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LANDSLIDE HAZARD PREDICTION OF KRAKÓW CITY USING ARTIFICIAL NEURAL NETWORKS AND GEOSTATISTICAL METHODS

SUMMARY

The main aim of the study was to quantify the landslide hazard (H, understood as the probability of a landslide occurrence within a specified period of time and a given place) in Kraków city using statistical methods based on the geographic information systems tools and present it in the form of a map. For the purpose of this task, first an attempt was made to identify landslides that were active in the years 1969 – 2019. These results were used as input data to create a time probability prediction model of the occurrence of landslides in the future (TP). This model, which is a time component of the landslide hazard equation, was prepared using geostatistical methods. A landslide susceptibility (LS), which is a spatial component of the equation, was developed using artificial neural networks. Finally, both components were multiplied with each other to obtain a surface representing the landslide hazard, which was applied to a specially prepared topographic map in the scale of 1: 25 000.

Krakow is located in the area of 4 main tectonic units: the Outer Carpathians on the south (podśląska unit), the Carpathian Foredeep, covering most of the city area and its Mesozoic base represented by the Śląsko–Krakowska Monocline in the western and north-western parts and a fragment of the Miechów Trough in the northern part. This causes the diversification of the topography and directly determines the occurrence and types of landslides. In Kraków 369 landslides have been documented in Kraków so far. Most of them (168) occur in the southern part of the city in Swoszowice, Zbydniowice, Wróblowice, Rajsko, Kosocice i Soboniowice regions (X district). They are directly related to the Carpathian overthrust zone. The predominance of shale-marly facies within the podśląska unit and the tectonic disturbances of the allochthonous miocene (Zgłobice unit), combined with the morphological conditions of the area, favor the formation of mass movements. A large concentration of landslides (67) is also in the area of the Las Wolski horst (district VII). This is, among other, related to the presence of gulfs filled with Miocene clays that reach the higher parts of the horst.

Mass movements in Krakow have been the subject of research for over 60 years. The first systematic registration was carried out in 1969 – 1970, the second in 2005 – 2007.

The intense rainfall lasting from May to August 2010 led to the activation of many landslides, which resulted in the occurrence of numerous damage or destruction of buildings and infrastructure. As a result of these events, the third registration of landslides was carried out in 2011-2012. The last update was done in 2018.

To identify landslides showing activity in the period 1969 – 2019 the data from airborne laser scanning from November 2006 and July 2012 were used. The former required prior filtering and classification. Based on these data, numerical terrain models and differential models were generated. As a result of the conducted analyzes, 65 additional landslides were identified, which were not marked in the existing registers. Differential models allowed to identify 111 landslides that were active in the years 2006 – 2012. In 53 cases, activity was found to be related to the occurrence of uncontrolled embankments within colluvias or in the immediate vicinity of the main scarp. The conducted research was supplemented with analyzes of archival materials (orthophotomaps from 1970 – 2019, landslide registers, landslide documentation cards, publications). Ultimately, it was found that out of 434 landslides, 234 were active between 1969 and 2019, of which 89 were related to the occurrence of uncontrolled embankments. The greatest number of activated landslides was found in the southern part of the city in the areas of Swoszowice, Zbydniowice, Wróblowice, Rajsko, Kosocice and Soboniowice (district X).

When comparing the obtained results spatially, it was noticed that the distance between landslides and their activity were related. This provided the basis for the application of geostatistical methods to determine the probability of landslide occurrence in the future. The technique of area binomial kriging was implemented, which is based on simple kriging and uses discrete count data for calculations. In the research area, a polygonal mesh with dimensions of 500 x 500 m was created, which was then reduced to the areas of landslides. For each polygon, the number of landslides and the number of units showing activity in the years 1969 – 2019 were determined. The prepared layer was used in the *Geostatistical Wizard* (*ArcGIS*) module to construct a predictive model. As a result, an area representing the probability of a landslide occurrence in the next 50 years was obtained (*LS*). A good fit to the input data was obtained, however, in several regions (Podgórze, Bronowice Wielkie) the obtained probability values seem slightly overestimated in the regional context.

Due to the differentiation of landslides in the study area, a multi-layer perceptron belonging to the non-linear, feed forward and supervised artificial neural networks class was

used to determine the susceptibility of landslides. The calculations were performed in the *r.landslide* module. The network learning was carried out on the basis of 8 thematic layers (slopes, slopes exposure, absolute height, relative height, convergence index, surface lithology, subquaternary lithology, distance from tectonic discontinuities). For modelling, 434 points representing landslides and the same number of points with locations without landslides were used. From the set of points, 70% was allocated to the training phase, and to the validation and test phase 15% for each. In order to assess the network performance, based on the results of the test phase, an error matrix with the calculation of basic statistical measures and ROC analysis were made.

Approximately 22% of the city's area are susceptible to landslides occurrence ($LS > 0{,}05$). They overlap with landslides and cover areas where they have not occurred yet. The greatest number of areas susceptible to landslides occurrence is located in districts X (54% of the district area) and VII (47%). There are the most susceptible areas also ($LS > 0{,}95$). The sensitivity analysis implemented in the module showed that among the thematic layers used for modelling the slopes, convergence index, distance from tectonic discontinuities and the subquaternary lithology have the greatest impact on the landslide susceptibility. In the first case, a significant increase of susceptibility was observed in the range 3–13°. Concave and straight slopes are the most susceptible. The farther from faults and overhangs, the susceptibility decreases. From the lithological point of view, the most predisposed to mass movements are a tectonically disturbed clay-sand deposits of the allochthonous Miocene, węglowieckie red marls, red shales, as well as gaize beds and upper Cieszyn beds.

By multiplying both components (TP i LS), the surface representing a landslide hazard was obtained. About 11% of Kraków area is covered by areas where the probability of a landslide occurrence in the years 2020 – 2070 exceeds the value of 0,2. The greatest hazard occurs in the south of the city, in the eastern part of district X, where 11% of its area is covered by areas with $H > 0{,}6$. High hazard values were also determined for the Las Libertowski area and locally within the districts IX, XI, XII and XIII. The high probability of a landslide occurrence ($H = 0{,}4 - 0{,}6$) was estimated for the area of Zesławice.

The conducted research has shown that numerical terrain models and differential models are an effective tool for identifying landslides and objectively assessing their activity, but only in conjunction with field studies, other remote methods and an in-depth analysis of archival materials, they give the best results. Uncontrolled embankments deposited within

colluvias or directly at the borders of landslides (especially in the areas of main scarps) are a disadvantageous factor and additionally contribute to their activation. Geostatistical methods may lead to local overestimation of the value of time probability in the areas of scattered landslides, constituting single occurrences unrelated to the natural predispositions of a given area to the formation of mass movements. In turn, artificial neural networks are useful in determining the landslide susceptibility in areas with complex geological structure and land relief with various types of landslides.