Geo-Informational Approach to Risk Analysis of Slope Mass Movement

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Abstract

The assessment of the development of dangerous erosion and slope mass movement processes has been done for the territory around Verhnie Vodiane and Solotvyno area (Transcarpathian region, Ukraine). The risk analysis has been carried out with reliance on the evaluation of meteorological and geomorphological factors. Remote sensing data have been processed using a geoinformation system and a database of indicators such as slope steepness and Normalized Difference Moisture Index (NDMI).

The risk matrix for analyzing slope mass movement was constructed. Risk gradation was assessed as the percentage of recorded landslide areas with different ranges of meteorological and geomorphological factors.

The indicator values with extreme risk of dangerous processes were determined.

It is shown that with an increase in the angle of slope steepness, a simultaneous increase in the NDMI value indicates the possible development of landslides. The risk matrix obtained can be used to predict the slope prone to mass movement for areas with a steepness of 5°40' to 24° and geological (lithological) conditions similar to Quaternary deposits of alluvial, deluvial, eluvial-deluvial and deluvial-colluvial genesis.

Keywords

Risk analysis, GIS techniques, landslides, slope steepness, moisture index.

1. Introduction

Hazardous exogenous geological processes occurring on the slopes of river valleys, ravines and gullies, mountain slopes and sea coasts in abnormal weather conditions (showers, snowfalls / snowmelt, floods, storms) can be destructive, they threaten the lives and activities of people, agriculture, create the risks of emergencies. The patterns of slope mass movement and erosion

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depend on geological, geomorphological, hydrogeological, meteorological, hydrological, seismic, neotectonic etc. natural conditions and anthropogenic activity as well.

Nowadays abnormal rains and prolonged droughts are observed in areas where they are not typical [1]. Climate change, namely the redistribution of heat and moisture, humidity conditions, affect the soil. Insufficient moisture or waterlogging of the soil leads to water or wind erosion. Slope soil saturation by water of intense rainfall, snowmelt leads to change in groundwater levels. An increase in the recharge of the groundwater aquifer and moistening of clay, sandy, sandy loam soils of the aeration zone are additional factors of the activation of existing landslides and the formation of new ones. Assessment of the slope stability in the work [2] showed that the value of the stability coefficient decreases from 1.7 to 0.9, while assessing excessive moisture. Consequently, moisture accumulation due to infiltration of atmospheric precipitation is one of the main factors for the loss of slope stability and landslides formation.

The aim of the research is to assess the risks of landslide occurrence by analyzing meteorological and geomorphological factors, i.e., slope instability depending on the moisture content in the upper soil layers and on the slope steepness.

In general, risk is understood as the danger of possible future losses, or the danger of adverse consequences of an event, identifying the risk with the danger, a dangerous process. Risk assessment is carried out at different levels from the national to the object one, including the concept of multi-risk (integral value), the cascade-like development of hazardous processes and risk matrices [3-5]. In this paper, by the risk of hazardous geological processes, we mean a set of meteorological and geological factors with the gradation of the values at which the process can be realized.

The study area is in the Transcarpathian region (Ukraine), around Verhnie Vodiane and Solotvyno townships.

The study area belongs to the low-mountain flat of the Solotvynska depression. The area is characterized by the development of dangerous mass movement processes (landslides) in Quaternary deposits of alluvial, deluvial, eluvial-deluvial and deluvial-colluvial genesis in southern part and Neogene deposits in the south-eastern part of Solotvynska depression. Within the study area, 15 ancient landslides with a total area of 0.5 sq. km have been mapped; landslides occur on slopes with angles of 4-28°, but most of them are typical on slopes with steepness of 8-20° [6-8].

2. Related works

The landslide study and measures for slopes stabilization on the territory of the Transcarpathian region, around Verhnie Vodiane and Solotvyno area were carried out and described in reports and papers by Barnichka V.Yu., Gabor M.M., Shekhunova S.B., Yakovlev E.O. and others. Database and landslide inventory map, relief horizontals, the tectonic disturbance map for Transcarpathian region were published in [7, 8].

The construction of digital model of terrain with using radar images was presented in a number of papers [9-12 etc.]. The ALOS World 3D, ASTER Global DEM, and SRTM-30 m are Digital Elevation Models (DEMs) that have a horizontal resolution from 30-m (1 arcsec mesh) to 12-m (0.4 arcsec mesh) and almost global coverage and are available to the general public free of charge. Among them the vertical accuracy of the ALOS World 3D was found to be the most accurate, especially under different land cover types and at various points throughout the world [9, 10]. This DEM has the lowest mean error, root mean square error and standard deviation. Regional studies of fluvial landforms and mountain landscapes with use satellite-derived DEM data sets showed the best representation of ALOS World 3D data for the geomorphological analysis in mountain areas [11]. All authors notice that it also contains a widespread elevation anomaly. This anomaly does not affect the research results, since in the present work, not the absolute value of the height was assessed, but the angle of the slope inclination.

Soil moisture and its estimation as a hydrologic variable and essential climate change factor were discussed in several works [2, 13, 14]. The knowledge of soil moisture at large scale, with reasonable temporal and spatial resolution, is required to improve hydrologic and climatic modeling and prediction. Remote sensing data are used to collect and analyze geospatial data on the moisture content of the first soil layers from the surface.

The ERDAS IMAGINE image processing method by using the LANDSAT 8 band 3 (Green), band 4 (Red), band 5 (NIR), band 6 (SWIR), and band 10 (TIR) data for determining various spectral indices was described in works [15, 16]. The LANDSAT 8 imagery with used of Arc GIS soft-ware depicts a band combination for visualize land/water differentiation sharply. Calculation of Normalised Difference Vegetation Index (NDVI), Normalised Difference Water Index (NDWI) and Normalised Difference Moisture Index (NDMI) allow to identify differently land and water by moisture content, considering band variations of different multi-spectral images. NDMI index is often used synonymously with the NDWI index, with using near-infrared radiation and shortwave infrared reflection combination as one of the two options [16]. Difference between them is that NDMI manifest water content of leaves, but NDWI – water content of water bodies. In our research, it was accepted to use the NDMI index as an indicator of abnormal rains, as the higher distribution of the rainfall leads the higher possibilities of the landslide occurrences.

3. Materials and methods

Remote sensing data processing was performed in ArcGis 9.3. Satellite images were downloaded from electronic resources EarthExplorer, Vertex, Coordinate projection – WGS 1984. All the satellite data are re-projected to a Universal Transverse Mercator (UTM) coordinate system, (datum WGS84, zone 34N). Interferometric radar images (ALOS-PALSAR radar systems) were used for analyzing the geomorphological factors. The elevation discreteness of the images is 1 m, spatial resolution – 12.5×12.5 m.

An image of the Landsat 8 satellite mission equipped with multispectral and thematic scanners (Operational Land Imager, Thematic Mapper and Thermal Infrared Sensor) was used to determine the values of the NDMI index. Cloudiness of images is less than 10 %, spatial resolution – 30×30 m.

The square-wise assessment method [12] was used to analyze the recorded landslides in the study area, followed by their comparison with the values of meteorological and geomorphological factors. A grid with a set of single squares (the side size of 12.5 m) was created for the test site.

The risk analysis of erosion occurrence and mass movement processes, determining the values of the factor indicators considered were obtained relying on the matrix principle. Risk gradation was assessed by the percentage of the recorded landslide areas with different range of climatic and geomorphological factors. Both factors were divided into five ranges. The area (in %) occupied by each combination of factors was estimated. The conditions for which the area of distribution was more than 5% were taken into account.

4. Obtained results

4.1. Calculation of the normalized moisture index

The assessment of moisture content according to remote sensing data was carried out indirectly through the calculation of the Normalized Difference Moisture Index (NDMI), according to Landsat8 data.

NDMI was used to determine the moisture content in vegetation. It was calculated as the ratio between the values of near-infrared radiation (NIR – band 5, Landsat 8) and shortwave infrared reflection (SWIR – band 6, Landsat 8) [16]:

$$NDMI = \frac{(NIR-SWIR)}{(NIR+SWIR)}. \tag{1}$$

The index can take values from -1 to +1. Positive values characterize the areas with varying degrees of moisture content. The distribution of NDMI index values is shown in Figure 1.

The NDWI classification has been divided into five classes. The classes of low values of NDMI are in between -0.63 to 0.12, moderate value is in between 0.12 to 0.16, the high value of NDMI is in between 0.16 to 0.24 and the extreme value is more than 0.24.

The index of moisture content could be related to the rainfall amount, which is as known one of the triggering factors for landslides. The total average annual precipitation of the research territory in the lowland is 600-800 mm, and in the mountains – 1000-1500 mm. There are years of high water, when 1600-2400 mm falls within the year with an average long-term rate of 1000-1200 mm.

If the rainfall amounts increase, that means the value of the NDMI will be also increasing. Areas with the high or extreme value of NDMI are potential places of the landslides. Up to 65.5 % of the study area is characterized by such values.

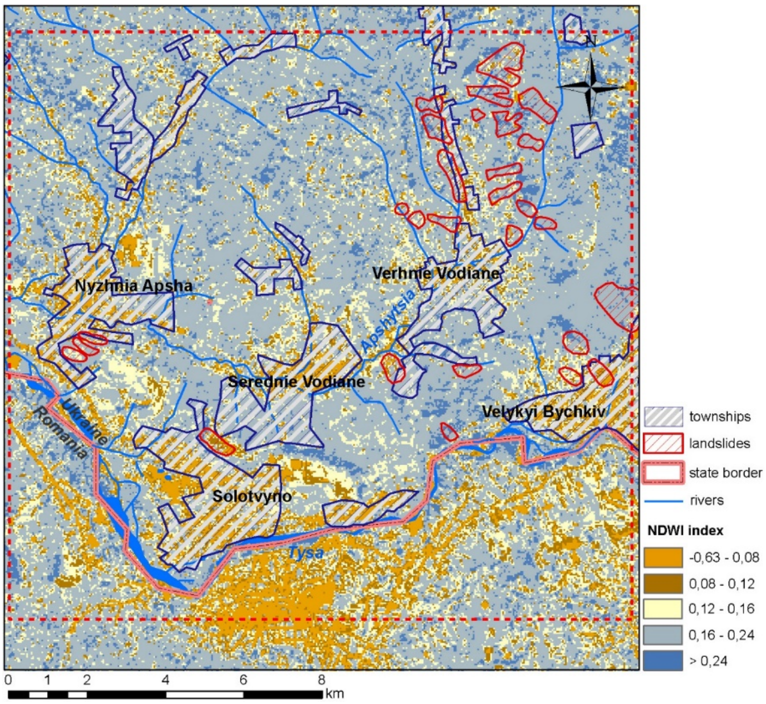

Figure 1: Distribution of NDMI index values

4.2. Geomorphological factor

The study area is located within the Tisza and Apshytsia rivers, in the southeast of the Transcarpathia. It is characterized by low-mountain relief and tectonically belongs to the Solotvynska depression [6, 8]. An altitude terrain ranging from 30 to 570 m above sea level. The slopes are characterized by steepness of 10-20° in the lower and middle parts, and steepness of up to 30-40° in the upper ones [7].

Besides the humidification regime, the geology (type of soil, lithology, thickness of layers), relief and slope steepness influence the development of hazardous geological processes (erosion, landslides). Loose sandy-clay soils in areas with the slopes of up to 5°40' (10 %) practically do not experience movements in bulk and at speeds that can pose a threat to objects/facilities and people [17]. At surface inclinations from 5°40' to 11°20' (10-20 %), deformations and displacements of clay soils at moisture-induced changes of their consistence from firm to plastic and fluid-plastic are possible. Such changes occur due to humidification from the surface by atmospheric precipitation, man-made leaks or as a result of rising groundwater levels.

Surface steepness was estimated by means of the ArcGIS "Slope". For each cell of the digital relief model (obtained by processing of satellite radar images), the "Slope" tool calculates the maximum degree of change in the value of height *z* between the cell and its neighbors [18]. The "Slope" determines the degree of surface change in the horizontal (*dz/dx*) and vertical (*dz/dy*) directions relative to the central cell. The calculation of the slope (deg) is performed automatically by the expression:

$$\alpha = \arctan\left(\sqrt{((dz/dx)^2 + (dz/dy)^2)}\right) \cdot \frac{180}{\pi}. \quad (2)$$

The results of slope steepness values in the study area are presented in Figure 2.

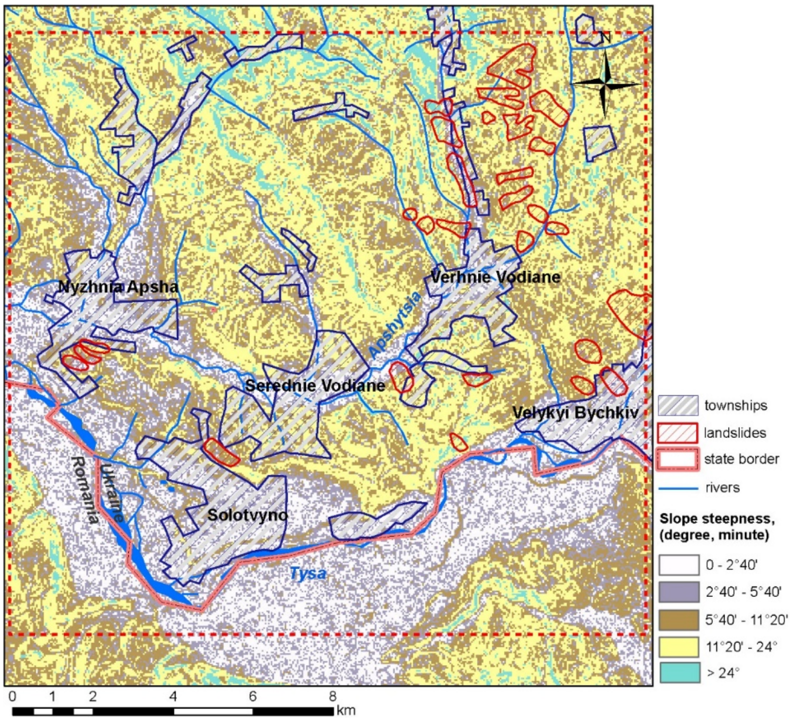

Figure 2: Slope steepness values on study area

The slope steepness classification has been divided into five classes according to the plucked out limit values. The most critical for the formation of landslides are the classes with values from 5°40' to 11°20', which is 24.5 % of the area and the class of values from 11°20' to 24° – 34.6 %. In general, 12.4 % of the study area has an angle of inclination of more than 18°, which, according to the work [2], is a critical value for slopes consisting of fluvial-glacial soils.

4.3. Risk matrix of landslide development

Using the geographic information system for the areas with landslides (see Fig. 1-2), data were selected from remote images of various missions. The percentage of areas with different sets of values for the "Slope steepness" indicator and NDMI index were calculated. The risk analysis carried out on the basis of meteorological – atmospheric precipitation (NDMI) and geomorphological (Slope steepness) factors are presented in Figure 3.

		Normalized Difference Moisture Index				
		-0.63 – 0.08	0.081 – 0.12	0.121 – 0.16	0.161 – 0.24	> 0.24
Slope steepness	0-2°40'	1,58	1,36	1,57	2,57	0,11
	2°40'-5°40'	1,63	2,11	2,92	**5,77**	0,56
	5°40'-11°20'	1,40	2,53	**5,09**	**19,21**	2,58
	11°20'-24°	0,85	1,57	4,79	**32,95**	**5,08**
	> 24°	0,00	0,02	0,17	3,06	0,50

Risk

Low Medium High Extreme

Figure 3: Risk matrix of landslide in terms of meteorological and geomorphological factors, cell areas (%)

The conditions considered as the most dangerous (Extreme Risk) are those with the values of parameters in terms of meteorological and geomorphological factors, whose area is more than 5 %. They are as follows:

- Slope steepness from 5°40' to 11°20' and NDMI is from 0.12 to 0.24;
- Slope steepness from 11°20' to 24° and NDMI is from 0.16 to 0.24 and more.

The low percentage of areas for dangerous values of slopes and humidity is explained by the lack of the sets of such conditions in the study area.

5. Conclusions

Abnormal rains and prolonged droughts activate hazardous exogenous geological processes nowadays. Risk analysis of slope mass movement were proposed relaying on analysis meteorological and geomorphological factors with geo-informational approach. The assessment of landslide occurrence has been done for the territory Verhnie Vodiane and Solotvyno townships (Transcarpathian region, Ukraine) for the first time.

The square-wise assessment method, statistical methods and the matrix principle were used for the test site. Geomorphological and remote sensing data have been processed using ArcGis 9.3.

As the result, the most dangerous values (Extreme Risk) of parameters meteorological and geomorphological factors are slope steepness from 5°40' to 11°20' and NDMI is from 0.12 to 0.24; slope steepness from 11°20' to 24° and NDMI is from 0.16 to 0.24 and more.

The climatic factor directly affects erosion processes due to the amount and the mode of precipitation. The geomorphological factor largely determines the development of mass movement processes on the slopes and the intensity of erosion, since the relief affects the speed and strength of water flows, their concentration in individual areas and linear natural boundaries.

Comparison of the respective values of these factors, taking into account the geological structure, will allow the identification of areas with a high risk of the occurrence of hazardous exogenous geological processes (landslides).

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