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Geostructural factors and spatial modelling of landslide processes in Transcarpathia based on GIS and multiple regression

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SUMMARY

Landslides are one of the most common forms of geodynamic hazards, causing significant damage to infrastructure and ecosystems, especially in mountainous regions. This study investigates the influence of geostructural, geomorphological, climatic and anthropogenic factors on the activation of landslide processes in the Ukrainian Carpathians, particularly in the Flysch Carpathians and the Transcarpathian Internal Depression. Using GIS and multiple linear regression, data on 2,325 landslides were analysed and classified according to slope morphotype, geological structure, absolute heights, proximity to watercourses, faults, roads and buildings, as well as microseismicity parameters. The model for the Flysch Carpathians revealed the decisive influence of slope morphology (especially complex and straight forms), high absolute elevations, seismic activity, and anthropogenic factors. Within the Transcarpathian depression, geolithological features and the influence of technogenic disturbances of slope equilibrium are dominant. The results confirm the spatial differentiation of the influence of factors within different tectonic units, which allows the creation of accurate landslide susceptibility maps for regional planning and risk management. The obtained regression models have high coefficients of determination ($R^2 > 0.79$) and can be used for further forecasting of landslide intensification in the context of climate change, increasing urbanisation and seismic activity.

Introduction

Landslides are one of the most common and destructive geological processes, causing significant economic damage, infrastructure disruption and threats to human life. It is particularly important to understand how local geological and tectonic conditions, seismicity of the territory, and geomorphology influence the initiation, scale, and frequency of landslides. Identifying these factors and quantifying them allows for the creation of reliable prediction models and susceptibility maps that facilitate effective risk management and land-use planning. The application of modern statistical methods, in particular multiple regression, in combination with spatial analysis in geographic information systems (GIS) opens up new opportunities for accurate and comprehensive research into landslide processes, which is of great practical importance for public safety and sustainable development of territories.

Research Methodology

Geographic information systems (GIS) are an indispensable tool for spatial analysis of exogenous geological processes, in particular landslides, as they allow for the integration, visualisation and analysis of various spatial data – topography, geology, hydrology, faults, climate, anthropogenic influences, etc. GIS enables the creation of detailed maps of predictor variables (angle of inclination, absolute elevations, distances to watercourses and faults, microseismicity) and allows spatially consistent data to be prepared for further statistical modelling. The use of multiple regression to study factors contributing to landslides is an effective method for analysing and predicting slope stability, as it allows the simultaneous modelling of the influence of various factors and provides a better understanding of their interrelationships and impact on the probability of landslides.

Inital data

The Transcarpathian region is one of the most affected by landslide processes (385.21 square kilometres) in Ukraine (Informatsiinyi, 2021) (Fig.1). The development of landslide processes is primarily controlled by favourable natural conditions (flysch rocks, steep slopes, dense drainage system, tectonic faults, seismicity of the territory), as well as anthropogenic influence. The landslide cadastre of Transcarpathian region, according to Geoinform, contains the results of surveys of landslide areas for the period 1980–2001. Each landslide is described by geographical coordinates, stage of development (active, stable), slope characteristics (concave, concave-convex, convex, convex-concave, straight, stepped, complex), its location on the slope (entire slope, upper, middle, lower parts of the slope, watershed), as well as absolute elevations, slope inclination, and geometric dimensions of landslide bodies. By supplementing this information with geological data on the lithology of underlying rocks (Derzhavna..., 2003), the network of fault zones (Tektonichna..., 2007), watercourses, seismicity of the territory, and precipitation data, it is possible to comprehensively analyse the leading factors for individual geostructural regions: the Flysch Carpathians and the Transcarpathian internal trough.

Method and Theory

The geomorphology of a slope can significantly affect rock stability. Straight slopes, especially those with a steep angle, are often the most vulnerable to landslides, as the absence of sharp changes in slope allows water and gravity to weaken the upper layer of rock. Stepped slopes, thanks to their natural protrusions, can reduce the speed and intensity of landslides, as each ‘step’ acts as a barrier. Concave slopes usually have an increased likelihood of landslides in the lower part due to water accumulation and soil weakening on steeper sections. Convex slopes, on the other hand, can distribute the load more evenly, reducing the likelihood of landslides and decreasing their scale, but this depends on other factors, such as geological conditions or precipitation levels. The location of a landslide on a slope (in the upper, middle, lower part or in the watershed area) significantly affects the mechanism of its formation, type, scale and activity.

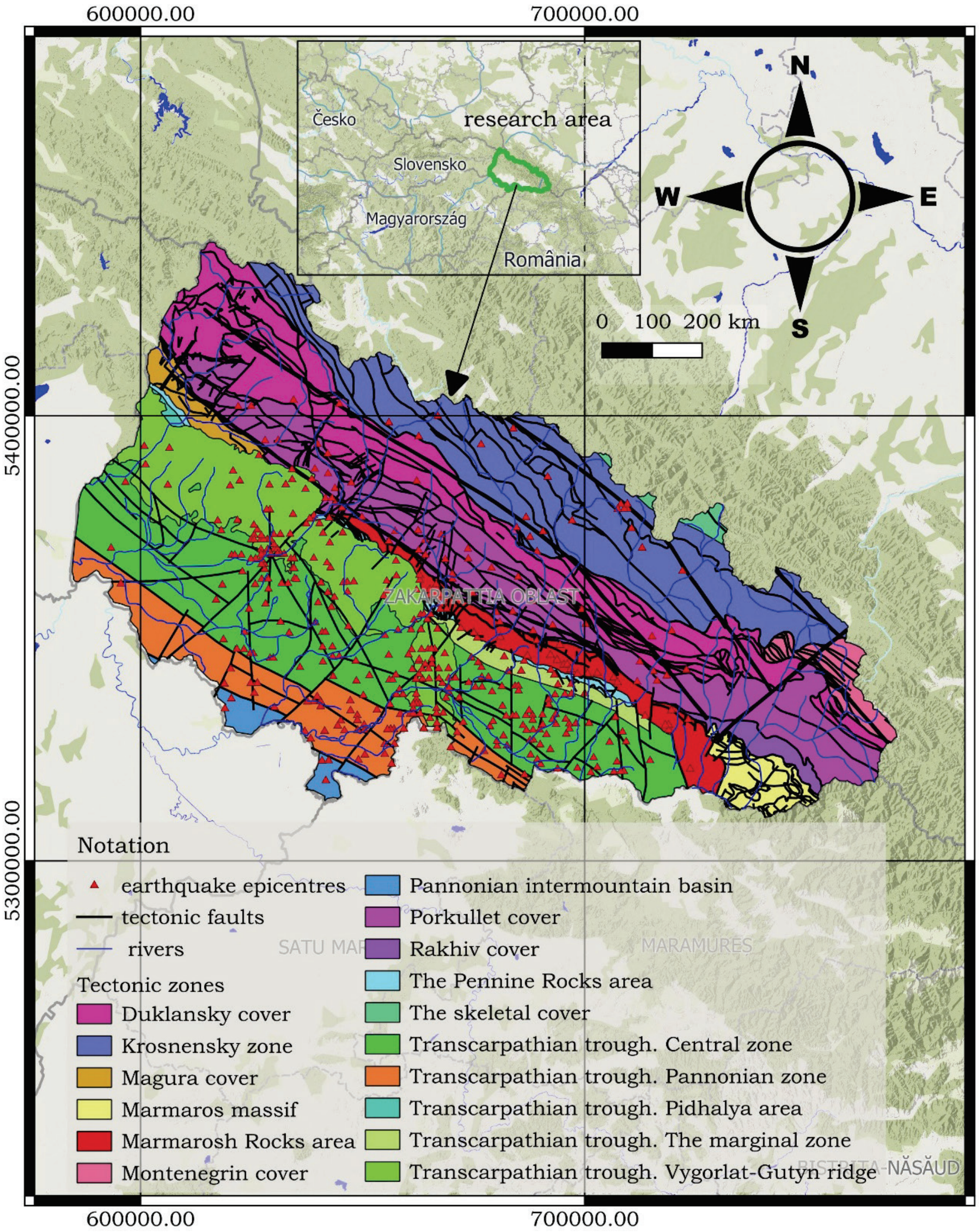

Figure 1 *The tectonic zonation of Transcarpathian region*

In the upper part of the slope, landslides most often occur due to excessive moisture in the rocks from atmospheric precipitation, drainage problems, or loss of stability due to erosion and slope undercutting (natural or man-made). This is where the 'head of the landslide' is mainly formed, from which the sliding begins. The middle part of the slope is an area where soil deformation, cracks and displacement are observed, and landslide bodies are formed. The lower part of the slope acts as a support – when it is deformed due to river erosion and man-made loads, stability is lost, which provokes the activation of the landslide. Particularly dangerous are the areas of the watershed, where there is an accumulation of infiltrated moisture, oversaturation of aquifers, an increase in pore pressure and a decrease in cohesion between particles in water-resistant rocks (clays).

Recent studies demonstrate the effectiveness of using GIS and geostatistics for multifactorial analysis of the interaction of factors affecting landslide activity. The work (Hablovska et al., 2022) proves the connection between geomorphology, river erosion, atmospheric precipitation, and the development of landslides. Based on time series observations and influencing factors, a time model for predicting their probable intensification has been developed. The importance of geological conditions – rock composition, structural features, and fault tectonics – is emphasised in the works (Segoni et al., 2020; Wasowski et al., 2000), and research (Hostiuk et al. 2021) also confirms the strong influence of geological structure and geomorphological features on the susceptibility to landslides in the Pokuttya Carpathians. One of the main aspects of using multiple regression in landslide studies is that this method allows calculating coefficients that show how each factor affects the probability of a landslide while taking other variables into account. For example, studies that take into account factors such as geological conditions, NDVI and soil type (Mandal & Mandal (2018), lithology, slope angles, distance to watercourses and faults, vegetation indices Sun et al. (2018) are key factors in landslide development. Spatial analysis was performed in QGIS, and regression modelling was performed in Statistica. After selecting the factors of landslide development, categorical variables (geomorphology and slope type, lithology of underlying rocks) were transformed into numerical ones. To bring all variables to dimensionless values, the data were normalised.

Results

In order to identify the impact of natural and anthropogenic factors on the intensity of landslide processes, multiple linear regression was applied to data from 1,663 landslides in the Flysch Carpathians region and 662 landslides in the Transcarpathian internal depression. Landslides were the dependent variable, while geomorphological, geological, climatic and seismic parameters were the independent variables. The regression models included statistically significant variables at a level of $p<0.05$, which with high probability describes spatial differences in factors in the studied area.

For the Flish Carpathians, the most significant influence on the development of landslides is exerted by the geomorphological characteristics of slopes – complex slope form (β* = 0.816, β = 546.4) and straight slope (β* = 0.113, β =75. 4), which indicate the instability of the environment. Magnitude (β* = 0.099, β = 66.1), proximity to buildings (β* = 0.073, β = 49.21), lithology (green schist facies) (β* = 0.049, β = 33. 6), convex slopes (β* = 0.060, β = 40.42), overall seismic risk (β* = 0.210, β = 141.0), high absolute elevations (β* = 0.300, β = 200. 9), slope steepness (β* = 0.080, β = 53.5), proximity to a river (β* = 0.061, β = 42.9), landslides predominantly developing on mountain slopes (β* = 0.053, β = 35. 7) western exposure (β* = 0.034, β = 22.7), proximity to faults (β* = 0.037, β = 24.8), proximity to roads (β* = 0.025, β = 16.6). Piedmont (β* = -0.178, β = -118.7) appears to be less prone to landslides. Thus, the regression equation for landslide formation factors will be as follows (1):

$$\begin{aligned} Fl\_C &= 1028.1 + 546.4Compl + 75.4Str + 66.1M + 49.2Dbuild + 33.6Green + 40.4Conv + 141E\_risk + \\ &+ 200.9Abs + 16.6Droads + 35.7M\_sl - 118.7S\_fl + 22.7Asp + 55.4Sl + 27.8Dfaults + 16.6Droads \end{aligned} \quad (1)$$

The following factors contribute significantly to the development of landslides in the Transcarpathian internal depression: complex slope shape (β* = 0.682, β = 395. 9), and andesite-basalt (β* = 0.182, β = 109.0), sandy-clayey marine and lake-delta facies (β* = 0.188, β = 33.6) rocks. Convex-concave (β* = -0.100, β =-58.0) and stepped (β* = -0.106, β = -61.7) slope forms demonstrate increased stability, possibly due to levelling in height differences. Landslides occur more often closer to earthquake epicentres – magnitude (β* = 0.039, β = 22.8), close to faults (β* = 0.037, β = 21.2), close to roads (β* = 0.052, β = 30.4), on eastern slopes (β* = -0.045, β = 26.1). The regression model is as follows (2):

$$\begin{aligned} Transcarp &= 1574.5 + 395.9Compl + 105.7And\_b - 58Conv = conc - 56Driver + 109S - cm + 22.9M - \\ &- 26.1Asp + 30.4Droads + 21.2Dfaults - 61.7Step \end{aligned} \quad (2)$$

Conclusions

Modelling results for the Flysch Carpathians region show that landslide activity increases in conditions of high absolute elevations, active microseismicity, near faults, on morphologically complex, straight slopes, near watercourses, and also when approaching man-made objects (roads, buildings). At the same time, the presence of sandy flysch partially reduces the probability of landslides. The regression model of landslide formation in the Transcarpathian internal trough shows a significant influence of geomorphology – complex slope forms, river erosion and tectonic activity in the region (distance to faults, earthquake magnitude), the lithological composition of rocks (andesite-basalt and sandy-clayey marine and lake-delta facies), and slope cutting during road construction.

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