Landslide25_16

Integrative Landslide Prediction Model in Zakarpattia Region

V. Hudak *(Taras Shevchenko National University of Kyiv)*, ***V. Semeniaka*** *(Taras Shevchenko National University of Kyiv)*, ***V. Zatserkovnyi*** *(Taras Shevchenko National University of Kyiv)*, ***I. Stakhiv*** *(Taras Shevchenko National University of Kyiv)*, ***L. Ilyin*** *(Lesya Ukrainka Volyn National University)*, ***T. Pastushenko*** *(Taras Shevchenko National University of Kyiv)*

SUMMARY

The article reviews the current state of landslide research in the Zakarpattia region, which is characterized by a high susceptibility to geodynamic processes. Particular attention is paid to landslide risk modeling based on cadastral data, remote sensing, and geoinformation technologies. A detailed landslide inventory map was created, covering over 3,000 events and taking into account the type, activity, area, geography, and other attributes of each landslide. A factor analysis of topographic, geological, hydrological, and anthropogenic parameters that affect slope stability was conducted. Based on this analysis, a landslide susceptibility model was constructed, implemented in the ArcGIS environment using the weighted overlay and hierarchical analysis methods. A landslide susceptibility map was obtained, which covers scenarios for both long-term risk assessment and short-term forecasting in the event of heavy precipitation or seismic activity. The results of the study can serve as the basis for early warning systems and spatial planning in the mountainous regions of Zakarpattia region.

Introduction

Natural disaster research in the Zakarpattia Region (Zakarpattia Oblast, western Ukraine) has a long history, and it has been particularly active after major catastrophic events that highlighted the vulnerability of the area. The study of natural hazards in this region combines several scientific disciplines, including geology, hydrology, meteorology and, increasingly, geoinformatics. This article reviews the current state of research related to one of the main natural hazards affecting the region, namely landslides. *(Ivanik, 2018; Karpinskyi & Kin, 2018)*.

Method and/or Theory

Landslide risk modeling in Zakarpattia Region began with a comprehensive mapping of existing and potential landslide areas. The main source of data was the landslide cadastre maintained by the State Service of Geology and Subsoil, which as of 2020 documented 3,288 landslides with a total area of approximately 385 km².
Each documented landslide was classified according to: type (rotational, translational, flow, complex); activity status (active, dormant, stabilized); size (area and estimated volume); date of event (if known) *(Zabokrytska, & Kuzmenko, 2017)*.

Spatial distribution analysis showed that landslides are concentrated mainly in the mountainous northeastern part of the region and along several linear structures that represent fault zones. Notable clusters were identified in the Rakhiv and Tyachiv districts in the east, as well as in the Velykoberezny and Perechyn districts in the north.

To supplement the list of known landslides, we used remote sensing methods, namely:
1. Analysis of multi-temporal Sentinel-2 images to detect changes in vegetation and relief indicating slope movements *(Bilianiuk, &Pavliuk, I.M., 2020).*
2. Processing Sentinel-1 SAR data using interferometric SAR (InSAR) techniques to detect ground deformation associated with slow landslides (*Hudak, Kril, & Zatserkovnyi, 2025*).
3. Visual interpretation of high-resolution images for recent landslide scars, especially after heavy rainfall.

For example, analysis of satellite images from January-February 2024 confirmed the presence of two large landslides in Tyachiv district (10.5 ha) and Rakhiv district (11.5 ha), which were triggered by prolonged rainfall. These recent events were included in the landslide database with detailed attributes, including precise locations, affected area, and environmental conditions at the time of the failure.

The integration of all data sources resulted in a comprehensive landslide inventory map (*Fig. 1*). This map not only documents the spatial distribution of past and current landslides, but also serves as training data for predictive modeling of potential future events.

After developing the landslide cadastre, we conducted a detailed analysis of the environmental and anthropogenic factors influencing landslide occurrence in Zakarpattia Region. This analysis aimed to identify key variables controlling slope stability and quantify their relative contribution to landslide susceptibility. The factor analysis focused on the following parameters:
1. Topographic factors:
• Slope angle: Statistical analysis of the existing landslide inventory showed that most landslides in Zakarpattia Region occur on slopes with a slope of 7.5° to 22.4°, with the highest frequency in the range of 17-20° (*Fig. 2a*). This pattern suggests that very gentle slopes lack sufficient gravity to trigger collapse, while very steep slopes often consist of solid bedrock or have limited soil cover.
• Slope aspect: landslides favor western, southwestern, southern, and southeastern slopes that receive more solar radiation and have more pronounced freeze-thaw cycles.

• Elevation: most documented landslides occur at elevations between 280 and 730 meters above sea level, corresponding to the mid-mountain belt, where human activity, geological conditions, and hydrological factors create optimal conditions for slope failure (*Melnychuk, Yu.H., 2021)*.

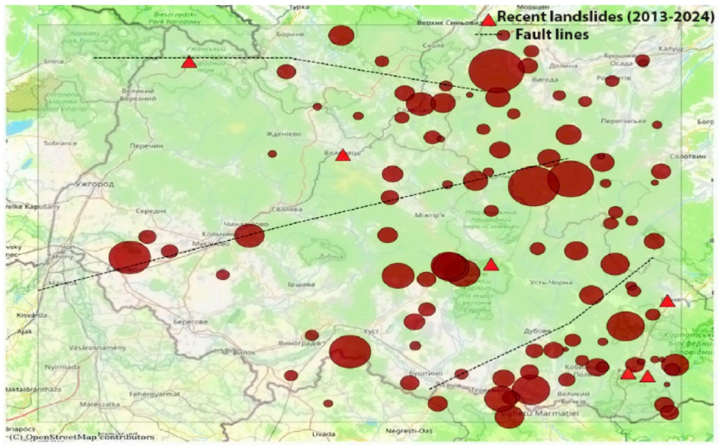

Figure 1. *Comprehensive landslide inventory for the Transcarpathian region of Ukraine (Zakarpattia Oblast)*

2. Geological factors:
• Lithology: Analysis of geological maps has shown that landslides are particularly common in areas dominated by flysch formations (alternations of layers of sandstone, shale, and marl) due to the presence of weak shale layers that can serve as sliding surfaces.
• Proximity to faults: A striking correlation has been found between landslide propagation and tectonic structures. Approximately two-thirds of all landslides in Zakarpattia Region are located within 1 km of fault lines, with the highest frequency in the range of 0-0.5 km (*Fig. 2b*).

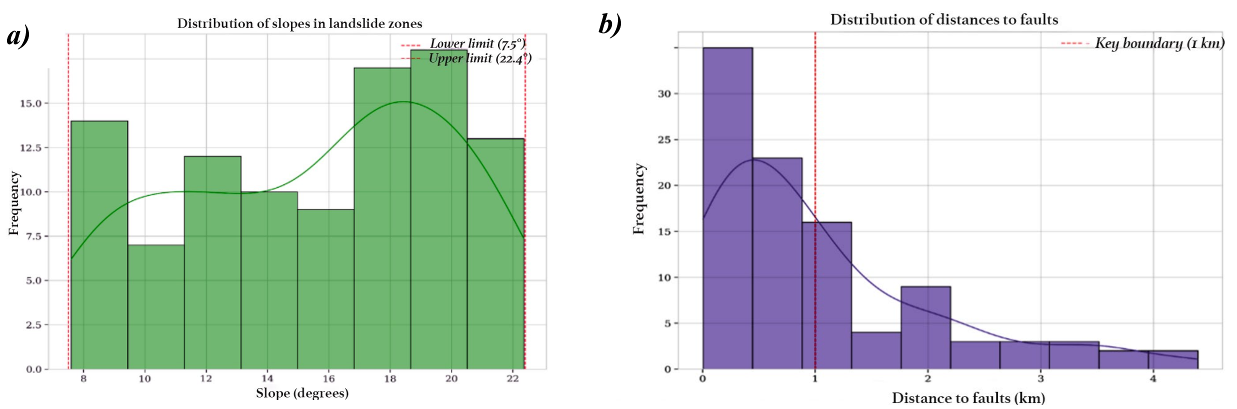

Figure 2. *Spatial relationships of landslides in the Zakarpattia Region:*

a) – distribution of landslides by slope angle based on the regional inventory; b) – distribution of distances from mapped landslides to tectonic faults across the study area.

3. Hydrological factors:
• Proximity to drainage networks: Many landslides (approximately 60%) occur within 500 meters of waterways, reflecting the role of stream erosion in slope erosion and the influence of groundwater on slope stability.
• Precipitation: Areas with higher annual rainfall tend to have higher landslide densities, especially those with rainfall exceeding 1000 mm per year.

4. Anthropogenic factors:
• Land use/land cover: Land cover analysis has shown that the transition from forest to agricultural or developed land significantly increases landslide susceptibility. In non-forested areas, landslide densities are 2.5-3 times higher than in similar forested areas.

The results of the factor analysis provided a quantitative basis for further modeling of landslide susceptibility, enabling a data-driven approach to predicting potential landslide locations.

Results

Based on the landslide inventory and factor analysis, we developed a comprehensive model for predicting landslide vulnerability and predicting potential landslide activation in the Zakarpattia Region. This predictive modeling used a multi-criteria assessment approach implemented in ArcGIS.

The landslide susceptibility modeling process included the following steps:
1. *Factor standardization*: each factor layer (slope, aspect, elevation, proximity to faults, proximity to drainage, soil cover, etc.) was converted into a raster with a common pixel size (30 meters) and standardized on a scale of 0-1, where higher values indicate a greater contribution to landslide susceptibility.
2. *Factor Weighting*: Based on the statistical analysis of the importance of the factors, weights were assigned to each variable. The weights were determined using the Analytic Hierarchy Process (AHP) with the following distribution: slope angle – 25%; proximity to faults – 20%; lithology – 15%; land use/land cover – 15%; proximity to sewers – 10%; format – 5%; elevation – 5%; precipitation – 5%.
3. *Weighted Overlay*: The standardized and weighted factor layers were combined using the Weighted Overlay tool in ArcGIS to obtain a landslide susceptibility index.
4. Classification: The permanent susceptibility index was reclassified into five categories: very low, low, moderate, high, and very high susceptibility.
5. *Validation*: The model was validated by comparing the predicted susceptibility classes with the distribution of known landslides (*Fig. 3a*) that were not used in the model development (validation dataset). The model showed good predictive performance: 83% of the landslides in the validation dataset fall into the high and very high susceptibility zones.

The resulting landslide susceptibility map (*Fig. 3b*) shows that approximately 8% of the territory of Zakarpattia Region falls into the category of high or very high landslide susceptibility. While most of these high-risk areas are in uninhabited mountains, several urban settlements are located adjacent to or partially on these unstable slopes. (*Kovalchuk, 2019*).

To predict the potential landslide activation in response to triggering events, we developed a dynamic model that includes:
1. *Precipitation thresholds*: Based on historical data on rain-induced landslides in Zakarpattia Region, we established threshold curves relating the intensity and duration of rainfall to landslide initiation. For example, 100 mm of rainfall within 24 hours or 150 mm within 72 hours were identified as critical thresholds for large-scale landslide activation in areas with high vulnerability.
2. *Earthquake triggers*: The model includes a component that estimates the potential for earthquake-induced landslides based on earthquake magnitude, distance from the epicenter, and landslide susceptibility. For example, a magnitude 5.0 earthquake is capable of triggering landslides within a radius of approximately 10-15 km in areas of high sensitivity.
3. *Seasonal factors*: The model takes into account seasonal variations in landslide activity, with spring (March-April) and autumn (October-November) identified as the most active periods due to snowmelt and seasonal rainfall, respectively. The predictive model was implemented as a set of conditional scenarios in ArcGIS ModelBuilder, allowing for rapid assessment of landslide potential under different launch scenarios. This approach allows for both long-term susceptibility assessment and short-term forecasting in response to weather events or seismic activity.

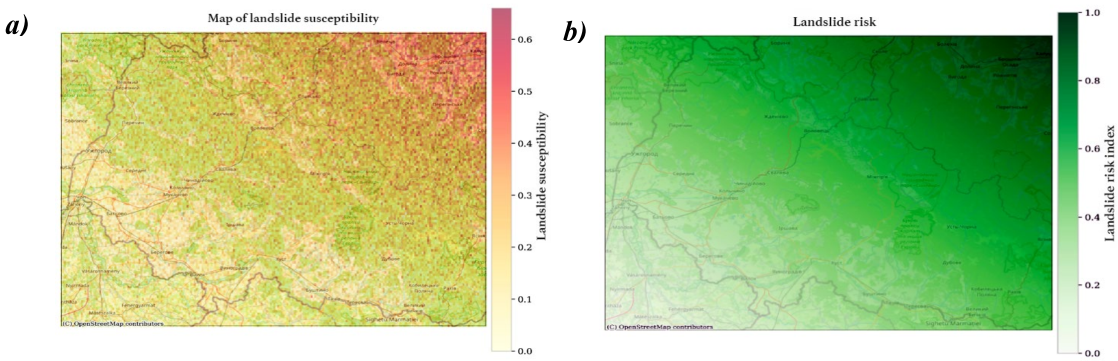

Figure 3. *Landslide assessment in the Zakarpattia Region:*
a) – landslide susceptibility map generated using weighted overlay analysis in ArcGIS; b) – landslide risk map showing relative risk index values across the region.

Conclusions

The resulting landslide risk map highlights several significant patterns. In particular, the eastern parts of the Zakarpattia Region exhibit a moderate level of risk (0.5–0.7), where landslide hazards are most prevalent.This study enabled the development of a highly accurate, multi-level landslide susceptibility model for the Zakarpattia Region, based on spatial analysis, inventory data, satellite observations, and geoecological modeling. The analysis identified the key risk factors as slope angle, lithological structure, proximity to tectonic faults, and land use characteristics. The modeling results indicate that approximately 8% of the region's territory falls within zones of high or very high landslide susceptibility, necessitating special consideration in the planning of development projects, road infrastructure, and landslide mitigation measures. Furthermore, dynamic predictive modeling incorporating critical precipitation thresholds, seismic activity, and seasonal variations provides an effective tool for rapid assessment and response to potential landslide events. The findings can serve as a foundation for the establishment of an early warning system and for strategic risk management in the mountainous areas of Ukraine.

Acknowledgements

This research has been done in the framework of the project Nº25БП049-01(M) "Integrated models and forecasting of natural and military geohazards and assessment of their impact on critical infrastructure" and was funded by the Ministry of Education and Science of Ukraine; and EU Project LOC3G, grant No 101129729 (MARIE SKLODOWSKA-CURIE ACTIONS (MSCA).

References

Bilianiuk, V., & Pavliuk, I. (2020). Geoinformation assessment of landslide hazard in the Carpathian region of Ukraine. *Geography and Nature Management*, 24, 45–53.

Ivanik, O. (2018). Modeling of landslides and assessment of their impact on infrastructure objects in Ukraine. In Springer Series in Geomechanics and Geoengineering (pp. 1487–1490). Springer Verlag. https://doi.org/10.1007/978-3-319-97115-5_129

Hudak, V., Kril, T., & Zatserkovnyi, V. (2025). Remote monitoring of vertical surface displacements as indicators of deformation of underground structures. Visnyk of Taras Shevchenko National University of Kyiv. Geology, 1(108), 94–102. https://doi.org/10.17721/1728-2713.108.13

Karpinskyi, Y., & Kin, D. O. (2018). Research on cartometric operations in a GIS environment [in Ukrainian]. Urban Development and Spatial Planning, 68(68), 706–711.

Kovalchuk, I. (2019). Application of geoinformation technologies for landslide forecasting in foothill areas of Ukraine [in Ukrainian]. Problems of Geography, 147, 115–122.

Melnychuk, Y. (2021). Landslide inventory of Zakarpattia and analysis of the factors of their occurrence [in Ukrainian]. Geoinformation Systems and Remote Sensing of the Earth, 29, 33–41.

Zabokrytska, M., & Kuzmenko, O. (2017). Risk modelling of natural disasters in mountainous areas [in Ukrainian]. Visnyk of the Lviv University. Series Geography, 51, 104–112.