Jr. of Industrial Pollution Control 33(1)(2017) pp 968-975
www.icontrolpollution.com
Research

ASSESSMENT METHODOLOGY FOR LANDSLIDE HAZARD IN LAND MANAGEMENT BASED ON GEOINFORMATIONAL SYSTEMS UPON GEODETIC DATA

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(Received 29 May, 2017; accepted 04 June, 2017)

Key words: GIS, Zoning, Landslide process, Digital map, Geodetic informational support

ABSTRACT

This article presents the results of studying the possibilities of applying geoinformational systems when studying landslide processes. A method for quantitative regional forecast of landslide hazards has been given, developed by Gulakyan, Kuntsel, and Postoyev. It was used as a basis to make up an assessment algorithm for landslide hazard by applying geoinformational systems (GISes) that were successfully tested when studying landslide-hazardous slopes of the Psehako ridge (the Krasnodar territory, Russia). Primary study stages were described, such as determining landslide formation factors and their relevance, geodetic informational support of the methodology, compiling an ArcGIS database for GIS analysis, calculating primary process parameters, preparing a landslide hazard map and assessing the efficiency of the suggested algorithm. As a geodetic basis, it is suggested to use a digital terrain model developed by using aerial laser scanning data.

INTRODUCTION

Due to no free areas, modern construction of engineering structures frequently takes place on landsliding slopes, which results in activation of old landslides and development of new landslide formations. The negative impact of landslide processes is widely known. In addition, it is possible to avoid or minimize any landslide damage by studying the area well in advance and selecting a safe site for construction based on the landslide hazard map.

Revealing landslide-hazardous areas and preparing the landslide hazard map is based on various methodological approaches (Moradi, *et al.*, 2012; Flentje, *et al.*, 2007; Calvello, *et al.*, 2013; Cascini, *et al.*, 2005). The geodynamic potential method is widely applied in practice (Gulakyan, *et al.*, 1977) to determine the degree of possible landslide susceptibility in each point of the area. This method is based on calculating the landslide potential for various classes of landslide formation factors and preparing a landslide forecast map by zoning using the values of this potential. To do it, the entire range of calculated geodynamic potential values is divided into a specific number of intervals, and those sections that fall within one of the intervals are combined into the areas of various degree of landslide susceptibility. The accuracy of this analysis depends on the completeness and accuracy of the initial information.

Russian regulatory documents (Methodological Recommendations to Engineering and Geological Surveys of Landslide Hazardous Slopes and Slants of Motorways, 2013; SP 116.13330.2012, 2012) suggest using computer technologies to study and process information on landslide-hazardous areas. The primary information for regional methods of studying landslide-hazardous areas is suggested to be obtained from topographic, geological-engineering, hydrogeological and other maps and plans scaled at 1:2,000 to 1:200,000 (Fell, *et al.*, 2008). Furthermore, remote sensing data are used (Kartic Kumar, *et al.*, 2013). Therefore, it is convenient to analyze a large amount of various information necessary for such a study in the GIS environment.

METHODS

The assessment of landslide hazard was studied by

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using a complex of interrelated methods:

- Studying regulatory and methodological documentation governing topographical and geological engineering surveys on landslide-hazardous ridges and analyzing technical literature to summarize data concerning previous studies in this connection;

– Collecting and analyzing mapping materials for the study area in order to reveal landslide-forming factors;

– Mapping (geoinformation) modeling of landslide-forming factors;

– Statistical analysis of obtained results in order to compile a zoning map of the area under study according to its landslide potential.

THEORETICAL AND EXPERIMENTAL STUDIES

The landslide potential calculation and preparing a forecast map is done in several stages (Gulakyan, *et al*., 1977).

1. Building a landslide propagation map by landslide types based on the analysis of initial materials (individually for each landslide type or overall).

2. Dividing landslide formation factors into classes. For each class, distribution bar charts for its values within the area under study are built. The number of classes is defined taking into account extreme points on the distribution curves.

3. Building analytical maps of class distribution for individual factors. For example, zoning maps and schemes: for lithological and petrological composition, depth of deposits, groundwater levels, abundance of groundwater, steepness and exposure of slopes, total annular atmospheric precipitation, etc.

4. Calculation of specific resistance of revealed factor classes (for small-scale maps when respective landslide area can't be shown).

5. Determining the probability of landslide occurrence. Occurrence probability p_{ji} or activation probability within the area of the i-th class of factor B_j is defined as a ratio between the landslide area within class N_{lsji} and the area of the entire classes under the following formula:

$$p_{ij} = p\left(\frac{A}{N_{ij}}\right) = \frac{N_{\mathrm{ls}\,ij}}{N_{ij}}. \quad (1)$$

6. Assessing the impact of individual factors onto landslide development. To assess the degree of impact of factors onto the landslide process, it is required to calculate the weighted coefficient V_j determined through the following expression:

$$V_j = I_j \times p_j \quad (2)$$

where I_j=informational coefficient as proposed by Vistelius that shows the degree of the factor impact on the landslide formation; p_j=standardized probability of occurrence or activation probability for j-factor classes.

The Vistelius coefficient (I_j) is determined from the entropy values (H) that show the degree of the system's uncertainty:

$$I_j = \frac{(H_{\max} - H_j)}{H_{\max}} \quad (3)$$

where H_j=entropy of the j-th factor;

$$H_{\max} = \log S \quad (4)$$

where S=the number of classes.

H_j is determined under the formula:

$$H_j = -\sum\left(p_{ji}\right)\times\log\left(p_{ji}\right) \quad (5)$$

7. Landslide potential calculation. Respective resulting probability (landslide potential) W_{ls} of occurrence or activation for the considered landslide type for each area where various classes intersect is defined as a probability of the sum of finite number of events with an allowance for factors' independence:

$$W_{\mathrm{ls}} = 1 - \prod_{k-1}^{m}\left(1 - p_k\right) \quad (6)$$

where п=multiplication sign; p_k=probability p_{ji} in the aggregate of m classes of various factors of specific combination of the above value.

8. Building a zoning map by using landslide potential values.

The number of zones distinguished in the zoning map is defined as 4 or 5 a priori. Example: 1) Area with very low probability of landslide occurrence of activation; 2) area with low probability, etc.

Initial information can be processed and the landslide hazard forecast map can be compiled by using standard GIS provisions that allow efficiently processing and interpreting huge arrays of digital data, which is achieved by creating and using the cartography model system.

The zoning map compilation procedure for landslide

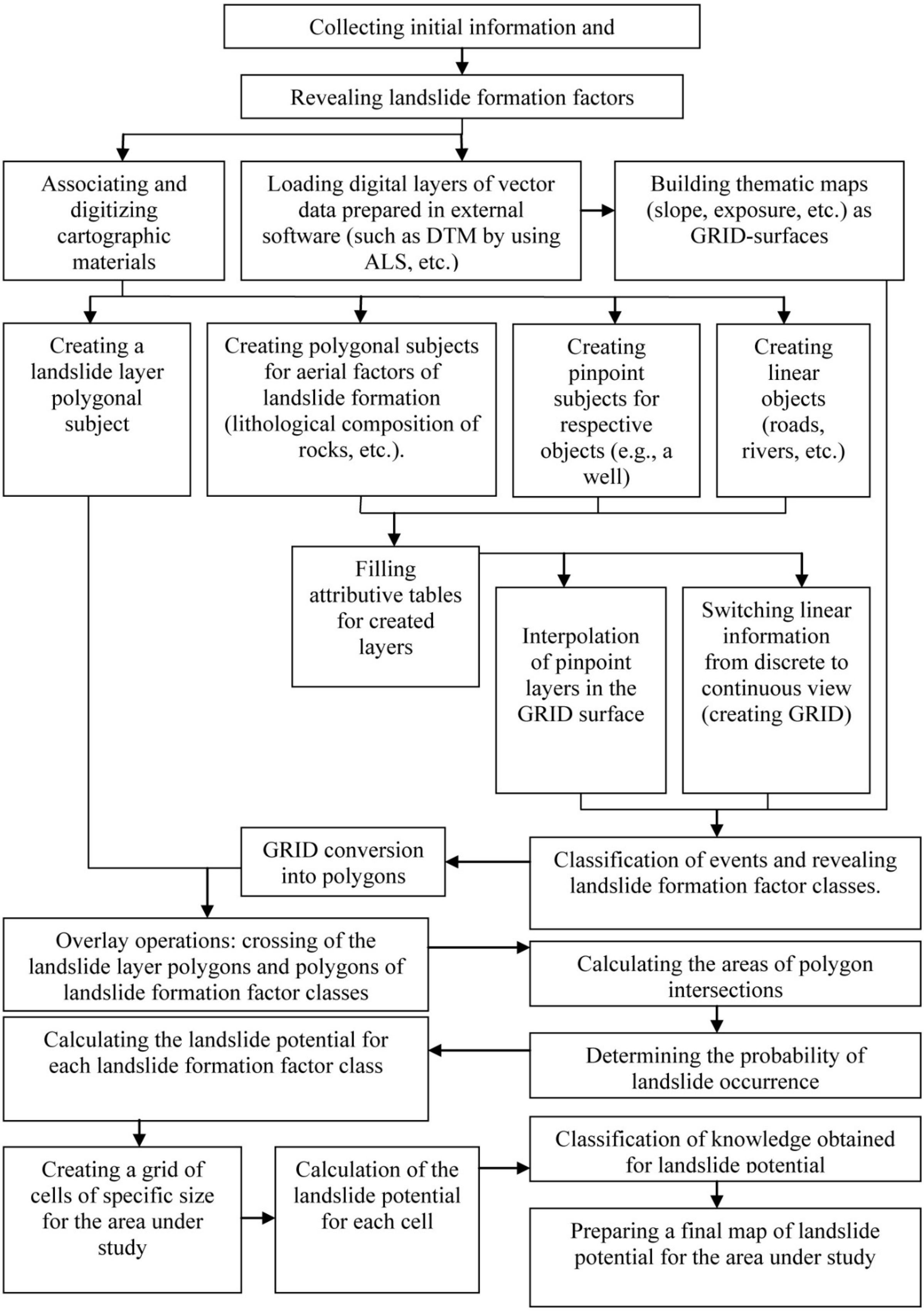

Fig. 1 Zoning map compilation procedure for landslide potential based on GIS technologies.

potential based on GIS can be represented as a flow chart (Fig. 1).

The developed algorithm was tested when preparing a zoning map for landslide potential based on ArcGIS for the area between the Mzymta and the Bzerpiya Rivers, on the slopes of the Psehako Ridge, 4 km from the Red Polyana in the Adler District of Sochi, Krasnodar Territory, Russia. The site is 24.64 km^2 in area and is stretched 8.2 km from west to east and 3.6 km from north to south. The study region is located within the Greater Caucasus mountain system and belongs to the mid-mountain erosion-tectonic type of terrain with prevailing altitudes between 500 m and 1500 m. The study includes a forecast estimate of the area in relation to the block-type landslide dpQIV (landslides of covering silts and clays). Such landslides are widely spread in the region under study.

Based on the analysis of the existing actual materials and knowledge of landslide processes, the following factors participating in the algorithm testing were determined:

- lithogical characteristic of rocks;
- depth of covering deposits;
- terrain and its primary morphometric indicators;
- hydrogeological conditions;
- tectonic deformations;
- erosion compartmentalization;
- engineering and economic human activities.

When considering seismic data and data on climatic conditions a decision was made to exclude them from consideration, since they are almost constant within the area under study.

Landslides were digitized in ArcGIS by using the map of hazardous geological processes within the area of the touristic and sports mountain complex Krasnaya Polyana scaled at 1:10,000 (Lizogubova, 2007). For each landslide, their areas were calculated in the attributive table of the layer.

Terrain features were one of the conditions to contribute to landslide formation, so it is important to study the earth terrain by using topographic maps and digital terrain models (DTMs), since the zoning efficiency of areas by the landslide hazard depends on their accuracy and level of detail. The DTM obtained after aerial laser scanning (ALS) was used as a basis. The accuracy of this DTM was assessed in details in the article (Kuzin, 2014). ALS was done by a Leica ALS-70-CP laser scanner. This work resulted in a cloud of Earth class points exported to the ArcGIS database to create a Terrain digital model based thereon.

Based on the DTM created with ALS data and using ArcGIS computational capabilities, a calculation was made for the primary morphometric indicators of the terrain-steepness of slopes, exposure of slopes, erosive compartmentalization of the terrain, and their respective digital models were created. The slope steepness defines the balance of forces that prevent landslide masses form sliding. Depending on the steep exposure, its moisture content may differ, which affects the progress of exogenous sloping processes. Linear erosion has an affect on landslide formation by means of slope undercutting. Erosion primarily activates surface landslides due to prolonged periods of rains that constantly maintain high level of surface water in the ravine and flat-bottom valley network, so the bottom part of the slope is washed away and eroded rocks are removed. Digital models of slope steepness and exposure were built based on the DTM using 3D Analyst module Slope and Aspect functions.

In the ArcGIS, an erosive compartmentalization map is created in several stages by using the Spatial Analyst module and Hydrology tools. At the initial stage, a flow accumulation surface is created using the DTM. After building the flow accumulation surface model, a network of streams is obtained by applying the threshold value. The threshold value is selected experimentally by using the value distribution chart. The model obtained is then vectored by using the Stream to Feature tool to create a linear layer of streams. The sum of lengths of all streams within each cell is calculated within the created grid with square cells with the sides of 1 km. When neither stream falls within a cell, it is assigned with a zero value. Cell centers are assigned with the calculated value of the relation between the sum of all lengths of stream and the cell area. These values are used to create the regional erosive compartmentalization model. For this purpose, the Bitmap Interpolation function of the ArcGIS 3D-Analyst module is used.

Based on the map of quaternary deposits, engineering, geological and hydrogeological maps scaled 1:10,000, a number of data for analysis were obtained, such as lithologic characteristic of rocks, depth of covering deposits, depth of underground water and lines of tectonic faults. The lithologic composition of rocks is the primary element of the slope's geological structure that affects its stability. In its turn, the depth of deposits and underground water defines the formation of landslide planes. Existing water-bearing layers promote lower shear resistance of rocks and higher density thereof. When approaching to tectonic faults, the probability of landslide deformations is increased because of Earth crust active movements.

A digital map of the lithologic characteristic of rocks factor is created by using tools for digitizing areas and assigning values of respective classes in the attributive table.

By using a spline interpolation tool in the GIS, the models of the depth of deposits and underground water are also created in the form of a GRID surface by using pinpoint layers of wells digitized from the map (according to the data included in the attributive table for each well).

Based on the topographic scheme and orthophotomaps obtained during aerial laser scanning, data were obtained concerning the location of water reservoirs and the human economic activity: location of roads, area development, location of utilities (power transmission towers, cable way pylons, etc.). By using ArcGIS tools, the modules of values for distances to these facilities were created.

Increased cleavage and erosion when distancing from rivers and respectively increased infiltration and decreased strength of rocks affects the formation of landslides. The transformation of natural landscapes by human activity also results in possible activation of landslide processes, since the economic activities cause slope undercutting, changed ground water dynamics, increased loading on the slope, etc. The road network affects the microseismic activity, which in its turn affects the stability of rocks. To analyze landslide hazard, remoteness models for these natural and man-made facilities are built in ArcGIS.

In this manner, GIS models of various factors of landslide formation were created. For each factor of landslide formation, an analytical zoning map was built. Detecting boundaries of class propagation, e.g., the factor values, was done using the value distribution chart. When dividing into classes, the boundaries of value variance for each factor in this are were taken into account. The number of classes was adopted to be from 3 to 6. Value distribution chart and factor division by classes was done in ArcGIS.

When dividing the Rocks factors by classes, the classifications of Popov and Kolomenskiy were used. For 1:10,000 scaling, lithologic types of rocks are used as classes of this factor.

The Exposure factor was classified in accordance with their cardinal direction orientations.

This resulted in analytical map for class distribution of various factors for the area under study. Factor classes are given in Table 1. The factor map displays distribution areas for factor classes. Each layer of the factor map is supplemented by the data concerning the area of each class in its attributive table.

The probability of landslide formation p_{ij} within each class of factors was calculated under the formula (1) based on the areas and landslides and areas of classes which boundaries it falls within. The calculation results are given in Table 1.

After all landslide probability values within each class are calculated, an output layer is created by using the Intersection tool based on all layers of landslide formation factors, which attributive table will contain information concerning the probability of landslide formation within the class.

The calculation started by combining the maps of the first and second factor. For each intersection of classes p of these factors, an assessment was made:

$$\left(1 - p_{1i}\right) \times \left(1 - p_{2l}\right) \tag{7}$$

where i=1,2,…,5, l=1,2,3.

By using the data obtained, zoning was then done, and the resulted map was merged with the map of the third factor. All required assessments were calculated under formula (7). After combining the maps of all landslide formation with the values of final assessment, the values of landslide potential were determined by using the formula (6) and the Field Calculator function.

The final map was created based on the grid of cells of specific size. For this purpose, a center of each cell was assigned with an average value of calculated landslide potentials falling within the intersection of the cell and the bitmap with calculated values of the landslide potential for class intersection areas. By using interpolation, the bitmap surface was then created upon the pinpoint layers with the values of landslide potentials, which was classified in accordance with the requirements of the zoning methodology for landslide potential by 4-5 classes. The classes reflected the landslide potential values from 0 to 1, which corresponds to the probability of landslide occurrence from very low to very high.

The landslide occurrence and activation probability scale was determined by using a so-called relevance level above which the landslide occurrence and activation probability for the area under study can be considered high and very high.

Table 1. Probability calculation of landslide occurrence and activation and weighted coefficient within landslide formation factor classes

Factor	Factor class	Class area, km^2	Landslide area within class, km^2	Probability p_{ij}	Weighted coefficient V_{ij}
Lithogical characteristic of rocks	Erratic masses of pre-Quaternary formations	1.401	0.218	0.156	0.013
	Alluvial of beds, flood plains and low terraces above flood-plain	2.111	0.042	0.020	
	Colluvial of steep slopes (mountain deluvial)	16.647	1.357	0.082	
	Colluvial, with partial deluvial soilfluction	0.031	0.002	0.065	
	Colluvial	2.496	0.106	0.042	
	Sea undaluvial of upper Pleistocene terraces	1.953	0.000	0.000	
Depth of covering deposits	0-5 m	10.115	0.816	0.081	0.008
	5-10 m	10.402	0.827	0.080	
	10-20 m	2.941	0.066	0.022	
	above 20 m	1.181	0.016	0.014	
Slope steepness	below 7°	1.390	0.021	0.015	0.019
	7-19°	7.107	0.541	0.076	
	19-30°	12.982	0.566	0.044	
	above 30°	3.160	0.597	0.189	
Slope exposure	Northern	4.645	0.079	0.017	0.010
	North-Eastern	1.257	0.024	0.019	
	Eastern	0.496	0.013	0.026	
	South-Eastern	1.662	0.011	0.007	
	Southern	4.248	0.264	0.062	
	South-Western	5.291	0.680	0.129	
	Western	2.802	0.239	0.085	
	North-Western	4.238	0.415	0.098	
Depth of groundwater	0-2 m	10.961	0.785	0.072	0.003
	2-5 m	5.870	0.586	0.100	
	5-10 m	5.110	0.279	0.055	
	10-15 m	2.274	0.055	0.024	
	15-30 m	0.424	0.020	0.047	
Erosion coefficient	below 2	7.164	0.148	0.021	0.009
	2-5	6.375	0.414	0.065	
	Above 5	11.100	1.163	0.105	
Remoteness from rivers	below 250 m	11.128	0.901	0.081	0.002
	250-500 m	8.380	0.486	0.058	
	500-750 m	3.886	0.296	0.076	
	above 750 m	1.245	0.042	0.034	
Remoteness from populated localities	below 250 m	12.148	0.910	0.075	0.003
	250-500 m	6.663	0.585	0.088	
	500-1000 m	4.571	0.180	0.039	
	above 1000 m	1.257	0.050	0.040	
Remoteness from roads	below 250 m	6.391	0.210	0.033	0.003
	250-500 m	7.095	0.679	0.096	
	500-1,000 m	4.815	0.393	0.082	
	above 1,000 m	6.338	0.443	0.070	
Remoteness from tectonic faults	below 250 m	9.798	0.592	0.060	0.002
	250-500 m	6.739	0.520	0.077	
	500-750 m	5.747	0.361	0.063	
	above 750 m	2.355	0.252	0.107	

The relevance level was calculated as follows. The landslide affection coefficient for the area under study is 1.725 km^2/24.64 km^2=0.07. Hence, the landslide potential equals (with all 10 factors equally relevant): $W = 1-(1-0.07)^{10} = 0.516 \approx 0.5$.

Considering that the landslide potential equals 0.5 when all landslide formation factors are equally relevant, there are five classes with the following probabilities revealed on the zoning map in terms of the landslide potential (Fig. 2);

– below 0.3-very low probability;
– 0.3-0.4-low probability;
– 0.4-0.5-medium probability;
– 0.5-0.6-high probability;
– above 0.6-very high probability.

The assessment of factors relevance in terms of their effect on the landslide process within the area under study was defined by calculating the weighted coefficient under the formula 2. The entropy value calculated under the formula (4) equals H_{max}=3, H_{max}=2.585, H_{max}=2.321, H_{max}=2, H_{max}=1.584, respectively for eight, six, five, four and three classes. It means that all factors shall be considered in further calculations. By using the Vistelius coefficient, I factors are ranged as follows: slope steepness (0.230), lithologic characteristic of rocks (0.206), slope exposure (0.191), depth of covering deposits (0.165), erosion coefficient (0.146), depth of underground water occurrence (0.058), remoteness from populated localities (0.047), remoteness from roads (0.045), remoteness from rivers (0.034), remoteness from tectonic faults (0.020).

The relevance of any class in the considered aggregate of factors is determined by its probability p_{ji}. If factors are ranged by maximum values of probability p_{ji} of each factor, we obtain as follows: slope steepness (0.189), lithologic characteristic of rocks (0.156), slope exposure (0.127), remoteness from tectonic faults (0.107), erosion coefficient (0.105), depth of underground water occurrence (0.1), remoteness from populated localities (0.088), remoteness from roads (0.096), depth of covering deposits (0.081), remoteness from rivers (0.081).

According to the weighted coefficient V_{ij} , ranking of factors according to their relevance for the development of landslide process in the area under study is more objective: slope steepness (0.019), lithologic characteristic of rocks (0.013), slope exposure (0.010), erosion coefficient (0.009), depth of covering deposits (0.008), depth of underground

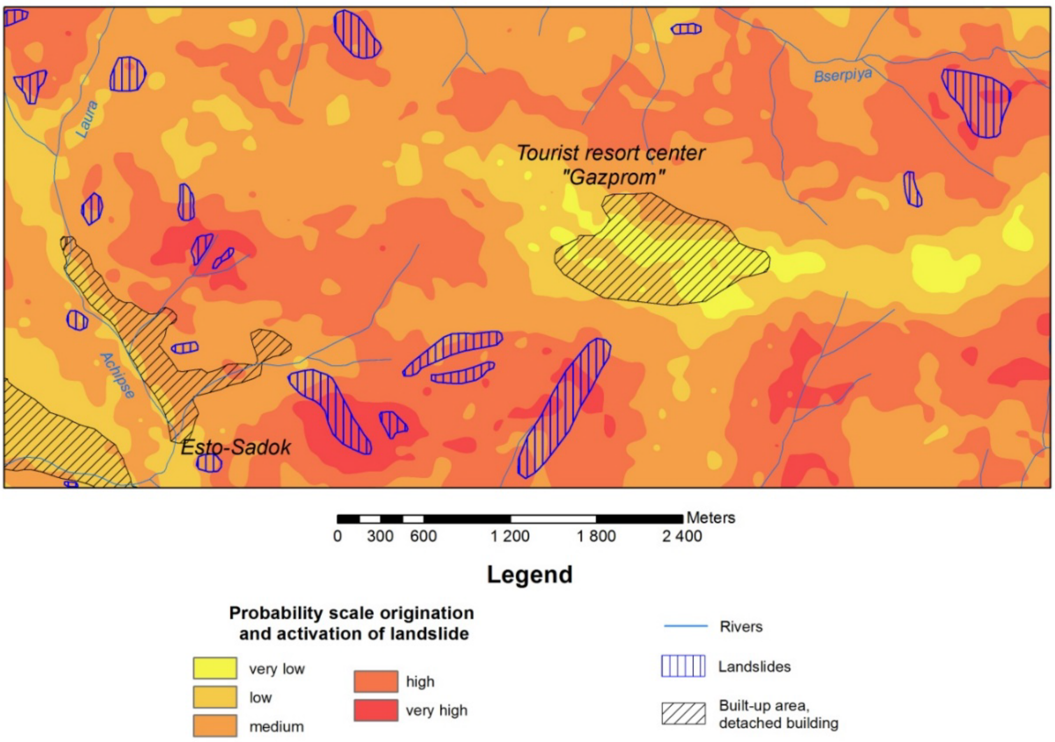

Fig. 2 Zoning map of the studied area in terms of the landslide potential.

water occurrence (0.003), remoteness from populated localities (0.003), remoteness from roads (0.003), remoteness from rivers (0.002), remoteness from tectonic faults (0.002).

DISCUSSION OF RESULTS

When considering slide formation factors, their relevance as a whole was considered. It was found that one of the most relevant factors is slope steepness and exposure and erosion coefficient. The models of these factors were created based on the DTM. This is another proof of the relevance of proper selection of the geodetic zoning methods in terms of the landslide potential.

When considering class probabilities within factors, it was revealed that the highest values are typical of slopes having steepness above 30°, the depth of covering deposits from 2 m to 5 m, low depth of groundwater occurrence (up to 2 m) and the erosion coefficient above 5. In terms of the lithological composition, the highest probability of occurrence of landslides is shown by the class of erratic masses of pre-Quaternary formations.

As shown in the zoning map of the area under study of the landslide formation (Fig. 2), the landslides obtained from the map of hazardous lithogical processes are located within the zones of very high, high and medium probability of landslide occurrence and activation. A conclusion can be made that zoning was satisfactory. By applying neutron networks to reveal landslide hazardous areas by using the analogy method, it becomes possible to assess the zoning results in terms of landslide formation by comparing landslide hazard maps obtained by using various methods. The landslide hazard map procedure is represented in detail in Kuzin, based on neural networks.

CONCLUSION

In this manner, geoinformational systems make it possible to assess the landslide hazard of areas, which is necessary to ensure their safe development. The suggested methodology may be included in the initial stage of planning, and its implementation in practice is possible by using cartographic materials resulted from engineering surveys. In maintaining databases of survey information in the GIS, labor efforts for land slide hazard evaluation are reduced due to no need to collect and digitize respective cartographic materials.

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