Utilisation of airborne laser scanning data in landslide hazard assessment – case study Čadca district, Slovakia

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Abstract: The objective of this study was to construct a prognostic landslide hazard map in the Čadca district utilising data obtained from airborne laser scanning of the terrain. In the creation of the predictive map, the input parameters were processed in the QGIS environment. These consisted of a DEM 5.0 (digital elevation model of the fifth generation), a map of engineering geological zoning, a database of slope deformations up to the year 2010, and a derivation of DEM 5.0 to obtain a model of elevation, slope angle, and aspect of slopes. The study presents a predictive map of landslide hazard in the Čadca district, together with a database of slope deformations in the area, created using data from airborne laser scanning. The database was also employed for the purpose of verifying the accuracy of the predictive map. To enable a comparison of the accuracy of the predictive map created based on airborne laser scanning data, a predictive map of landslide hazard was also created based on the register of documented slope deformations in Slovakia.

Key words: landslide hazard, slope deformation, DEM 5.0, forecasting

1. INTRODUCTION

Slope movements are a common geodynamic phenomenon in Slovakia. They occur as a result of both natural influences and anthropogenic activity. These phenomena often result in the destruction of human-made structures, including residential buildings, transportation infrastructure, and other forms of civil engineering. In some cases, they can even endanger human lives. Slope movements are a common phenomenon in Slovakia, particularly in the flysch zone and in neovolcanites, where they are formed in large quantities.

For many decades, geologists have been engaged in research aimed at forecasting landslide hazards, with the objective of anticipating the potential for future slope movements. Consequently, quantitative and qualitative methods were gradually developed, with statistical analysis becoming one of the most prevalent over time. It has been in development since 1960. The greatest development in this field was seen with the advent of geographic information systems, which enabled scientists to efficiently process a large amount of necessary data in statistical files. In Slovakia, the dissertations of Pauditš (2005) and Bednarik (2007) represent some of the most significant contributions to the field of statistical analysis. Other studies that employ statistical analysis include, for example, those Tornyai and Dunčko 2013; Shahabi & Hashim, 2015; Buša et al., 2019; Mersha & Meten, 2020; Azeze, 2021; Roccati et al., 2021; Ye et al., 2022; Zhao et al., 2022; Das et al., 2023, Zvara, 2023; Zvara and Tornyai, 2023, Yang et al., 2023; She et al., 2024.

In the past, statistical analyses in our territory were primarily based on the register of documented slope deformations in Slovakia which is available online on the website of the State Geological Institute of Dionýz Štúr. For the purpose of the digital elevation model, topographic maps were used, in which vectorised contours were employed. However, in 2023, a fifth-generation digital relief model was made available for the entire territory of Slovakia. The model was constructed using data obtained from airborne laser scanning of the terrain surface. The digital relief model exhibits vertical and horizontal accuracy of up to 10 cm. Furthermore, the digital model of the relief allows for the precise determination of the location of morphologically evident slope deformations. This leads to the question of what benefit such technology offers in the context of landslide hazard assessment. To what extent will such forecast maps prove successful, given that their input parameters are based on such precise data? This article will attempt to address these questions.

The territory under investigation is situated in the northwestern region of Slovakia, within the administrative boundaries of the Čadca district (Fig. 1). The area encompasses the cadastral

Fig. 1: Delimitation of the territory within the Slovak Republic

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territories of the city of Čadca and the municipalities of Horelica, Svrčinovec, Čierne, Skalité and Oščadnica. The total area of the territory is 186.42 km^2.

2. METHODS

The study was conducted primarily within the Quantum GIS (QGIS) 3.32.3 software environment, employing multivariate statistical analysis techniques. Our methodology was guided by the diagram depicted in Fig. 2. The multivariate analysis is founded upon the tenet of concurrent utilisation of all input parameters. In the context of multivariate analysis within a GIS environment, the utilisation of both vector and raster graphics is employed. The vector form is employed for the processing of individual input parameters in the form of parametric maps. Subsequently, the vector parametric maps are transformed into raster form for statistical processing via map algebra. When transforming a vector format to a raster format, it is essential to accurately define the geometry of the raster grid. In practice, this entails ensuring that each parametric map contributing to the analysis has the same number of cells and identical cell sizes. Otherwise, the results of the statistical analysis may be unreliable and unusable. In this study, the fundamental grid size of 1 x 1 metres was selected.

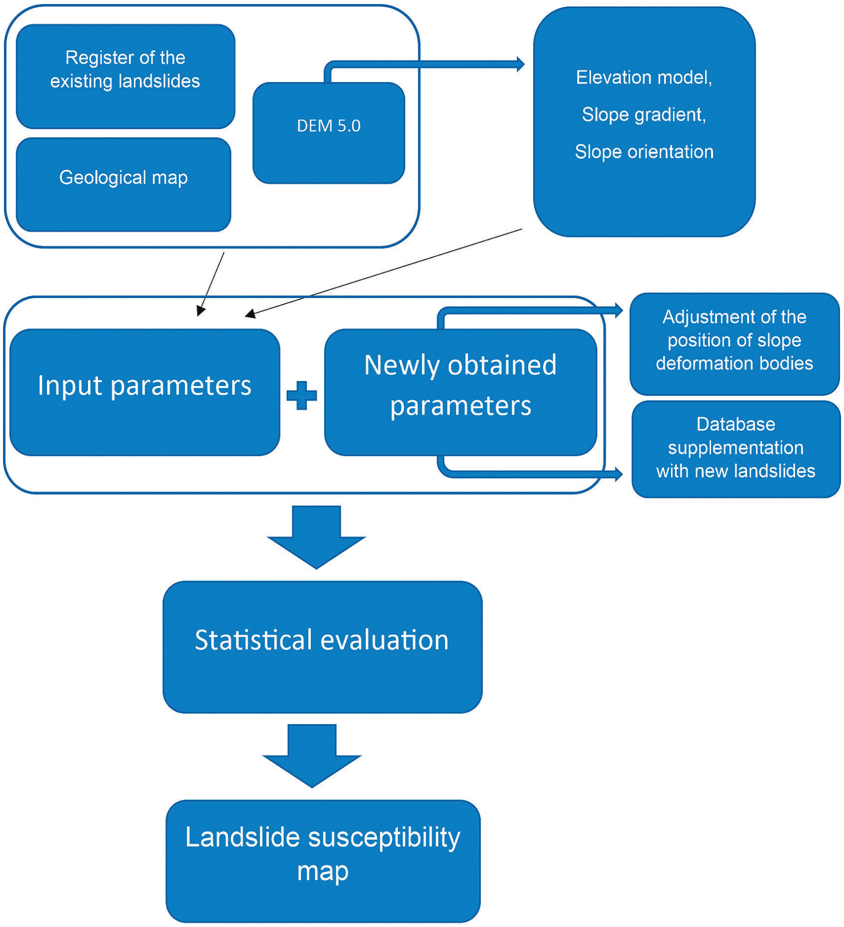

Fig. 2: Methodology of the study

3. INPUT PARAMETERS

The selection of appropriate input parameters is of paramount importance when developing prognostic maps of landslide hazards. Such parameters should be selected in a manner that optimally characterises the factors within the specified area influencing the formation of slope deformations. In Slovakia, numerous authors employ a range of input parameters, including lithology, altitude, slope gradient, slope orientation, slope length, relief curvature, contributing areas, current landscape structure and existing slope deformations, in the creation of forecast maps.

The following parameters were used as input for the creation of the prognostic maps (Fig. 3): Lithology, according to the map of engineering geological zoning (Liščák et al., 2017)(Fig. 3a), digital elevation model, (Fig. 3b), slope gradient (Fig. 3c), slope orientation (aspect) (Fig. 3d) and existing slope deformations. These parameters were selected for their significant influence on the formation of slope deformations. Additionally, the altitude, slope, and orientation of the slopes were obtained, as well as a new register of slope deformations based on the DEM 5.0 base, which allowed for an accuracy of up to 10 cm. Consequently, these parameters exhibited greater accuracy than those used by previous authors.

4. EXISTING SLOPE DEFORMATIONS

In the case of slope deformations, two databases were utilised. One such database is accessible via the website of State Geological Institute of Dionýz Štúr. It contains information on slope deformations that have occurred in Slovakia. A total of 481 slope deformations were recorded in the model area, representing 22.66% of the territory (Fig 4a). We also constructed the second database based on airborne laser scanning data – digital elevation model of fifth generation (DEM 5.0) (Fig 4b). In the process of creating this register, the morphologically visible slope deformations, as observed in the digital relief model, were delineated manually in the vector shape file layer in the form of polygons.

A significant benefit of this approach in slope deformations mapping is that the constructed digital relief model using airborne laser scanning data allows to filter out forest cover. Conversely, however, the precision of such a digital relief model is limited to 10 cm, which ensures that the resulting register of slope deformations is characterised by highly accurate positions (Fig. 5). However, a limitation of this approach is that it only allows the precise identification of morphologically visible slope

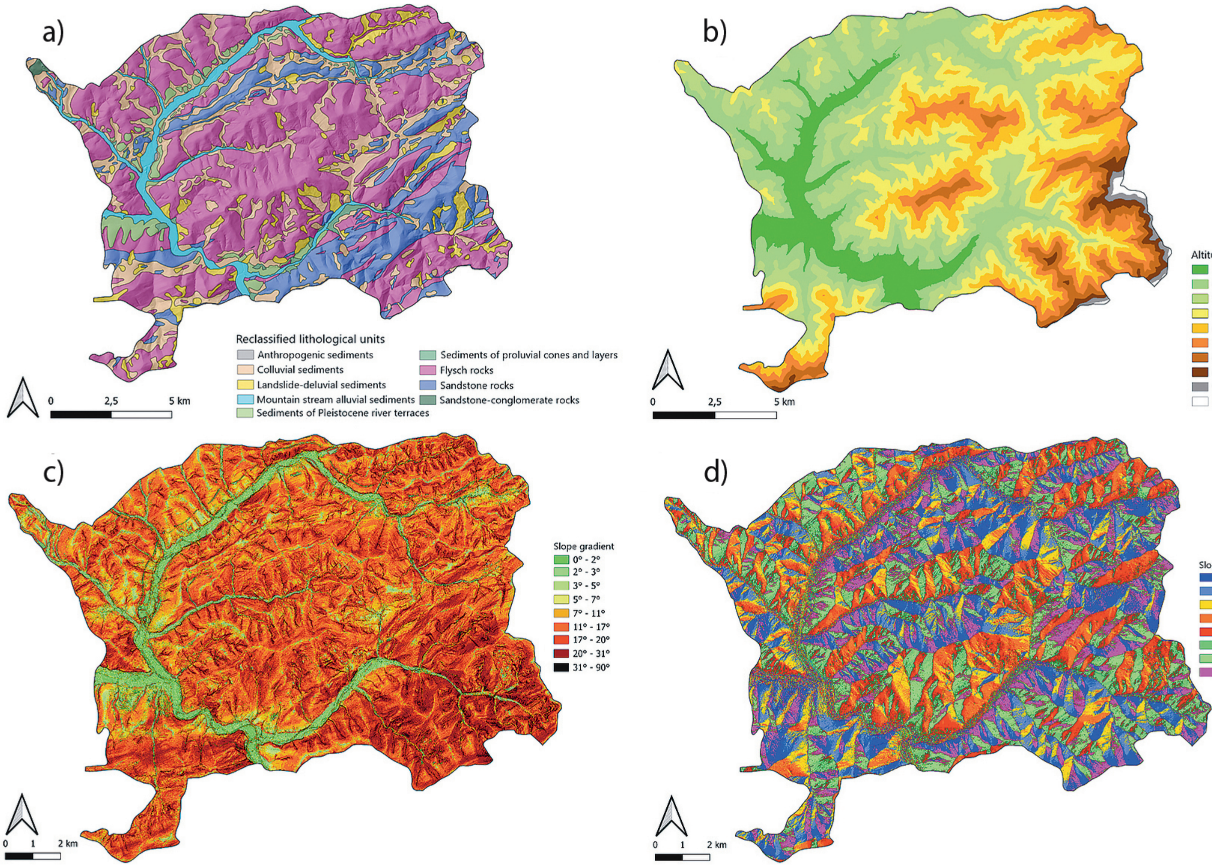

Fig. 3: Input parameters

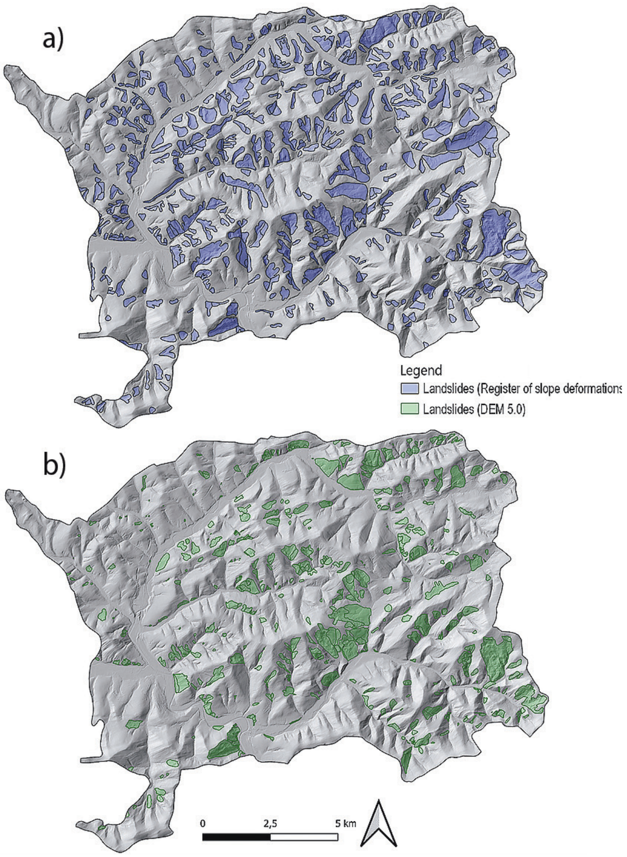

Fig. 4: Comparison of the register of slope deformations (a) with the slope deformations obtained from airborne laser scanning data (b)

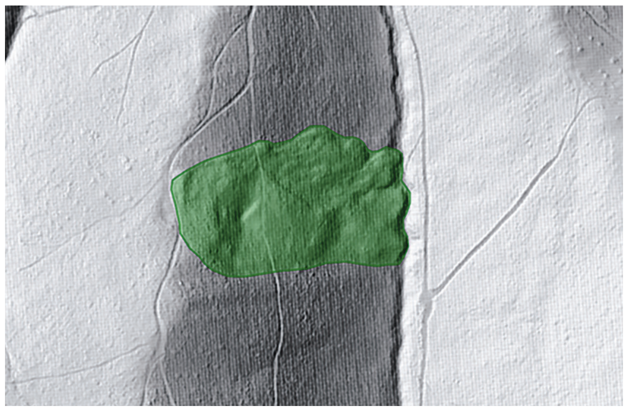

Fig. 5: Example of the precision and reliability of plotting slope deformation on the DEM 5.0

deformations that are captured in the digital relief model. This may be one of the reasons why this slope deformation register has a smaller area coverage. In the case of the landslide register obtained from airborne laser scanning data, the area covered by slope deformations is 10.74%.

5. RESULTS AND DISCUSSION

The outcome of this research is the production of two prognostic landslide hazards maps (PLHM) within the Čadca district. The principal objective of this study was to construct a prognostic map of landslide hazards utilising data obtained from airborne laser scanning (Fig. 6a) and prognostic map of the landslide hazard created using the register of documented slope deformations in Slovakia (Fig. 6b) for the purpose of comparison. In both cases, multivariate statistical analysis was employed, with the input parameters of lithology - represented by a map of engineering geological zoning, altitude, slope gradient, slope orientation (aspect) and register of existing slope deformations. Subsequently, quantile classification was employed to reclassify the territory into grades following the creation of both forecast maps into 5 classes (1 -very low, 2 - low, 3 - medium, 4 - high, 5 - very high). The comprehensive distribution of the discrete levels of prognostic landslide hazards map, which was created based on revised slope deformations from DEM 5.0 (PLHM-1) and the prognostic landslide hazard map from the register of documented slope deformations in Slovakia (PLHM -2), can be seen in tabular form 1.

Tab.1: Area distribution of the individual levels of landslide hazard of the calculated prognostic maps

Hazard class	Area PLHM-1 [km^2]	Area PLHM -1 [%]	Area PLHM -2 [km^2]	Area PLHM -2 [%]
1	32.97	17.69	36.75	19.72
2	42.09	22.59	37.17	19.95
3	38.48	20.65	38.69	20.76
4	37.21	19.97	36.16	19.40
5	35.59	19.10	37.59	20.17
Total	186.42	100	186.42	100

found to be 64.20%. Nevertheless, when the medium level of landslide hazard threat (level 3) was taken into account during the verification of the forecast map, the success of the map created on the basis of airborne laser scanning data reached 93.28%. In the case of the forecast map created on the basis of the register of documented slope deformations in Slovakia, the success rate was 82.76%. However, in both cases, the success of the forecast map created based on airborne laser scanning data was considerably higher.

6. CONCLUSION

In the past, statistical analyses in our territory were based on the creation of forecast landslide maps derived from the register of documented slope deformations in Slovakia, which is recorded in the register of documented slope deformations in Slovakia. In the past, numerous parameters were also derived from the digital relief model, which was obtained from the contour lines of topographic maps. In this study, however, numerous input parameters, including the register of slope deformations, were derived from the fifth-generation digital relief model. This model was created based on airborne laser scanning data. It achieves high accuracy, with a precision of up to 10 cm in both the horizontal and vertical directions. As a result, we were able to work with data of a considerably higher accuracy than was previously possible. To evaluate the efficacy of the forecast map derived from the register of

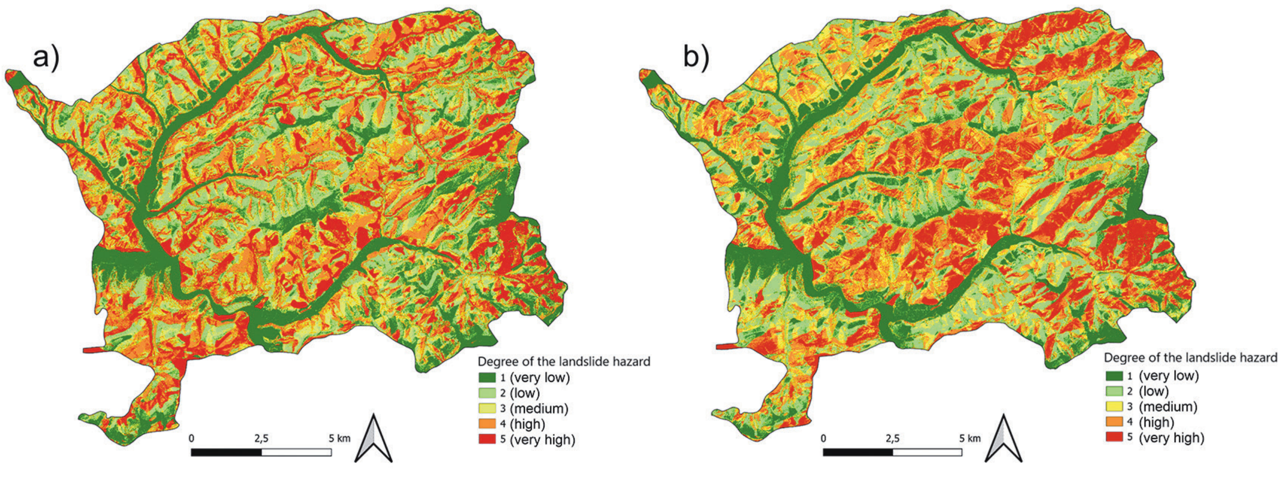

Fig 6: **Prognostic landslide hazard maps (a – compiled from the data of the register of documented slope deformations in Slovakia; b – compiled from DEM 5.0)**

The success rate of the forecast maps was calculated in percentages by summing the density of slope deformations in the high (level 4) and very high (level 5) degrees of the landslide hazard. With regard to prognostic landslide hazard map created on the basis of airborne laser scanning data, the success of this map was found to be 81.44%. In the case of the forecast map of landslide hazard created based on the register of documented slope deformations in Slovakia, the success of this map was

slope deformations obtained from DMR 5.0, a second forecast map was constructed using the online register (The register of documented slope deformations in Slovakia). To evaluate the effectiveness of the prediction map derived from the DEM 5.0 slope deformations, a second prediction map was created using the Register of Documented Slope Deformations in Slovakia. The success rate of the landslide hazard forecast map, created from the new register of slope deformations obtained from airborne laser scanning data, was found to be significantly higher (81.44%) than that of the forecast map created based on the old register (64.20%).

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