (ARSO, 2023). Intense and warm precipitation triggered sediment displacement in the entrance collapse doline, depositing large amounts of rock debris into the cave. It is hypothesized that this event contributed to permafrost melting, leading to the destabilization of the entrance slope.

Since March 2023, temperature measurements and ice mass monitoring have been conducted in Snežna Cave. These measurements utilize Tinytag Plus 2 (TGP-4500) data loggers, distributed throughout the cave. All loggers recorded a temperature increase on August 4th at 3:00 AM, coinciding with the inflow of significant amounts of precipitation into the cave. Sediment displacement is monitored using a Leica BLK2GO terrestrial LiDAR scanner, which enables the creation of 3D models.

At least 4500 m^3 of sediment has been accumulated in the entrance collapse doline. The average slope inclination between the collapse doline and the "Ice Hall" is 42°, reaching up to 75° in certain sections. In some areas, up to 8 m of sediment was displaced into the cave during the August 2023 rainfall event. Stabilizing the entrance slope to an inclination below 30° (Chandler, 1973) would require the movement of at least 2100 m^3 of sediment. Additionally, the ongoing melting of the 10 m-thick ice body in the "Ice Hall" further reduces slope stability and accelerates sediment movement.

This study analyses the impact of the August 2023 storm on geomorphic changes in Snežna Cave and explores the relationship between extreme weather events, permafrost melting, and sediment destabilization.

KEYWORDS: ice caves, mass movements, lidar, Raduha, Slovenia

The micro-frost weathering in the most extreme climatic conditions as an example of the McMurdo Dry Valleys (East Antarctica)

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The McMurdo Dry Valleys (MDVs) are the largest ice-free areas located in eastern Antarctica. They are among the coldest and driest places on Earth, where the mean annual air temperature is −17°C, and precipitation (entirely as snow) ranges from 3 to 50 mm water-equivalent, making the MDVs a polar desert. Dry permafrost, ice-cemented permafrost, and massive ice form the continuous permafrost underlying the MDVs. The active layer in this area varies spatially but does not exceed 0.40 meters. One of the processes occurring in these extreme conditions is frost weathering—both mechanical and chemical—or their combination, referred to as cryogenic weathering. To better understand weathering in this unique polar desert environment, we analyzed the microtextures (micro-scale forms of relief) of quartz sand-sized grains. Quartz is one of the less soluble minerals in the Earth's crust, but it is more susceptible to mechanical weathering, particularly frost weathering, compared to minerals like feldspar, magnetite, garnet, or muscovite.

The analysis included four active-layer profiles: Wright Valley (active layer thickness: 0.35 m), Bull Pass East (0.20 m), Bull Pass (0.30 m), and Mt Acheron (0.020 m). These sites represent alluvial fan and lateral moraine deposits, respectively. According to the WRB system, soils in these locations are classified as cryosols and categorized as Anhyorthels, Haploturbels, or Haplorthels, respectively.

To determine the scale and range of micro-frost weathering, the quartz grains were analyzed using a scanning electron microscope (SEM). Additionally, to determine the factors influencing the intensity of micro-frost weathering, sediment grain size distribution, sediment geochemistry, pH, and CaCO3 content were examined.

The results indicate variable intensity of frost mechanical weathering at the micro-scale in the examined profiles, as well as the susceptibility of individual grains in the samples to this type of weathering. The examined sediments represent the early stages of frost weathering, characterized by a low number of microtextures resulting from frost processes, mostly observed at the top of the profiles (to depth of a few centimetres). In the Wright Valley and Mount Achernar profiles, temperature fluctuations around 0°C is observed only within the depth range of 0 to 2 cm. Among mechanically frost-induced microtextures, the most common are small conchoidal fractures (<10 μm), indicating an initial stage of frost weathering. Only as an accessory are recorded microforms indicating a more advanced stage of weathering, such as large and small breakage blocks (>10 μm and <10 μm, respectively).

This is due to limited water access and temperature below 0°C persisting for most of the year, resulting in a low number of temperature cycles crossing 0°C. Moreover, is observed a result of the chemical frost weathering. It manifested as uncrusted of grain's surface.

KEYWORDS: micro-frost weathering, permafrost, active layer

THEMATIC SESSION 19

REMOTE SENSING AND MODELLING OF PERMAFROST AND PERIGLACIAL LANDFORMS

Chairpersons:

Flavius Sîrbu, Tazio Strozzi, Oana Berzescu

Assessing snow cover variability and its climatic drivers over marginal periglacial areas in the Southern Carpathians (2000–2020) using MODIS CGF and ERA5 data

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Snow cover plays a crucial role in periglacial environments, influencing ground thermal regimes and periglacial processes. Its temporal and spatial variability directly affects permafrost distribution and seasonal ground freezing, thereby controlling the behavior of high-mountain landforms. This study investigates the spatiotemporal evolution of snow cover across the periglacial belt of the Southern Carpathians including permafrost-prone zones by integrating remote sensing and reanalysis datasets. To analyze long-term snow cover trends, MODIS Cloud-Gap-Filled (CGF) daily snow cover data at 500 m resolution from 2000 to 2020 are used, extracting Normalized Difference Snow Index (NDSI) values to track seasonal and interannual variations in snow persistence. These snow cover trends are then correlated with ERA5 downscaled temperature and precipitation data at 1km resolution, including air temperature and land surface temperature (LST), to assess potential climatic drivers. The analysis is conducted at two spatial scales: first, across the broader periglacial region of the Southern Carpathians to evaluate overall snow cover dynamics and their variability in relation to temperature changes; second, over permafrost areas, where snow cover persistence is analyzed in relation to its potential influence on ground thermal conditions. The study aims to identify long-term trends in snow cover persistence across different elevations and slope orientations, as well as potential shifts in seasonal snow duration in response to temperature fluctuations. By integrating MODIS-derived snow cover data with ERA5 temperature data, the study seeks to reveal relationships between snow dynamics and ground surface temperature, contributing to a better understanding of periglacial evolution in the context of regional climate change in the Southern Carpathians. Additionally, the findings will serve as a foundation for further monitoring efforts. Future work will incorporate higher-resolution optical imagery from Sentinel-2 and PlanetScope to enhance snow cover mapping accuracy and refine correlations with permafrost conditions, allowing for a more detailed assessment of snow distribution patterns and their seasonal variations.

KEYWORDS: snow dynamics, mountain permafrost, remote sensing, climate variability, Southern Carpathians

A comparative analysis of retrogressive thaw slumps across the Northern Hemisphere

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The average yearly temperatures and precipitation in the Arctic and subarctic areas have increased in the last decades, resulting in an increase in the number of permafrost disturbances. Permafrost covers around 15% of the exposed land surface area in the Northern Hemisphere. Permafrost thaw can lead to mass movements, such as active layer detachments, retrogressive thaw slumps and frozen debris lobes. The increase of global air temperature will likely trigger these mass movements due to permafrost degradation, and extreme events such as heavy rainfall and rapid snowmelt could intensify this phenomenon. Here, we focus on retrogressive thaw slumps (RTSs) that are characterized by the exposure of ice-bearing permafrost deposits to the ground surface due to erosion, wildfires, dredging and other activities. As RTSs advance by thawing and slumping, they can shed large amounts of sediment into water bodies and release soil organic carbon for decomposition. We study different areas across the Northern Hemisphere permafrost region using published datasets and manual mapping with remote sensing data. Then we used statistical modelling techniques to examine the environmental factors that affect RTS occurrence and what are the differences between the different regions. This study provides new insights into the circumarctic susceptibility of ice-rich permafrost soils to rapid disturbances like RTSs, where their formation impact on landscape evolution, affects hydrology, and releases soil organic matter and carbon fluxes that contribute to global warming.

KEYWORDS: retrogressive thaw slumps, permafrost disturbance, statistical modelling

Building a rock glacier inventory of the Baralacha La area, Western Himalaya, India

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In the Western Himalaya, a homogeneous database of rock glaciers, including their quantitative degree of activity, is missing. This represents a critical limitation and a major challenge for geohazard assessment associated with the kinematics of creeping permafrost, particularly in relation to ongoing infrastructure development in a warming climate. In this context, the area around the Baralacha La and Shingo (Shinku) La passes, along the border between Himachal-Pradesh and Ladakh states of India, is of specific interest, as it hosts key transportation corridors linking the regional centers of Leh and Zanskar with Manali and includes the proposed Leh-Manali Railway line (~270 km). To start addressing this regional need, we: (1) have compiled a morphological rock glacier inventory; and (2) are characterizing rock glacier kinematics through InSAR analysis of Sentinel-1 scenes. The study area (~530 km^2) is centered across the drainage divide that separates Lahaul and Zanskar regions in the Western Himalaya. Elevation ranges from 3752 m a.s.l. along the Bhaga River floodplain, up to 6111 m a.s.l. of Mount Yunam. Glaciers currently cover about 20% of the mountain terrain. The climate is dry (semi-arid), with mean annual precipitation decreasing northward as terrain becomes increasingly sheltered from humid, monsoon-driven air masses. The morphological inventory, compiled through visual inspection of Google-Earth imagery and complemented by confirmatory fieldwork, and the rock glacier kinematic characterization follow the technical guidelines proposed by the International Permafrost Association Working Group on Rock Glacier Inventories and Kinematics (RGIK). The compilation of the inventory is being conducted by four operators using a consensus-based approach. The provisional version of the inventory contains 82 rock glaciers and 46 uncertain lobate landforms that will require further consolidation. Of the former, which are about evenly distributed across the main eight slope aspect categories, 72 and 10 are respectively classified as intact and relict features, with corresponding minimum front elevation of ~4230 m a.s.l. and 4088 m a.s.l. Within the landscape, most of the rock glaciers display talus upslope connection (66.7%), followed by poly connection (18.1 %) – mostly jointly fed by talus slopes and glacier forefields – glacier forefield connection (8.3 %), debris-mantled slope connection (5.5%), and nearly negligible glacier connection (1.4 %). Ongoing kinematic characterization performed on Sentinel-1 interferograms will allow to reduce uncertainty on landform typology, improve inventory completeness, and refine the current classification of rock glacier activity chiefly based on qualitative morphological attributes.

KEYWORDS: rock glaciers, geomorphological mapping, InSAR, upslope connection, Western Himalaya

A new rockglacier inventory, based on PSI derived moving areas, in the Pirin Mountains

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Rock glacier inventories (RoGI) area valuable tools to understand permafrost distribution, climate change effects, and even the past and present state of periglacial environments and the cryosphere. The inventories offer information on distribution, size and kinematics of the rock glaciers, with the last one being the most difficult to measure, especially in areas with sporadic permafrost and minimal velocity (i.e. mm/year).
The Rock Glacier Inventory was build using a three steps procedure: i) Marking the location of rock glaciers, ii) delineating moving areas, iii) delineating the restricted and extended contours of the RGs. At first the RGs were marked using a combination of optical aerial and satellite images, terrain data (e.g. slope, hillshade) and field surveys. The moving areas (MA) were derived using Persistent Scatterer Interferometry (PSI) applied on Sentinel-1 images from 09.07.2015 to 07.10.2023. And they were validated using in-situ measurements performed with a Topcon Hyper V Differential GPS with real time kinematics and millimetric accuracy, from 2019 to 2023. The final delineation of rock glacier units (RGU) used the MA to identify their limits and to classify them.
The new inventory consists of 76 RGU, out of which only 15 contain MA into their outline. The displacement rates of the moving areas are up to 30 mm per year. All the RGU with moving areas were classified as transitional and the rest of the RGU were classified as relict. The MA are not evenly distributed on RGU. Thus, most RGU in the present inventory have at least two areas with different displacement rates and even areas with no displacement at all, which is typical of transitional RGU in areas with patchy mountain permafrost.

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KEYWORDS: Sentinel 1, Persistent Scatterer Interferometry, remote sensing, rockglacier, permafrost

Monitoring Rock Glacier Velocity (RGV) using satellite SAR Interferomety (InSAR)

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Mountain permafrost is undergoing significant transformations due to climate change. One key way to identify mountain permafrost is by looking at rock glaciers. These are debris landforms formed by the creep of permafrost, having distinct shapes with clear edges and surfaces marked by ridges and grooves. This makes them easy to study using remote sensing tools. While the velocity at which rock glaciers move depends on various factors like the landscape, structure, and climate, changes in their movement rate are mostly tied to the temperature and water content of the permafrost. Because of this, variations in movement are considered one of the most important short- to medium-term responses of rock glaciers to environmental changes. As a result, they serve as a key indicator of overall mountain permafrost conditions and in 2022 Rock Glacier Velocity (RGV) was added as a related Quantity of the Essential Climate Variable (ECV) Permafrost.

RGV is defined as "time series of annualized surface velocity values expressed in m/y and measured/computed on a rock glacier unit or a part of it". These measurements can be gathered using different techniques, including on-site observations and remote sensing methods. Recent studies have shown that satellite Synthetic Aperture Radar Interferometry (InSAR) is particularly effective for mapping rock glaciers and tracking their movement rates. Specifically, Sentinel-1 C-Band SAR is gaining popularity due to its open and free data access. So far, various methods and software tools have been used in these studies to calculate RGV from InSAR data. To ensure consistent and reliable data for future climate monitoring, it's important to assess how well different methods and operators align and to identify the key steps in InSAR processing and RGV calculation that need to be standardized across different software and users.

To tackle these questions, several working groups have calculated RGV time series for three rock glacier sites in Switzerland, Italy, and France. Each group used their own methods and different InSAR software tools. The results from these various InSAR approaches were compared and analyzed alongside RGV data from GNSS on-site measurements and airborne photogrammetry. The findings highlight that handling phase unwrapping errors and defining the moving area (spatial aggregation) are among the most critical factors influencing the consistency and accuracy of RGV values. Other processing factors, such as the size of the multi-looking window, the criteria for selecting suitable interferograms, and the duration of the seasonal observation period, may also impact the results. We will provide an analysis of the current findings from this comparison, share insights into the best practice guidelines currently being developed and give an outlook to the production of RGV time-series in various regions worldwide.

KEYWORDS: permafrost, rock glaciers, SAR interferometry

THEMATIC SESSION 20

SOIL EROSION PROCESSES IN A CHANGING CLIMATE: THEORETICAL ADVANCEMENTS AND PRACTICAL PROGRESS

Chairpersons:

Anita Bernatek-Jakiel, Matthias Vanmaercke, Lilian Niacșu, Mihai Niculiță

Detection of soil piping-related features at various spatial scales: field studies and remote sensing techniques

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Soil erosion is a widespread global issue that affects agriculture, water quality, and even urban areas worldwide. Soil piping is a type of subsurface soil erosion process that leads to the formation of underground tunnels, called soil pipes, which become visible on the surface when the pipe roof collapses. This process can significantly contribute to land degradation, although its subsurface nature continues to pose a methodological challenge for research. Moreover, there is still a lack of knowledge about the regional distribution of this process. This presentation aims to demonstrate methods for detecting soil pipes using both field studies and remote sensing techniques. The specific objectives are: i) to present geomorphological mapping of pipe collapses as a tool for exploring soil piping in the field at the hillslope and catchment scales, (ii) to introduce near-surface geophysics (ERT, GPR, EMI) for detecting soil pipes at the hillslope scale, and iii) to demonstrate the use of orthophotos and LiDAR data for identifying soil piping-related features at the regional scale. The research was carried out in the Bieszczady Mountains (SE Poland) at the hillslope, catchment and regional scales. Enhancing detection techniques is a crucial step towards gaining a deeper understanding of soil erosion processes and developing more sustainable soil management practices. Knowledge of the distribution of soil piping features may help identify areas that require sustainable management.

KEYWORDS: soil erosion, subsurface erosion, remote sensing, geophysics

Using semi-automatic methodology and drone survey to identify and monitor the gully erosion in the Moldavian Plateau

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Gully erosion represents one of the most important and severe land degradation processes in the Moldavian Plateau. A precise inventory of gullies from vulnerable regions, could help us understand the dynamics of this type of erosion, assess land degradation risks and to implement land management strategies. Traditional gully mapping methods are time consuming, and, to address this challenge, a semi-automatic methodology was developed to identify and map gullies from the Moldavian Plateau. This methodology integrates LiDAR data and GIS analysis, through topographic openness module, to identify, classify and map gullies. By creating the inventory of all the gullies from the Moldavian Plateau, the decrease of the subjectivity and generalization of the statistics will be consistent, and the final results will be significantly closer to field reality. By the use of new techniques in the constant monitoring of gullies, such as drone surveying and GIS analysis, we can have a more precise assessment of gully dynamics over time, and we can analyze different typologies of gullies. The most important achievements of this study are the full inventory of gullies from the Moldavian Plateau and the dynamics monitoring of two different typologies of gullies from this area using a new methodology based on specific GIS techniques.
Acknowledgment is given by Ionut Costel CODRU, Andrei ENEA & Lilian NIACSU to the infrastructure support from the Operational Program Competitiveness 2014-2020, Axis 1, under POC/448/1/1 Research infrastructure projects for public R&D institutions/ Sections F 2018, through the Research Center with Integrated Techniques for Atmospheric Aerosol Investigations in Romania (RECENT AIR) project, under grant agreement MySMIS no. 127324 and from the Department of Geography, Faculty of Geography and Geology, "Alexandru Ioan Cuza" University of Iasi

KEYWORDS: gully erosion, gully inventory, drone surveying, LiDAR, GIS techniques

Assessment of the mountain-hiking trails condition and their erosion rates in the Bucegi Mountains, Southern Carpathians, Romanian Carpathians. Case study: the alpine zone

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Given the increased interest in visiting mountainous areas, it is important to assess the current condition of mountain-hiking trails as the main means of access to these regions. The erosion caused by tourist traffic, manifested largely through trampling, leads to and intensifies the degradation of these mountain-hiking trails.

Our study was conducted in the Bucegi Mountains, located at the eastern extremity of the Southern Carpathians-Romanian Carpathians. During two field campaigns in 2022 and 2024, we focused on the most frequently used mountain-hiking trails in these mountains, namely: Bușteni – Babele Chalet (Jepii Mici), Bușteni – Piatra Arsă National Sports Complex (Jepii Mari), and Babele Chalet – Omu Peak.

The aim of the study was to evaluate the current erosion of these mountain-hiking trails using satellite images, morphometric parameters such as slope and width by sections, as well as a series of cross-profiles at 1-meter intervals. We also examined the geological substrate, observing that sandstone, a friable and highly susceptible to degradation rock, predominates in these mountains.

The results indicate a high level of erosion and, consequently, degradation of the mountain-hiking trails, evidenced by significant widths and long sections where the main mountain-hiking trail is accompanied by parallel trails. This is especially true for the Babele Chalet – Omu Peak trail, where sections with parallel trails exceed 1,600 meters, accounting for over 30% of the length of this mountain-hiking trail.

Cross-profiles revealed average erosion surface areas ranging from 1,941 cm^2 on the Jepii Mici mountain-hiking trail to 6,980 cm^2 on the Babele Chalet – Omu Peak mountain-hiking trail, with soil erosion volumes varying from 0.2 m^3/m on the Jepii Mici mountain-hiking trail to 0.69 m^3/m on the Babele Chalet – Omu Peak mountain-hiking trail. Additionally, the satellite images used provide an overview, illustrating the areas degraded by tourist traffic.

While in forested areas, the erosion rates of tourist trails degraded by trampling can be evaluated through dendrogeomorphological approach, we consider that for the alpine zone direct field measurements complemented by satellite images represent an effective method for assessing the erosion rates of the trails.

We believe that the results obtained can be useful both for monitoring the erosion rates of mountain-hiking trails in the alpine zone and for their maintenance, as well as for facilitating tourist access based on their interests and fitness levels.

KEYWORDS: mountain-hiking trails, slope, cross-profiles, erosion, Bucegi Mountains, Romanian Carpathians

Typological diversity of collapsed pipes on thick loess covers – a case study from Eastern Poland

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Piping is subsurface erosion by concentrated flowing runoff, which results in a network of subsurface pipes that may collapse under the weight of the overlying sediment, generating collapsed pipes that vary in size and form.
Piping erosion is an essential and widespread land degradation process occurring in almost all climatic zones and under various land use conditions, but loess landscapes are particularly susceptible to piping (Bernatek-Jakiel, Poesen, 2018). Piping plays a critical role in landscape evolution by initiating and transforming gully networks (Rodzik et al., 2024). Previous studies in the loess areas of Europe indicate the impact of natural and anthropogenic factors controlling the distribution of collapsed pipes (Faulkner et al., 2006; Verachtert et al., 2010).
The study was conducted in the western part of the Nałęczów Plateau (Eastern Poland). A field inventory of collapsed pipes and analyses of high-resolution LIDAR data were performed. The studied catchment is covered by loesses several metres thick. They overlie glacigenic sediments, covering a bedrock composed of Upper Cretaceous opoka-rocks. Several active and inactive collapsed pipe types were inventoried, measured and classified, including sinkholes (Sh) and pipe roof collapse a) horizontal (RCh), b) vertical (RCv), c) spotty (RCs), closed depressions (CD), blind gullies (Bg), pipe outlets (Po), pipe inlets (Pi).
A Sh is formed by a roof collapse in underground channels. It has steep walls and its bottom is filled with collapsed loess packets.
An RCh is formed by the collapse of the roof of one or more underground channels of similar course and at different depths (overlapping). It has steep walls and an elongated shape. The bottom is filled with loess from the collapsed roof. An RCv is formed by the collapsing parts of roofs of underground channels crossed over each other at various depths or a single channel in a rapid slope gradient increase zone. An RCs results from the collapse of a piece of underground horizontal channel. A Pi is an opening through which surface water flows in. A Po is an opening through which underground waters flow out. A CD is formed by surface subsidence above the underground channel. A Bg is a complex landform, which may include all other collapsed pipe types. The outlet section hangs above the main gully bottom.

KEYWORDS: piping erosion, loess, collapsed pipes, LIDAR data

Gully inventory in the Moldavian Plateau, NE Romania

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Gullying is recognized as a major environmental threat in the Moldavian Plateau (MP) from eastern Romania, which imposes this typical hilly unit as one of the most representative hotspots of gully erosion in Europe. During the last half century, using topographical maps & classical surveys, there were mapped over 9000 gullies for the entire region, resulting an average gully density of 0.1-1.0 km/ km^2, with maximum values >3 km/ km^2 (Radoane et al., 1995).
Based on modern GIS techniques and using different new source data (DEMs, including LIDAR datasets, different series of aerial photos, satellite images), we achieved a fully up-to-date inventory of the gullied lands comprising 64838 polygons, which cover 238.6 km^2 (1.27%) of the whole study area (18738 km^2). Calculated as the proportion of surface of 1x1 km rectangles covered by gullies, the gully index shows that the density ranges from 0 (55.5% of total rectangles) to a maximum of 26.64%. Relative to gully number, our results show that the mean gully density increases from 2.27 gullies/ km^2 in the Jijia Hills (northern subunit of the MP), 4.36 gullies/ km^2 in the Barlad Plateau (central-southern part of PM), to a maximum of 6.7 gullies/ km^2 in the Covurlui Plateau (the southern subunit of MP), resulting an average value of 3.46 gullies / km^2 for the entire geographical unit. On average, the descriptive statistics of the gullies geomorphometry shows that the ordinary (typical) gully within the MP has an area of 3680 m^2, 2.47 m in depth, 10105.77 m^3 in volume. Also, it develops at 202 m in altitude, on average slopes of 11.9%, presenting an altitudinal difference between the gully head and the gully outlet of 14.63 m.
Our comprehensive data on gully development demonstrates an exclusive scientific importance, contributing to a better understanding of the spatial distribution of gullies at regional scale. Given the specific gully types and patterns, the Moldavian Plateau of Eastern Romania represents one of the most important case-scenarios of human impacts on land degradation through gullying in Europe.
Acknowledgment is given by Lilian NIACSU & Ionut Costel CODRU to the infrastructure support from the Operational Program Competitiveness 2014-2020, Axis 1, under POC/448/1/1 Research infrastructure projects for public R&D institutions/ Sections F 2018, through the Research Center with Integrated Techniques for Atmospheric Aerosol Investigations in Romania (RECENT AIR) project, under grant agreement MySMIS no. 127324 and from the Department of Geography, Faculty of Geography and Geology, "Alexandru Ioan Cuza" University of Iasi.

KEYWORDS: gully erosion, gully head-cut inventory, GIS techniques, LIDAR

The geomorphometric signature of gullies in the Moldavian Plateau

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The purpose of this study is to develop a geomorphometric analysis of gullies in the Moldavian Plateau through slope-drainage area analysis, with the goal of identifying a signature of the gullies that is geomorphometrically distinctive. Such an analysis uses a plot with the log of drainage area on the X-axis and slope on the Y-axis. The log drainage area is often binned as it can better depict general trends in the plot. As previous studies have found, a high-resolution representation of the surface may be needed to accurately identify regions in a slope-area plot. Therefore, a high-resolution LiDAR-derived digital elevation model was used. The plot can be divided into different regions, which are often identified with threshold-based methods, and they can depict process domains (e.g., diffusive flow, debris flow, fluvial, etc.). For identifying the thresholds, the pattern of the derivative of the plot is often used as it can better display changes in the slope-area relationship.

Previous studies have used the slope-area relationship to determine the topographic conditions that lead to the development or spatial distribution of gully heads. The current study aims to explore the trends of the slope-area plots of gullies in the Moldavian Plateau and whether or not the presence of certain geomorphological processes can be identified based on the form of the graph. More precisely, we are interested in finding out if a region with fluvial processes can be delineated in the plot. Identifying such a region would provide valuable insights into understanding how gullies transition into fluvial landforms as they reach a stable development state. We are also interested in observing whether or not significant regional differences occur between the geomorphometric signatures of gullies in the Moldavian Plateau. The results of this study could further contribute to defining a typology for the gullies in the study area.

KEYWORDS: geomorphometric signature, gullies, Moldavian Plateau

Assessment of soil erosion intensity caused by land use/cover changes in the Bălăciţa Piedmont (Romania)

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Soil erosion is one of the most significant forms of land degradation in Romania. The past decades had been marked by the changes in land use/cover, with numerous implications in the intensity of erosion processes. Moreover, the soil erosion process is influenced by a series of geomorphological factors like: slope length, slope steepness, climatic factors, soil features and land cover management. The Bălăciţa Piedmont represents the western subdivision of the Getic Piedmont, being located in south-western Romania. The unit under study is an early inhabited space that is affected by numerous active geomorphic phenomena. The man-induced changes, especially in land-use management, had significant influences upon the environment and the relief, thus the increased vulnerability of the terrains to dangerous geomorphologic phenomena being one of the most important problems for local communities. This study proposes a GIS based model for the computation and representation of areas from the Bălăciţa Piedmont that are exposed to soil erosion. In the implementation process of the USLE/RUSLE model, we created a vector and raster GIS database that covered the study area, using specific spatial analysis methods and database interrogations for the quantitative estimation of the eroded soil volume. The validation of each USLE/RUSLE factor influence on the soil erosion process was made with the help of comparative temporal analysis. The results can be used to prevent soil erosion and applied in the field of spatial planning and soil management on local and regional level.

KEYWORDS: soil erosion, land use/cover change, anthropic impact, RUSLE, GIS

THEMATIC SESSION 21

TECTONIC GEOMORPHOLOGY

(organized by the IAG WG Tectonic Geomorphology)

Chairpersons:

Giandomenico Fubelli, Konstantinos Tsanakas, Esra Tuncel, Andrew Howell

Morphotectonic processes and their outcomes at the Northern Apennine front in the Oltrepo Pavese area (Sheet 160 - Pavia CARG Project, South-western Lombardy, Italy)

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The investigation of the landscape evolution of the transition zone between outcropping thrust-fold belts and their buried outermost fronts can be challenging to unravel, due to difficulties in homogenizing and correlating field and subsurface data. An attempt to clarify this complex relationship is being pursued in the central-western sector of Emilian Arc in the Northern Apennine (Italy), benefiting from the activities for the implementation of the "Foglio 160-Pavia", as part of the Italian CARG Project of geological mapping. The main purpose of this work is the comprehensive reconstruction of the landscape evolution, with particular emphasis on assessing the role of Plio-Pleistocene tectonic activity in shaping landforms, both in the outcropping sector of Northern Apennines front and in the buried outermost ones.

The study area, located in the south-western Lombardy region (Oltrepo Pavese), features the units exposed in the Northern Apennines outcropping chain, which rapidly slopes below Quaternary deposits of the Po Plain covering the front of the belt and its foreland. The hill sector of the area includes a Paleocene to Pleistocene sedimentary succession, involved in the SW-NE oriented tectonic vergence of the Apennines tectonic units. A detailed 1:10.000 scaled original map of the hillslopes and a 3D model of the regional stratigraphic and tectonic surfaces of the sector of Po Plain facing the Northern Apennine margin are already available for the study area.

Within this framework, we apply morphometric analysis to evaluate the influence of the tectonic structures of the Northern Apennine front, both outcropping in the hill sector and buried under the Po Plain deposits, and to understand the role of surface processes on the geomorphological evolution of this area. The combination between morphometric results and stratigraphic, structural, and geomorphological markers observed and collected from fieldwork or derived from a 3D subsurface model of the regional scale structures, provides valuable insights for interpreting the landscape evolution of this sector of the Northern Apennines and possible evidences of recent/ongoing tectonic activity.

KEYWORDS: Northern Apennine front, morphometric analysis, landscape evolution

Mobility of the Hron River drainage divides: from regional active drivers to local passive controls

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Drainage Divides are fundamental topographic boundaries often perceived as stable landscape features from the perspective of human life. However, from a long-term perspective, drainage divides are often dynamic features, changing their positions at various rates, from slow continuous divide migration to rapid discrete capture events. Recognising the unstable segments of drainage divides and identifying regional drivers or passive controls of their mobility is an essential part of landscape evolution studies, which is important from various perspectives. Migrating watershed divides can alter the catchment drainage area, and this process may affect the incision rate of the mainstem and its tributary system. Incision rate affects the landscape evolution and related processes, including landsliding or flooding. Thus, beyond mere knowledge of landscape evolution history, identifying mobile drainage divides can have many practical applications, including the geohazard assessment or study of climate history.

In this presentation, we applied DEM-based morphometric indices to reveal potential instability of the watershed boundaries (divides) constraining the Hron River drainage basin, which is a left-side tributary of the Danube River and the second largest river of the Western Carpathians. We applied two categories of morphometric indices: those assessing cross-divide differences in erosion rates at the hillslope scale (also referred to as Gilbert metrics) and those evaluating differences in channel erosion rates, specifically chi-index (χ) and normalised channel steepness index (ksn). The metrics based on fluvial erosion rules revealed a spatially consistent migration trend of the catchment boundaries limiting the upper, roughly E-W-oriented part of the Hron River drainage basin. Regional, most probably tectonic drivers likely control this migration trend towards N – NW. In contrast, Gilbert metrics, including channel head elevation, hillslope relief and hillslope gradient, are more affected by local passive controls, including structural features like faults or specific landforms.

The contribution was prepared in the framework of the project no. 2/0014/25 supported by the VEGA grant agency.

KEYWORDS: drainage divides, topographic analysis, morphometric indices, Hron River, Western Carpathians

Morphological changes in the mud volcanoes of Buzău: insights from historical data and recent UAV-based monitoring in the context of Vrancea seismicity

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Mud volcanoes are fascinating yet unpredictable geological features, shaped by underground gas emissions, fluid migration, and external forces like seismic activity. In the Buzău region, close to the seismically active Vrancea zone, these formations constantly shift, creating an ever-changing landscape. Understanding how and why these changes occur is crucial for both scientific research and hazard assessment.

This study combines historical data with cutting-edge UAV-based LiDAR and photogrammetry surveys to track the evolving morphology of the Buzău mud volcanoes. By generating high-resolution Digital Elevation Models (DEMs) and detailed orthophotoplans, we can precisely map surface changes, measure the volume of expelled material, and detect subtle deformations that might indicate increased activity. Unlike traditional field surveys, UAV technology captures these transformations with unprecedented accuracy and frequency.

One of our main objectives is to explore the possible link between local seismic activity and mud volcano dynamics. Do earthquakes in the Vrancea zone trigger more eruptions? Can we observe shifts in mudflow patterns following seismic events? By comparing elevation changes over time with regional seismic records, we aim to find answers to these questions.

Preliminary findings suggest that seismic activity may play a role in mud extrusion rates and surface deformations. These insights could help refine our understanding of the relationship between deep-earth processes and surface geological phenomena. Beyond the scientific implications, this research underscores the power of modern drone-based remote sensing in monitoring and predicting environmental changes

KEYWORDS: Mud volcanoes, UAV monitoring, LiDAR, photogrammetry, Vrancea seismicity

The role of tectonics and river network in shaping the landscapes of the Sultanate of Oman

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Rivers significantly shape the Earth's surface, responding to tectonic events while eroding and depositing sediments through various processes that transform the surrounding topography, from the watershed to the alluvial plains. The resulting landscape is a complex outcome of multiple interacting factors, including tectonics, litho-structural setting, and climate. These factors influence river networks, imparting distinct signatures on fluvial landforms and processes, and driving notable modifications in the landscape across several timescales.
This study focuses on the riverscapes of the Sultanate of Oman, aiming to elucidate the evolution of the landscape and the interactions between fluvial systems and tectonic activity. The unique geodynamic framework of Oman provides a distinctive context for examining the role of river networks and tectonics in the formation of landscape. Several methods have been employed in this region, including geomorphological mapping, which combines remote sensing and field surveys to understand the main active and fossil surface processes. This mapping was further enhanced through the application of deep learning techniques to analyse the Pliocene-Pleistocene evolution of local alluvial fans, alongside geomorphometric analysis to quantify the landscape modifications.
The geomorphological mapping of different areas emphasizes that the action of rivers in terms of erosional and depositional processes in the mountainous and plain regions is closely linked to tectonics and litho-structural frameworks, as well as Quaternary climatic fluctuations. The integration of deep learning and geomorphometric techniques provides objective methods to quantify the role of litho-structural setting and the effects of changes in riverine agency on the landscape. Specifically, deep learning enhances the detection and accuracy of fluvial landforms on satellite imagery, shedding light on past hydrological conditions and illustrating the climatic and tectonic influences on the evolution of alluvial fans at the foothills of mountain belts. Concurrently, geomorphometry quantifies landscape variations through topographic and river network analysis, permitting the detection of portions of the landscape in disequilibrium with ancient stable surfaces. This reveals that the current landscape is still in a state of evolution, indicative of ongoing geodynamic processes.
The integration of geomorphological mapping, deep learning and geomorphometry provides a comprehensive understanding of the complex interactions within the river network, allowing for the quantification of the role of both regional tectonic processes and local structural settings in shaping the landscapes of the Sultanate of Oman.

KEYWORDS: landscape evolution, Oman, river network, geomorphometry, deep learning

TnT – Tectonics and topography. Geomorphic markers of tectonic deformation in sandstone areas, NW Intra-Sudetic Trough, Central Europe

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The study area is located in the northeastern part of the Bohemian Cretaceous Basin and includes the Police Basin, which occupies the northwestern portion of the Intra-Sudetic Trough. This region is a platform area primarily composed of Middle Turonian to Coniacian quartzose sandstones. Its distinct tableland landscape is characterized by extensive plateaus, residual hills, vast rock cities, cuestas, and isolated rock towers. Additionally, it features numerous concave landforms, including cleft-and-valley systems and minor box-shaped valleys—both channelless and those carrying streams—despite their relatively limited attention in geomorphological research on sandstone terrains. This study aims to investigate the relationship between valley form distribution, macromorphological features of platform sandstone areas, and underlying geological controls. It is hypothesized that drainage patterns can provide new insights into the tectonic framework of sandstone areas along the Polish-Czech borderland.

To assess the influence of faults on the present-day relief and to identify potential intra-montane fault courses, an analysis of drainage patterns was conducted. Digital Elevation Model (DEM) analyses focused on evaluating the spatial distribution and geomorphic characteristics of valley forms using spatial and statistical approaches. The erosional dissection pattern was examined through a set of primary and secondary topographic indices derived from airborne LiDAR-based DEM data. Field investigations included geophysical surveying via Electrical Resistivity Tomography (ERT) and on-site validation of DEM-derived analyses.

The low-gradient topography of sandstone plateaus appears to be an important factor in the development of canyon networks within quartz-rich sandstones, as it promotes chemical weathering relative to mechanical erosion and denudation. Complex, hierarchically structured valley systems are particularly prevalent in tectonically dissected areas and along fractured zones. Furthermore, a multi-faced analytical approach shows that the morphological diversity of valley systems in platform sandstone areas reflect the complexity of geological settings. Relief parameterization facilitates comparative morphological analyses across different regions and scales in varying geological settings. The results contribute to a deeper understanding of tableland landscape evolution, as valleys serve as important indicators of relief development stages.

This research is a contribution to the research project no. 2021/41/N/ST10/00598 of the National Science Centre, Poland.

KEYWORDS: drainage network, neotectonics, spatial analysis, geomorphometry, Electrical Resistivity Tomography

Response of fluvial systems to Quaternary sedimentation and neotectonic deformation on an alluvial fan surface

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Neotectonic deformations show strong influence on recent fluvial systems and related sediment dispersal patterns in the Himalayan foreland. This study aims to establish the relationship between fluvial response and sedimentation pattern on a Quaternary alluvial fan surface in the Himalayan foothills, which has been subjected to neotectonic thrust emplacement. The fan surface is traversed by E-W trending blind thrusts, named Samsing, Matiali, and Chalsa, from north to south, which are considered southward translations of the Himalayan Frontal Thrust and raised as scarp due to fault-propagated folding. The deformation of the fan sediments caused by the emplacement of the Matiali and Chalsa thrusts, between 171 ka and 41 ka brought distinct changes to channel morphometry and sediment dispersal patterns across the thrusts. The residuals from the polynomial curve fitting applied to the channel long profiles on the fan surface reveal distinct differences in channel reaches, with deposition dominance in the upstream segments and an increased rate of erosion in the immediate downstream stretches of the Matiali thrust. Moreover, the application of stream length gradient and normalized steepness properties to the channel long profiles shows a concentration of high channel gradients and the development of knickpoints in close proximity to the Matiali thrust respectively. Although, the aspect of knickpoint migration upstream could not be established in this study significantly. This finding primarily raises question regarding the synformal structure developing between the Matiali and Chalsa thrusts. Statistical grouping of selected morpho-tectonic indices, applied to the fan-bound sub-catchments of the rivers, reveals similarities in formation between the channels flowing across the Matiali and Chalsa thrusts through the middle and between channels that are part of radial drainage developed on the east and western flank of the fan. The rivers in this radial drainage, have bypassed through the trailing part of the Matiali thrust and joined the Neora and Murti rivers in the west and east respectively. This study has utilized Optically Stimulated Luminescence (OSL) dating technique to date terrace sediments for understanding the timing of sedimentation and tectonic perturbations. This study suggests that, during the post-deformation period (after 171 ka), a possible obstruction caused by the Matiali thrust clogged sediments upstream, leading to rapid channel filling and the burial of the palaeo-channel system. However, the southern downthrown segment, relative to the Matiali Thrust, experienced deeper channel incision due to an enhanced gradient and possibly during the post-deformation period deposition of upstream-derived sediments on the relatively subsided limb compelled the channels to further incise their existing courses. The presence of channel floor deposits on a subsided strata (with soil formation) on T2 at multiple locations verify this claim. In addition to neotectonic influence, climatic perturbations (variations in monsoon strength) played an important role in channel evolution and sediment dispersal on the studied fan surface.

KEYWORDS: fault-propagation, Matiali fan, OSL, paleoclimate, thrusts

Large landslides in active tectonic areas: assessing the role of seismic events in slope movements using InSAR data in the Western Gulf of Corinth, Greece

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In recent years, several studies have analyzed landslide movements using satellite interferometric data. However, in tectonically active regions, isolating landslides can be challenging without prior knowledge of geomorphological context. This study investigates large landslide movements in a seismically active area located 30 km east of Nafpaktos, in the Western Corinth Rift, Greece. The aim of this work is to understand the relationship between seismic activity, rainfall, and landslide movements. We explore how time-series clustering of Interferometric Synthetic Aperture Radar (InSAR) data can aid in identifying and analyzing slope instabilities in complex geological settings.
We utilized the InSAR technique with Sentinel-1 data processed by the European Ground Motion Service (EGMS), to analyze ground displacement from 2019 to 2023. A time-series clustering approach was applied to classify temporal displacement patterns based on trends rather than solely on displacement magnitude. This method proved crucial in distinguishing Persistent Scatterers (PS) with similar mean annual velocities (mm/year) but differing displacement trends. By categorizing PS according to their displacement trends, we identified specific clusters associated with landslides. Further analysis assessed the correlation between slope instabilities, rainfall, and seismic activity. Additionally, geomorphological field surveys and remote mapping were conducted to deepen the understanding of instability phenomena.
Seven landslide-affected areas were identified, including sites that have experienced first failures in recent decades, such as the Marathias landslide. Our findings reveal a correlation between the seismic sequence from late 2020 to early 2021 in the area and a significant acceleration in landslides displacement rates. In contrast, the influence of rainfall appeared less significant, suggesting that most of the mapped landslides exhibit a constant displacement rate. Our results highlight the significant role of seismic activity in accelerating slope instabilities in this tectonically active region. The application of time-series clustering to InSAR data offers a valuable approach for distinguishing different types of ground movements and enhancing landslide hazard assessments in seismically active areas.

KEYWORDS: large landslides, InSAR, seismic activity, time-series clustering, natural hazard

Tectono-sedimentary evolution of a marginal fault: insights from the Dead Sea Transform Fault System

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The Dead Sea Transform (DST), a prominent tectonic feature on Earth's crust, provides an exceptional natural laboratory for investigating the dynamic processes associated with continental rifting and its subsequent evolution. This study focuses on the sedimentary and tectonic evolution of the Yesha Fault, a marginal fault of the DST. Along the Yesha Fault, a distinct, elongated depression, known as the Yesha Valley was formed. Through detailed analysis of sedimentary sequences from boreholes and geochronological data obtained by optically stimulated luminescence and magnetostratigraphy, this research aims to refine the understanding of sedimentation patterns, rates, and tectonic activity associated with this marginal fault. The initial formation of the Yesha Valley, postdating the Brunhes-Matuyama reversal (~773 ka), was driven by normal faulting, resulting in an accommodation space progressively infilled with clastic and aeolian sediments. The sedimentary record reveals four distinct cycles of calcic soil between ~780 ka and ~450 ka, indicative of short episodes of tectonic subsidence, each followed by a period of tectonic quiescence, during which carbonate accumulated and calcic soils have developed. Following ~450 ka, the sedimentary sequence accumulated in the subsiding valley lacks evidence of abrupt tectonic events, suggesting a transition to a tectonic regime dominated by gradual creep. During the last glacial period, sedimentation is characterized by clay deposition, with more hydric conditions and increased organic content observed between 4 and 6.5 m, whereas the uppermost 2 m of the soil reflects the influence of recent anthropogenic activity. Sediment accumulation rates within the Yesha Valley exhibit considerable variability, ranging from 20.8 cm/ka to 1.8 cm/ka, with an average of 3.2 cm/ka. These rates are an order of magnitude lower than those observed in the adjacent Hula Basin, indicating a slower tectonic regime along the marginal Yesha Fault and valley.

KEYWORDS: Dead Sea Transform, Yesha fault, sedimentation rate, OSL, magnetostratigraphy