

Landslide25_08

Landslide Inventories and Key Hazard Drivers in the Ukrainian Carpathians: The Upper Latoritsa Basin Case

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SUMMARY

A landslide inventory database was developed for the Upper Latoritsa basin, Mukachevo district of the Transcarpathian Region in Ukraine. Comprehensive analysis using remote sensing data, detailed field-based geological and geomorphological surveys, GIS tools, and statistical methods allowed for a thorough assessment of the influence of geological and geomorphological factors on the development of landslides. Spatial and temporal patterns of landslides were identified, confirming their complex, multifactorial genesis. The results confirm a strong spatial correlation between landslides and fault systems of various origins, with most landslides occurring within 100–500 meters of fault zones. This highlights the key role of structural-tectonic features and destructive processes in the initiation and propagation of slope instability. Terrain parameters such as slope steepness, curvature, topography wetness index and elevations were identified as critical contributors to landslide susceptibility, as they directly affect shear and normal stress conditions within landslide bodies. Seismicity was also found to be an important triggering factor. The results of the conducted research serve as a scientific basis for forecasting landslide hazards and assessing associated risks, they provide essential insights for land-use planning and effective georisks mitigation in the Carpathians.

Introduction

Landslides are a major natural hazard in the geodynamically active Carpathian Mountains region. They cause significant damage to infrastructure, geocology, and local communities. This hazard type is increasingly relevant in the context of climate-induced precipitation anomalies and land-use pressures, particularly in mountain catchments like the Upper Latoritsa basin. This effect is particularly pronounced during periods of intense rainfall, such as the early July 2025 event, which caused flooding and contributed to the destabilization of structurally weakened flysch zones. In the Ukrainian Carpathians, the complex geology, active tectonics, and climatic conditions contribute to the development of landslide hazards. Landslides are the result of various factors and mechanisms, the combination of which leads to the manifestation of landslides of different genetic types and structure. In the Carpathians, these are mainly rotational and translational landslides, rock falls, and debris flows (Ivanik, 2024). Landslides also vary in types of material involved in the movement process, including flysch deposits, volcanic rocks and different genetic types of Quaternary deposits.

This study aims to create the inventory landslide database in the Upper Latoritsa river basin. This area belongs to the Mukachevo district, Transcarpathian region of Ukraine. By integrating remote sensing data, field observations, geological mapping, and structural analysis, the research aims to identify the main geological and geomorphological factors that influence landslide processes of different types in the study area.

Study area and landslide inventory

The study area (Fig.1) is located within the Ukrainian Carpathians, in Mukachevo district, Transcarpathian region (Ukraine).

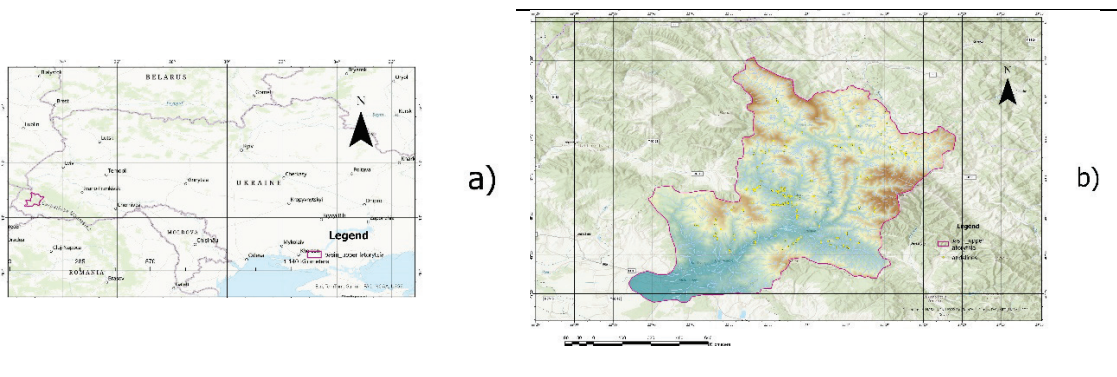


Figure 1 Location of the study area: Transcarpathian region, Ukraine (a), Upper Latoritsa basin (b)

Within this area, landslides, debris flows, large rockfalls, and significant riverbank erosion processes are actively developing. The occurrence of landslide processes in the Latoritsa basin is largely influenced by the region's major geological structure and the intensity of denudation processes. The lower structural layer consists of the Carpathian Folded Belt, composed primarily of carbonate and terrigenous formations from the Mesozoic and Cenozoic eras - mainly flysch deposits. These formations are organized into several structural zones: the Krosno, Dukla, Porkulets, and Rakhiv zones (in the Outer Carpathians), as well as the Pieniny Klippen Belt and Marmarosh Massif (in the Inner Carpathians). The southwestern part of the area belongs to the Transcarpathian depression. The upper structural layer is composed of Neogene and Quaternary sedimentary, volcanic, and volcanoclastic rocks (in Vihorlat-Guta Volcanic Massif), typically characterized by nearly horizontal bedding. The landslide database was compiled using a multi-source approach, including remote sensing data (satellite imagery), detailed field investigations, existing landslide inventories, and information provided by local inhabitants. The developed database includes 206 landslide sites. Such an approach ensures spatial completeness and lays a foundation for reproducible landslide susceptibility and hazard modelling.

Materials and methods

To evaluate the impact of geological and geomorphological factors on landslide occurrence, an integrated methodological approach was applied. This included detailed field observations, geological and geomorphological mapping, and the use of spatial analysis tools in ArcGIS Pro. These methods allowed for the identification of structural features, relief characteristics, and lithological variations that contribute to slope instability. For the DEM of the study area the ALOS Global Digital Surface Model (AW3D30) has been used. This dataset allows consistent geomorphological analysis of slopes, curvature, and hydrological patterns and has been previously validated in mountainous regions under similar climatic and geological conditions. It is a global dataset generated from images collected using the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) aboard the Advanced Land Observing Satellite (ALOS). It was provided by the Japan Aerospace Exploration Agency (JAXA) releases the global digital surface model (DSM) dataset with a horizontal resolution of 30-meter mesh (1 arcsec) (Japan Aerospace Exploration Agency, 2021).

Key factors of landslide hazards in the Upper Latoritsa basin

The *lithological-stratigraphic structure* serves as the foundation for the development of landslide processes, as it determines the varying influence of geodynamics and the physical and mechanical properties of rock complexes. The highest concentration of landslides has been recorded within the rock formations of the Cretaceous-Paleogene flysch deposits represented by interbedded fine- to coarse-grained micaceous calcareous sandstones, argillites, and siltstones: 129 – in fine clay rhythmic flysch deposits 49 – in coarse-grained sandy flysch deposits, 12 – in interbedded mudstones, siltstones, and marl layers. Landslide processes in the mentioned stratigraphic units are mainly caused by interbedded argillites and siltstones, which, under high water saturation and structural weakening, lead to slope instability. Deposits of the upper structural layer represented by the horizontally layered Neogene–Quaternary sedimentary, volcanogenic, and volcanoclastic rocks are favorable for landslides (the total number is 18), especially in tuffs, lava breccia of the Pliocene volcanic complex with thicknesses from 120 to 800 m.

Structural and tectonic factor of slope instability. The study area features complex fault systems with multi-stage reactivation. These structures fragment flysch formations into blocks that, in certain geomorphological and lithological conditions, may be prone to landslide hazards (Fig. 2).

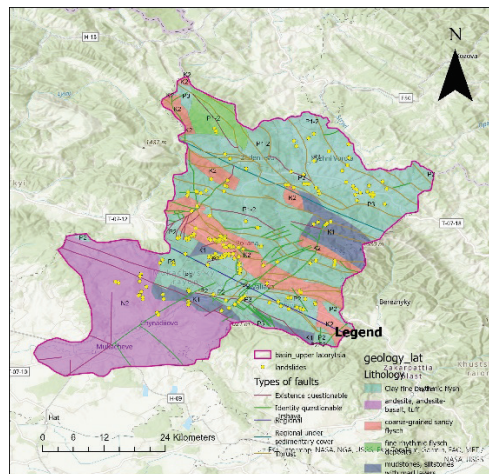


Figure 2 Lithology and tectonic map of the Upper Latoritsa basin, Transcarpathian region, Ukraine

The results of distance-based analysis confirm a strong spatial correlation between faults of various origins and landslide distribution (Ivanik et al., 2019). The majority of landslides (201) are situated within a 100–200 meter range from fault zones, highlighting the controlling influence of tectonic structures on slope instability. Additionally, analysis of the structure and spatial relationships of fault zones of different ranks with river valleys revealed their influence on landslide processes. These zones may align sub-parallel, perpendicular, or diagonally to river channels. An example of a sub-parallel relationship is observed near

the village of Holubyne, downstream of the bridge on the left bank of the Pynya River. Here, in the Huchalo stream, a series of sub-parallel faults is expressed in the relief as sequential slope terraces aligned with the river channel and trending northwest (Fig.3).



Figure 3 Surface expression of sub-parallel fault structures and formation of scarps in the relief on the northeastern outskirts of Holubyne village (strike – NE 40°) (a) and on the left bank of the Huchalo stream (b) (Holubyne village, Svaliava Territorial Community, Mukachevo district, Ukraine).

The main topography characteristics influencing landslide development are slope steepness and elevations, as these parameters directly affect the normal and shear stress within or at the contact of a landslide body. To assess these factors the key morphometric landform parameters were identified. A 3D terrain model of the selected region has been used, along with a slope gradient map (Fig. 4a), aspect map, plan curvature map (Fig.4b), and topography wetness index map (Fig. 4c) have been created.

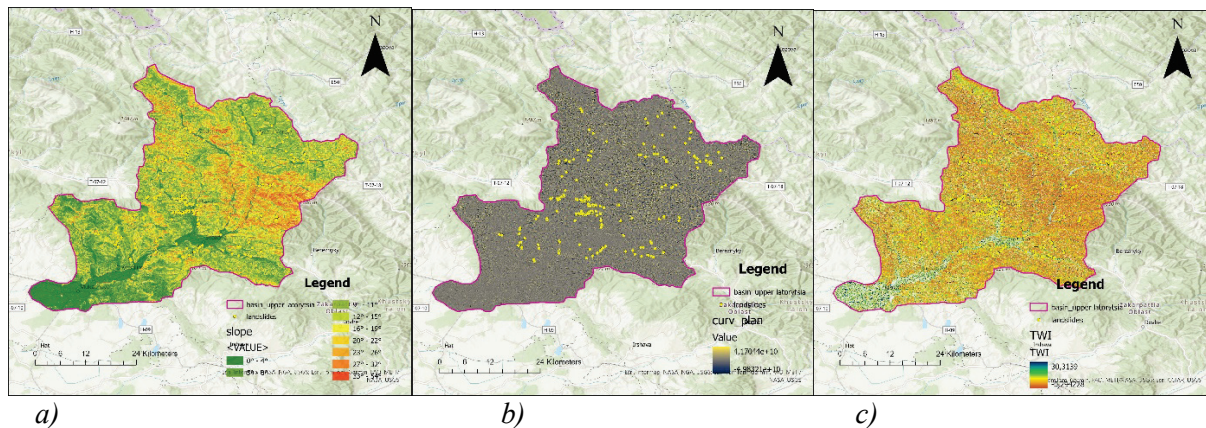


Figure 4 Maps of slope (a), plan curvature (b) and topography wetness index (c), the Upper Latoritsa basin, Transcarpathian region, Ukraine

Plan curvature characterizes the horizontal curvature of the terrain surface and reflects the divergence or convergence of surface flow. Areas with negative plan curvature (concave shapes) tend to concentrate surface runoff, increasing pore water pressure and promoting landslide initiation, while positive values (convex shapes) are associated with flow dispersion and greater slope stability. Topographic Wetness Index (TWI) indicates zones of potential water accumulation based on slope and upstream contributing area. High TWI values typically mark areas of increased soil moisture, which are more susceptible to landslides, especially during periods of intense precipitation or prolonged saturation. Absolute elevations of landslide bodies were also determined.

Seismicity is one of the factors influencing the development of mass movement processes. The Carpathian region is among the most seismically active areas in Ukraine. It experiences noticeable seismic activity, with over 10 earthquakes annually, typically ranging in magnitude from 0.6 to 2.0 or higher. On average,

every 5–10 years, earthquakes of magnitude 2.5–3.0 occur, producing macroseismic effects with intensities of 5–6 on the MSK scale. Additionally, every 60–100 years, stronger local or nearby earthquakes (magnitude up to 4.0–4.7), originating in adjacent regions of Slovakia, Hungary, or Romania, can cause shaking in Transcarpathian region with intensities reaching up to 7 (Nazarevich et al., 2023). During the instrumental observation period from 1961 to 2003, 54 earthquakes were recorded along the Third Transport Corridor in the Ukrainian Carpathians. Notably, the Chop–Mukachevo Basin shows higher seismic activity compared to the surrounding Carpathians. The highest concentration of low-magnitude earthquakes is observed near Mukachevo and Svaliava.

Conclusions

As a result of this study, a landslide inventory database was developed for the Upper Latoritsa basin. Spatial and temporal patterns of landslides were identified, confirming their complex, multifactorial genesis. Comprehensive analysis using remote sensing data, detailed field-based geological and geomorphological surveys, GIS tools, and statistical methods allowed for a thorough assessment of the influence of geological and geomorphological factors on the development of landslides in the Mukachevo districts of the Transcarpathian Region in Ukraine. The results confirm a strong spatial correlation between landslides and fault systems of various origins, with most landslides occurring within 100–500 meters of fault zones. This highlights the key role of structural-tectonic features and destructive processes in the initiation and propagation of slope instability. Terrain parameters such as slope steepness, curvature, TWI and elevations were identified as critical contributors to landslide susceptibility, as they directly affect shear and normal stress conditions within landslide bodies. Seismicity was also found to be an important triggering factor. The highest concentration of seismic events corresponds to the Mukachevo - Svaliava area. The results of the conducted research serve as a scientific basis for forecasting landslide hazards and assessing associated risks. By integrating geological, geomorphological, and geospatial data, the study provides essential insights for developing early warning systems, informed land-use planning, and effective risk mitigation in the Carpathians.

Acknowledgements

This research has been done in the framework of the project “Risk assessment of landslide hazards and impact on communities” as part of the Fulbright U.S. Scholar Program sponsored by the U.S. Department of State, and the EU Project LOC3G (MARIE SKŁODOWSKA-CURIE ACTIONS (MSCA), grant No 101129729. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Fulbright Program or the U. S. Government.

References

- Ivanik, O. (2024). Modelling and Assessment of Debris Flow Impact on Infrastructure in the Carpathians. In: Wu, W., Wang, Y. (eds) Recent Geotechnical Research at BOKU. Springer Series in Geomechanics and Geoen지니어ing. Springer, Cham. https://doi.org/10.1007/978-3-031-52159-1_5
- Ivanik O., Shevchuk V., Kravchenko D. et al. (2019). Geological and geomorphological factors of natural hazards in Ukrainian Carpathians. *J Ecol Eng* 20:177–186. <https://doi.org/10.12911/22998993/102964>
- Japan Aerospace Exploration Agency (2021). ALOS World 3D 30 meter DEM. V3.2, Jan 2021. Distributed by OpenTopography. <https://doi.org/10.5069/G94M92HB>. Accessed: 2025-05-28
- Nazarevych, A & Nazarevych, Lesya & Bayrak, Galyna & Pyrizhok, Natalia. (2023). Seismotectonics of the Oash and Transcarpathian deep faults junction zone (Ukrainian Transcarpathians). *Geodynamics*. 2(33). 99-114.