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Application of quantitative methods for the assessment of landslide susceptibility of the Aghsuchay river basin

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ABSTRACT

Problem statement. Azerbaijan is making a lot of efforts to reduce the impact of dangerous geological processes on natural geosystems, but they still cause huge damage. To a greater extent, the region of the Greater Caucasus, namely the southern slope, is subject to such processes, where the whole range of dangerous geological processes occurs: earthquake (7-8 b and above), landslides, landslides, screes, mudflows, etc. All of them are large-scale processes in terms of damage - they affect large areas and lead to economic losses.

Purpose - to identify the main factors of the formation and spread of landslides in the basin of one of the most mudflow-bearing rivers not only in Azerbaijan, but also in the South Caucasus - the Agsuchay river, identify the conditions for their formation, assess the risk of the territory's susceptibility to landslide processes, as well as ways to prevent and protect.

Research method. To assess landslide susceptibility and create maps of the potential development of landslides in the basin of the Agsuchay river we used the Frequency Ratio method (FR).

Research results. For minimize damage from landslides on the example of the Agsuchay river basin a detailed study of the factors (hypsometry, slope angles (slope steepness) was carried out by us. Also slope exposure, geological structure (lithology), distance from faults, average annual precipitation, distance to the erosion network, distance to roads and land use) that determine the development of landslide processes with taking into account the mechanism of their development, as well as an analysis of the obtained values of landslide susceptibility and their potential development was studied. In the ArcGIS software environment, using the "Raster Calculator" spatial analysis tool, summing up each landslide factor multiplied by its weights, a map of the landslide susceptibility of the Agsuchay river basin was obtained.

In the river basin Agsuchay we identified over 120 landslide areas. Most of the landslides were recorded along the Baskal tectonic cover, the Steppe Plateau, as well as on the slopes of the Langyabiz ridge, and also partially on the slopes of the Nialdag ridge.

Conclusion. Using the natural boundary classification method in the ArcGIS software environment, the study area was divided into five landslide potential zones: very low, low, medium, high, and very high. The result of the analysis showed that zones with very low, low, medium, high and very high landslide development potential are: 13.75; 24.48; 31.51; 20.51 and 9.74% of the study area, respectively.

Ultimately, the reliability of the obtained models was evaluated using AUC ROC (area under the error curve) analysis, which showed high performance of the method used (82%). Due to the high reliability, the method used can be used to assess the landslide susceptibility not only of the territory of Azerbaijan, but of similar regions of the Alpine-Himalayan belt.

Keywords: *landslide, mud river, geosystem, tourist and recreational potential, damage, landslide hazard, susceptibility, quantitative methods.*

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Introduction. Studying hazardous geomorphological processes and the zoning of developed territories based on the complexity of engineering and geomorphological conditions and the intensity of development of unfavourable geomorphological processes is regularly conducted and appears relevant for many years (Tarikhazer, 2022). Slope (landslide) processes are listed among such dangerous geomorphological processes. The term landslide refers to the gravitational movement of rock masses and fragmental debris, as well as loose soils that have lost their balance due to a complex of factors under the influence of their weight down the slope. In contrast with other natural perils, landslide risk assessment requires a comprehensive study of the spatial interaction of factors provoking landslides.

The southern slope of the Greater Caucasus, specifically the Shamakhi-Ismail region, is a unique region for the peculiarity of its geographical location. It should be noted that some factors i.e. the diversity of landscapes, vegetation, and the animal world, including the existing developed infrastructure and transportation network, determine the region's role as one of the largest resort and tourist regions of Azerbaijan. Vast recreational potential attracts a sheer number of investors and holiday-makers to places subject to landslide. In recent decades, the studied territory has been actively settled down. There have been done several work on the construction and expansion of settlements, roads, industrial facilities, and hotels. Some of these objects pass through or are in mountainous/ highland areas, requiring increased attention to the conditions for landslide formation (Tarikhazer, 2020). The suddenness of emergence, unpredictability, and close connection with other geological processes, specifically with mudflow processes and phenomena, make landslides a severe, sometimes even insolvable problem in construction, requiring the development of landslide prevention works.

An assessment of the formation and distribution of landslide processes in a given region will allow solving many practical and economic problems, preventing undesirable consequences caused by the catastrophic transformation of the primary relief, applying the results obtained for more rational use of the territory, and reducing the potential hazard and damage from landslides. All of the above stated reasons define the relevance of the addressed topic.

The **purpose of the study** is to determine the prime drivers in the formation and distribution of landslides in the Aghsuchay River basin, one of the most mudflow-bearing rivers not only in Azerbaijan but also in the South Caucasus, elucidate the conditions conducive to their formation, and assess the sensitivity risk of the territory for landslide processes, and provide a way of protection and prevention.

The object of the study is the landslides developed in the basin of the mud-bearing Aghsuchay River.

Characteristics of the study region. Aghsuchay River basin is located between 40°25'-40°50' N and 48°15'-48°45' E (Figure 1). In terms of altitude, the river basin belongs to low-sited water-collecting headers, where 45.5 km^2 or 8% of the basin area falls to a height above 1500 m. The rest of the river basin is located at an altitude of less than 1500 m. The average height is 666 m; the area of the Aghsuchay basin is 572 km^2, while the river length makes 85 km. The reason for the widespread occurrence of landslides here is the complex geological and tectonic (thick member of clay materials and the existence of acting tectonic faults) and geomorphological (large slopes) structure of the territory.

The mountainous part represents the middle altitudes, with the absolute elevation reaching 2200 m. The geographic area is strongly split by the river valleys and streams, where the steepness of slopes does

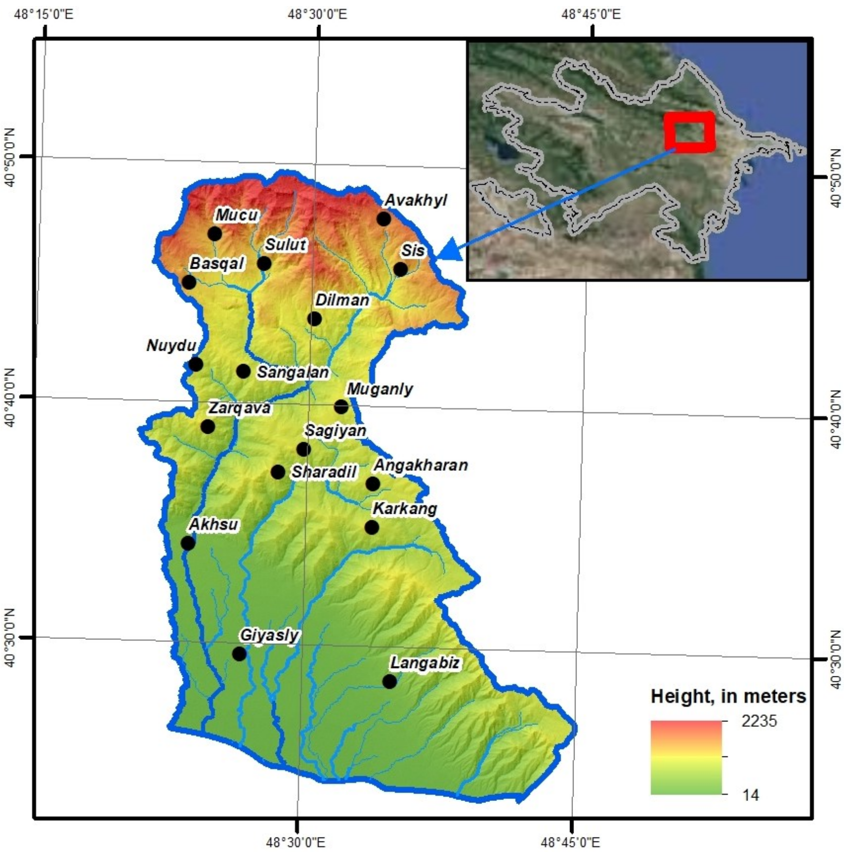

Fig. 1. The geographical location of the basin Agsuchay river

not exceed 30-40°. Tertiary sedimentary and volcanogenic sedimentary rocks of the Cretaceous Period primarily take part in the geologic aspects of the study area. The Aghsuchay river flows through a billowy area, a relatively wide plateau, rising in places to a height of up to 1000 m. The Gurjivan Plateau borders the basin in the west and the Langabiz Ridge - in the east. The average density of the river network makes 0.46 km/km^2. The main mudflow centres, specifically landslides and landslides-flows, are located at an altitude of over 1200 m.

In recent years, the number of landslide (slope) processes has increased dramatically in the basin of the Aghsuchay River (Figure 2). Based on fund and own field data, a table of manifestations of landslide processes in this basin over the past 23 years has been compiled (Table 1). As can be seen from the table, the main triggers of landslide processes are atmospheric precipitation (mainly heavy rains) and anthropogenic activity, expressed by cutting slopes during construction work. As field studies (observations) show, improper laying of the drainage network during the construction of new roads in this basin causes rapid destruction of the roadway. If earlier these processes were mainly developed in the upper parts of the middle and high mountains, now they are actively developing in the low-mountain and foothill zones of the basin. Along with natural factors, anthropogenic activities (earthmoving operations on slopes in the course of road construction) played a significant role as well (Figure 3).

The territory, through which the Aghsuchay River flows, is characterised by a complex orotectonic plan. The structure of the relief reflects the fold-block basis of the territory, representing a combination of large and small, positive and negative structures, disjunctive dislocations, and overthrust masses. Structural features stem from even greater differentiation due to the close relationship between endogenous and exogenous processes.

At the riverhead, the valley of the Aghsuchay River is represented by a gorge with steep, often sheer slopes, ravines, and waterfalls. In the middle reaches, the river valley expands. Gorge with steep rocky slopes is formed in places where it cuts through effusive rocks with interlayers of sandstones and li-

Fig. 2. Active landslides in the basin of the Agsuchay river

Fig.3. Retrospective analysis of landslide formation. a) satellite image of 2004, b) satellite image of 2012
The landslide began to form after the construction of the tourist complex

Table 1

Dates of manifestation of the most dangerous landslide processes
within the basin of the Agsuchay river (for 2000-2022)

№	Date of manifestation	Place of manifestation	Causes of a landslide	The aftermath of a landslide
1	2	3	4	5
1	March 2000	Chaily village	Rains	The landslide intensified in the south-west of Chaily village at an altitude of 710-860 m. Landslide length 250-300 m, width 150-160 m
2	April 2000	Muganli village	//-//	The landslide is developed in the central part of the Muganly village. Landslide length 920-930 m, width 85-100 m
3	April 2001	The villages of Shirvan and Sheradil	//-//	Several residential buildings are under the threat of a landslide. Landslide length 250-300 m, width 200-220 m
4	April 2001	Geylardag village	//-//	The landslide occurred in the central part of the village of Geylardag. The building of the Historical and Cultural Reserve was under threat. Landslide length 640-670 m, width 150-170 m
5	April 2001	Dilman village	//-//	Landslide activation in Dilman village
6	May 2002 г.	Adnaly village	//-//	Landslide activation in the south of Adnaly village. Landslide length 120-130 m, width 30-40 m
7	April 2003	Chabany village	Leakage of water from the reservoir	Damaged rural road. Landslide length 1200 m, width 300-330 m
8	May 2003	Nuydu village	Rains	A landslide intensified at an altitude of 720-860 m south-west of the village of Nyuidyu
9	May 2003	Dedegunesh village	//-//	The landslide is developed at an altitude of 1000-1150 m. Several houses are under threat. Landslide length 5400 m, width 200-220 m
10	May 2003	Kalva village	//-//	Landslide activation in the north-west of Kalva village at an altitude of 770-880 m
11	May 2004	Sangalan village	//-//	Landslide activation in the eastern part of Sangalan village. Landslide length 270-280 m, width 300-320 m
12	May 2004	Garavelli village	//-//	Landslide activation. Small cracks were recorded in several houses. Landslide length 300-320 m, width 120-130 m
13	March 2005	Khazydere village	//-//	Activation of a landslide in the north-eastern part of the village of Khazydere. Landslide length 80-100 m, width 100-120 m
14	April 2005	Sheradil village	Rains, slope cutting	The landslide is developed at an altitude of 750-880 m. The landslide first appeared in 1985. Landslide length 200-250 m, width 120-150 m
15	February 25, 2010	Villages of Sangan, Kalva, Surakhani, Girrar, Guzai	Rains	80 houses and 4 office buildings were damaged. In Sangalan village (38 houses), Kalva village (35 houses), Surakhani village (2 houses), Girrar village (1 house), Guzay village (1 house)
16	April 21, 2010	Chagan village	//-//	The 700-meter highway Shamakhi-Uncle Gunash was closed. Cracks appeared in 20 houses of Mirikand and Muganli villages
17	March 20, 2012	Agsu district, Chagan and Dedegunesh villages	//-//	The activity of landslide processes. Landslides and subsidence phenomena have developed on the 2nd km of the Muganly-Ismayilli highway, landslides have intensified in the villages of Chagan and Dedegunesh
18	March 21, 2012	Muganli village	Melting snow and rains	There are 50 residential buildings in the landslide zone. 18 houses, a school, a club, an outpatient facility are severely deformed
19	February 27, 2014	147, 149, 150 and 152 km of Shamakhi-Agsu highway	Rains	Cracks and several subsidence of the asphalt pavement of the road formed
20	March 7, 2015	Agsu-Shamakhi highway	//-//	Vehicular traffic blocked

21	April 2, 2015	Shamakhi regions, Agsu pass	//-//	Activation of landslides on the Baku-Shamakhi, Muganly-Ismayilli and Agsu Pass roads
22	October 22, 2015	Roadbed of Baku-Shamakhi, Agsu pass	//-//	Activation of landslides at 106, 109 and 111 km of the Baku-Shamakhi highway, at the Agsu pass. Numerous cracks found
23	November 12, 2015	106-109 and 111 km of the Shamakhi-Ismayilli highway, 132 and 135 km of the Baku-Agsu highway	//-//	Vehicular traffic blocked
24	February 26, 2016	Sheradil village	Rains and melting snow	Cracks 1.5 m deep and more than 60 m long formed on Baku-Shamakhi-Yevlakh main road
25	June 3, 2016	106-107 km of Baku-Shamakhi-Yevlakh highway	Rains	Vehicular traffic blocked
26	September 22, 2016	Agsu and Shamakhi regions	//-//	Numerous landslide processes on the right bank of the Agsuchay River, at 147-154 km of the Baku-Shamakhi-Agsu highway. Difficulty in traffic
27	November 14, 2016	Madras village	//-//	Cracks appeared on the main road. Landslide area 40 ha
28	December 6, 2016	Shamakhi-Gyzmeydan highway	//-//	Blocked communication with 4 villages
29	January 18, 2017	Madras village	Melted waters of snow and rains	7 houses in disrepair
30	February 4, 2017	Agsu pass	//-//	Activation of landslides on the Agsu pass, on the Baku-Shamakhi-Yevlakh highway. Landslides damaged concrete barriers. Numerous cracks were found on the asphalt pavement. Difficulty in traffic
31	February 17, 2017	149 km of the road of the Agsu pass	Rains	The road sank to a depth of 40-50 sm. Landslide length 40 m
32	March 29, 2017	The villages of Chabany, Madras, Meysari, Birindzhi Chaily, Muganly, Ajidere, Galeybudug	//-//	The road at 4, 6 and 10 km Shamakhi-Gyzmeydan was destroyed. Blocked traffic
33	June 2, 2017	106-107 km of Baku-Shamakhi highway	//-//	Landslide intensified on 106-107 km of Baku-Shamakhi highway
34	June 28, 2017	106-107 km of Baku-Shamakhi highway	//-//	Landslide intensified on 106-107 km of Baku-Shamakhi highway
35	July 21, 2017	106-107 km of Baku-Shamakhi highway	//-//	Landslide intensified on 106-107 km of Baku-Shamakhi highway. Asphalt collapsed in two places
36	August 28, 2017	106-107 km of Baku-Shamakhi highway	//-//	Landslide intensified on 106-107 km of Baku-Shamakhi highway
37	September 12, 2017	106-107 km of Baku-Shamakhi highway	//-//	Landslide intensified on 106-107 km of Baku-Shamakhi highway
38	October 5, 2017	The villages of Dilman, Khatman, Khadzhman	//-//	Cracks appeared in many houses in the villages of Dilman, Khatman and Khadzhman. About 70 houses are in disrepair
39	October 16, 2017	Sagyan village	//-//	In the village of Sagian, fences were destroyed, ceilings sagged in the houses, and there were numerous cracks on the walls. Residents evacuated

40	October 19, 2017	142, 148 and 152 km of Baku-Agsu-Yevlakh road	//-//	The asphalt sank in some places, cracks appeared 20-30 m long, 10-20 m deep, in some places up to 30 sm
41	January 5, 2018	106-111 km of the Baku-Shamakhi road and 132-156 km of the Baku-Agsu road	Melted waters of snow and rains	Landslide activity at km 106-111 of the Baku-Shamakhi highway, at km 132-156 of the Baku-Agsu highway
42	April 3, 2018	The villages of Shabany and Dedegunesh	Rains	Landslides also intensified in the villages of Shabany and Dedegunesh. Landslide length 150 m, width 100 m
43	April 13, 2018	Adnaly village	//-//	There are 12 residential buildings in the landslide zone. Cracks appeared in 4 houses. Residents evacuated
44	April 19, 2018	Road Shamakhi-Pirguli-Damirchi	//-//	In many places of the Shamakhi-Pirguli-Damirchi road, asphalt subsided, numerous cracks developed
45	April 24, 2018	3 km Gushchu-Chayly road		On the 3rd km of the Gushchu-Chayly road, landslide-subsidence phenomena are developed. Overturned road signs along the road
46	April 24, 2018	19-20 km of Shamakhi-Geylyar-Padarchel road	//-//	Numerous cracks developed on the 19-20th km of the Shamakhi-Goylar-Padarchel road
47	June 15, 2018	Zaratheiberi village	//-//	In the village of Zaratkheyberi, a landslide destroyed a road bridge. Communication of 300 villagers with the regional center was interrupted
48	December 11, 2018	Gushchu village	//-//	In the village of Gushchu, cracks appeared in 15 houses. Damage was caused to personal plots, vegetable gardens, orchards. Roads damaged
49	April 1, 2019	Agsu-Khanbulag road	//-//	Landslide processes on the Agsu-Khanbulag roadbed. Blocked communication between the villages of Khanbulag Khingar, Girda, Kendahan, Zargava, Yenikend and Kevludzh with the regional center
50	January 10, 2020	Agsu pass	//-//	Activation of landslide processes in 4 places of the Agsu pass. Large cracks formed on the roadway, numerous landslides and subsidence
51	May 5, 2021	Agsu pass	//-//	Threatened destruction of a rural cemetery
52	January 13, 2022	22 km of the highway Chukhurdyurd-Sis-Galeybugurd-Kechmeddin-Galaderesi	//-//	A landslide descended on the 22 km of the Chukhurdyurd-Sis-Galeybugurd-Kechmeddin-Galaderesi highway. Several sections of this 16 km road, which was reconstructed and put into operation at the beginning of 2020, were destroyed, cracks formed on the asphalt surface

mestones. Its tributaries are characterised by their nesting in folds overturned to the south. The northern slopes are steep, while the southern slopes are relatively slightly sloping, corresponding to the bedding of rocks. The valleys of lateral tributaries developed in thick and relatively rapidly eroding rocks are deeper. In the lower reaches, the Aghsuchay River takes the form of a wide box canyon with a high floodplain and stream terraces.

The sub-mountain region and low-hill terrain, along which the Aghsuchay River valley passes, are characterised by the development of a strong debris cone plume, in the upper parts of which the largest material of mudflows has accumulated. The middle altitudes of the Aghsuchay River basin, are characterised by the development of landslide-scree slopes in dense sandstone-limestone deposits of the Cretaceous and Jura. The high mountain regions are an area of nival-denudation impact and gravitational processes.

Huge landslide massifs, amphitheatres, circuses, slowly moving streams, and landslide disruptions cover the middle course of the Aghsuchay River, mainly complicating the relief and obscuring the structural features of the relief. These processes and landforms of gravitational origin have erased the structural features of low-order morphostructures. Massive landslide flows with powerful plume cones fill the bottoms of the basins of their slopes.

According to N. Shirinov (1982), the presence of intensely dissected slopes of the longitudinal part of the Aghsuchay River stems from the intense fragmentation of the Lower Cretaceous limestones, marls, and sandstones by a series of longitudinal fractures active in the latest stage. It is also due to the scaly structure of the slope with the layers falling to the north.

One of the main factors in the development of landslide processes is the orotectonic structure, which is confirmed by the geological and geomorphological analysis of the structure of the region under study.

Materials and research methods. The danger posed by landslides encourages researchers to look for the most advanced approaches and tools for their prediction. In recent years, probabilistic-statistical methods have been increasingly applied for forecasting purposes. As of the current date, a considerable number of works have been published on this problem (van Westen CJ, 1997; Suzen, Doyuran, 2004; Guzetti et al., 2005; Lee, Pradhan, 2007; van Westen CJ., 2008; Nefeslioglu et al., 2008 ; Ozdemir, 2009; Castelanos Albella, Cervi et al., 2010; Oh, Lee, 2011; Pendin V.V., Fomenko I.V., 2015; Ciurleo et al., 2017; Arabameri et al., 2019; Cantarino et al., 2019; Mandal, Mondal, 2019; Nahayo, 2019; Shano et al., 2020; Kharchenko S.V., Shvarev S.V., 2020; Mersha T., Meten M., 2020; Rocatti et al., 2021, etc.). It is not possible to list all researchers in this study. However, the features, often found in these works, could be generalised.

The most popular methods for forecasting landslide processes include the frequency ratio (Akgun et al., 2008; Akgun and Needet, 2010; Constantin et al, 2011; Ram Mohan et al., 2011; Yalcin et al., 2011; Pourghasemi et al., 2012; Berhane, Tadesse, 2021; Duong et al., 2022), logistic regression (Getachew, Meten, 2021), linear discriminant analysis, and hierarchy analysis method (Pourghasemi et al., 2013; Duong et al., 2021). In recent years, new methods have been increasingly used: region-partitioning approach (Hong et al., 2018), random forest (Yesilnajar, 2005), decision tree (Saito et al., 2009; Nefeslioglu et al., 2010), neural networks (Lee et al., 2003; Sezer et al., 2011; Pradhan, 2013; Xiong et al., 2019), and Support Vector Machine.

Similar sets of variables are often used to develop models. Positive altitude, angle of gradient, layout, distance to faults, distance to watercourses, etc. take the lead among the quantitative variables in terms of frequency of use (Fell et al., 2008; van Westen et al., 2008; Gaidzik, Ramirez-Herrera, 2021). Along with this, qualitative variables are also applied: the composition of a subsurface rock, the type of vegetation and land management, and rainfall amount.

Landslide susceptibility is "*the spatial probability of landslides occurring in a given area, depending on local conditions, indicating where landslides may occur*" (Sestrash et al., 2019; Kose and Turk, 2019). In other words, landslide susceptibility is considered as the likelihood of a landslide occurring in a particular area, being estimated based on the quantitative and qualitative interpretation of certain natural and anthropogenic factors leading to the landslides emergence. Landslide Susceptibility Mapping (LSM) is "*the process of defining the positional relation and classifying units of territory based on their propensity to cause landslides. Topography, geology, soil property characteristics, climate, vegetation, and anthropogenic environmental impact influence this process as well*" (Fell et al., 2008). Spatial analysis using GIS "*clarifies the connections between various elements of slope stability and the development of landslide processes, being an effective method for assessing landslide susceptibility*" (Van Westen et al., 2006; McColl, 2015).

Landslide susceptibility analysis is the most commonly used statistical approach. In this analysis, landslides and their causing factors are used to develop a landslide susceptibility model to forecast future landslides (Aleotti and Chowdhury, 1999; Gokceoglu et al., 2005; van Westen et al., 2006; Tiranti and Cremonini, 2019). Approaches to assessing landslide susceptibility could be classified as quantitative and qualitative (Guzetti et al, 1999; Yalcin et al, 2011; Pendin, Fomenko, 2015; Gaidzik, Ramirez-Herrera, 2021). Recently, the number of quantitative estimates of landslide susceptibility has been considerably expanded. It stems from the fact that quantitative approaches deliver the most accurate results. Nevertheless, qualitative approaches remain relevant in assessing landslide susceptibility in large regions or in cases where quantitative approaches are not feasible due to a lack of data.

Quantitative methods are widely applied in assessing landslide susceptibility due to the following advantages:

1) The results can be easily explained owing to an independent analysis of each of the maps of the development factors of landslide (slope) processes;
2) Analysis can include the expert assessment, since specific combinations of variables can be considered and assessed in terms of their significance in the occurrence of landslides;
3) The accuracy of the developed maps can be verified using data on the spatial distribution of landslides.

The study has used the Frequency Ratio method (FR) and the Index of entropy method to assess the landslide susceptibility and compile maps of the potential development of landslides in the Girdimanchay River basin. When forecasting the landslide (slope) processes, it is reasonable to assume that causal factors define their occurrence. In addition, it is assumed that future landslides can occur under the same conditions as the previous ones.

Frequency ratio as a bivariate statistical method represents a straightforward and efficient model for assessing landslide susceptibility. This method is based on the observed correlation between the distribution of landslides and each associated factors to reveal the correlation between the places of manifestation of the process and the factors that cause it in the study area. According to it, each causative factor is subdivided into several classes. In addition, the frequency rate (FR) for each class of factors is defined by applying the following equation (1):

$$F_{ij} = \frac{\frac{N_i}{N}}{\frac{P_i}{P}} \quad (1)$$

where N_i is the number of points (pixels) of landslides in the class of factors i; N is the total number of points (pixels) of landslides on the map of the study area; P_i is the number of points (pixels) in the class of factors i; and P is the total number of points (pixels) on the map of the study area.

The Frequency Ratio (FR) model is commonly practiced in forecasting geological and geomorphological processes. It was first proposed by Lee, Talib (2005). FR is a usable geospatial assessment tool, predicting the probability distributions of occurrence and non-occurrence of geological processes for each class of related factors. Classes are assessed based on the ratio of observed landslides to the entire study region. FR is one of the best geospatial assessment tools for defining the spatial correlation between the record of stocktaking and a class of related factors. The amount or percentage of stocktaking record in each class refers to the significance of correlation with the development of geological processes. FR shows the correlation between the locations of geological processes and the factors influencing the occurrence of processes in a given area. Process development factors could be assessed, considering the ratio of observed processes in the territory under consideration. The correlation among the class factors could be determined through FR, which is quite a useful geospatial estimation tool.

As a result of the analysis, five zones of potential development of the landslide process have been identified in the study area: very low, low, medium, high, and very high.

The results of quantitative methods in assessing landslide susceptibility are verified by AUCROC (area under the error curve) analysis.

ROC-curve or curve of errors (Receiver Operating Characteristic) is a graph, allowing estimating the quality of two-class classification. It shows the dependence of the number of correctly classified positive examples on incorrectly classified negative examples. The Area Under the ROC-curve is an aggregated characteristic of the classification quality, independent of the ratio of error rates. The higher the AUC value, the better the resulting classification model.

Landslide inventory. One of the main elements of the FR methodology is the compilation of an inventory map of landslides and fall-scree processes. A map of manifestations of slope processes can be compiled based on both field studies and by interpreting multispectral images obtained using remote sensing.

The sources for the inventory of landslides are satellite images of 2008-2022 taken from open sources (Google Earth, Earthexplorer), field surveys and geomorphological maps of the region.

The Landslide Inventory Mapping (LIP) is a map, showing the number of active manifestations of landslide processes. The compiling inventory maps of landslides (LIM - Landslide Inventory Mapping) calls attention to the selection of the boundaries of landslides and ignores the specifics of landslide deformations. LIP is a major element in landslide risk assessment. At the same time, with the image of the spatial distribution of landslides, the landslide inventory map can contain the following types of information, such as the geometrical features of the landslide (scale, area, and depth of capture of the slope mass by landslide deformations), structural style (lithology, structure, and soil properties) and hydrogeological conditions.

Compiling the landslide and avalanchine-scree inventory maps will be conducted by applying the contrast enhancement algorithm proposed by Gond and Brognoli in 2005. This technique is based on a combination of spectral bands to generate a normalized difference vegetation index (NDVI) and normalized difference water index (NDWI). Afterwards, the resulting layers are combined with mid-infrared (MIR) to increase terrain contrasts (Figure 3).

The study has identified over 120 landslide areas in the Aghsuchay River basin. Most of the landslides have been observed along the Baskal tectonic cover, the Steppe plateau, as well as on the slopes of the Langabiz Ridge and partially on the slopes of the Nialdagh Ridge. Slope processes are long-term successive events, starting from their formation and ending with the results. Sometimes there is a need only to prevent its destructive consequences. In many cases, it is not possible to eliminate the primary reason for a landslide. Then it becomes efficient to mitigate the impact rather than trying to eliminate the cause. It is more common for landslides to emerge under the influence of geological-tectonic, topographic, hydrological-climatic, and anthropogenic factors.

Research results. The research has selected ten factors, associated with landslides, for landslide susceptibility mapping and compiling maps for the potential development of landslides based on the available data, the characteristics of landslides, and the relationship between the formation of slope deformations and factors causing landslides. These factors

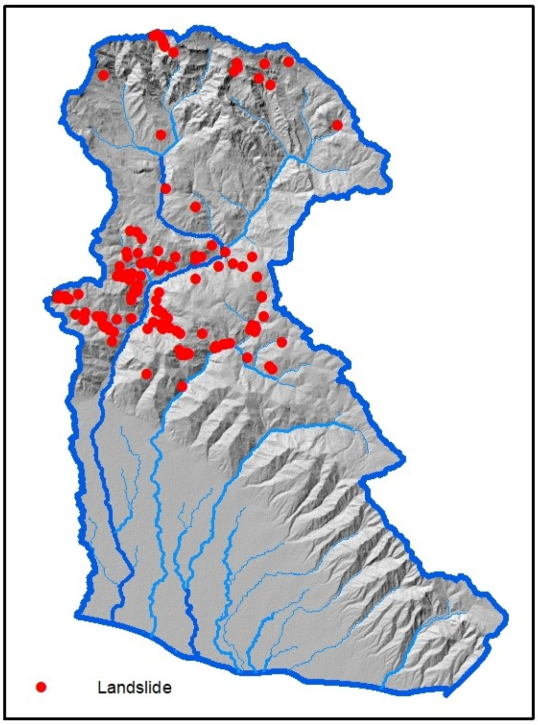

Fig. 4. Map of the distribution of landslides in basin Agsuchay river

include hypsometry, slope angles (steepness of slopes), slope exposure, topographic moisture indices, geological structure (lithology), distance from faults, average annual precipitation, distance to erosion network, distance to roads, and land use (Fig. 5).

Maps for hypsometry, slope and aspect were compiled using a digital elevation model (DEM). To create a digital elevation model were used SRTM (resolution 30m) and Alos Palsar (resolution1 2.5m) data. Fault distance, road distance, and streams distance were estimated using the "Euclidean distance" tool in Spatial Analyst Toolbox in ArcGIS Desktop (ArcMap). A map of average monthly precipitation was developed by interpolating rainfall data for nearby settlements (Figure 6). The Land use and land cover map was developed based on the classification training in the ArcGIS software environment.

Data on the lithology and tectonic disturbances were digitised from the geological map of the Mountainous Shirvan economic region at a scale of 1:200,000. Afterwards, to conduct analysis, these maps were transformed into a raster format to calculate the weights of classes and factors and compile maps of landslide susceptibility.

The slope angle is considered one of the key triggering agents in landslide events and is widely utilised in landslide susceptibility mapping; this parameter was obtained from the DTM using spatial analysis tools and reclassified into five classes based on the natural boundaries (intervals) algorithm.

Aspect is the most important source of changes in soil properties. It determines the direction of the slope and is measured clockwise in degrees from 0 (North) to 360 (North again), forming a full circle. Flat areas have a value of -1. The effect of slope exposure is reflected in differences in temperature and humidity between polar and equatorial exposure. Accordingly, slopes facing south and west are warmer than slopes exposed to the east and north. On the other hand, the southern slopes in the mountainous area make it possible to determine the places where the snow can melt first. Differences in impact on slopes determine changes in soil properties due to their effect on microclimatic and vegetation conditions. Such parameters related to the orientation of the slope as exposure to sunlight, dry wind, rainfall, and discontinuities, can influence the occurrence of landslides. The slope exposure was split into nine categories: flat (–1°), northern (0°-22.5°; 337.5°-360°), northeastern (22.5°-67.5°), eastern (67.5°-112.5°), southeast (112.5°-57.5°), south (157.5°-202.5°), southwest (202.5°-247 .5°), western (247.5°-292.5°-292.5°-337.5°), and northwestern (292.5°-337.5°).

The distance to rivers is one of the factors determining the stability of the slope as they destroy the toe of the slope, resulting in erosion processes. Consequently, the risk of soil slippage decreases due to an increase in the distance from watercourses.

Based on the Distance to Rivers parameter, the research has identified three classes using the ArcGIS Euclidean distance tool: up to 200 m, within 200-500 m, and over 500 m.

The Topographic Wetness Index (TWI) is a robust index of wetness. It is mainly used for quantitive evaluation of the topographic control of hydrological processes. TWI is an indicator of the hydromorphism of the soil continuum, commonly defined by the relief features of the studied territory. Large values of the index correspond to the wet deposition, and its increased content in the soil. TWI is estimated using the following formula (2), where a is the total runoff into the cell (non-dimensional value); tan b is the surface slope within the cell (in radians):

$$TWI = ln\frac{a}{\tan b} \quad (2)$$

Based on the ***Distance to roads*** parameter, the research has identified three classes using the ArcGIS: distance up to 500 m, within 500-1000 m, and over 1000 m.

Discussion. The article has analysed the relationship between the factors causing landslides and the actual occurrence of landslides in the study area. The frequency ratios (F_{ij}) and the weight factor (W_j) were calculated using the FR models, respectively (Table 2).

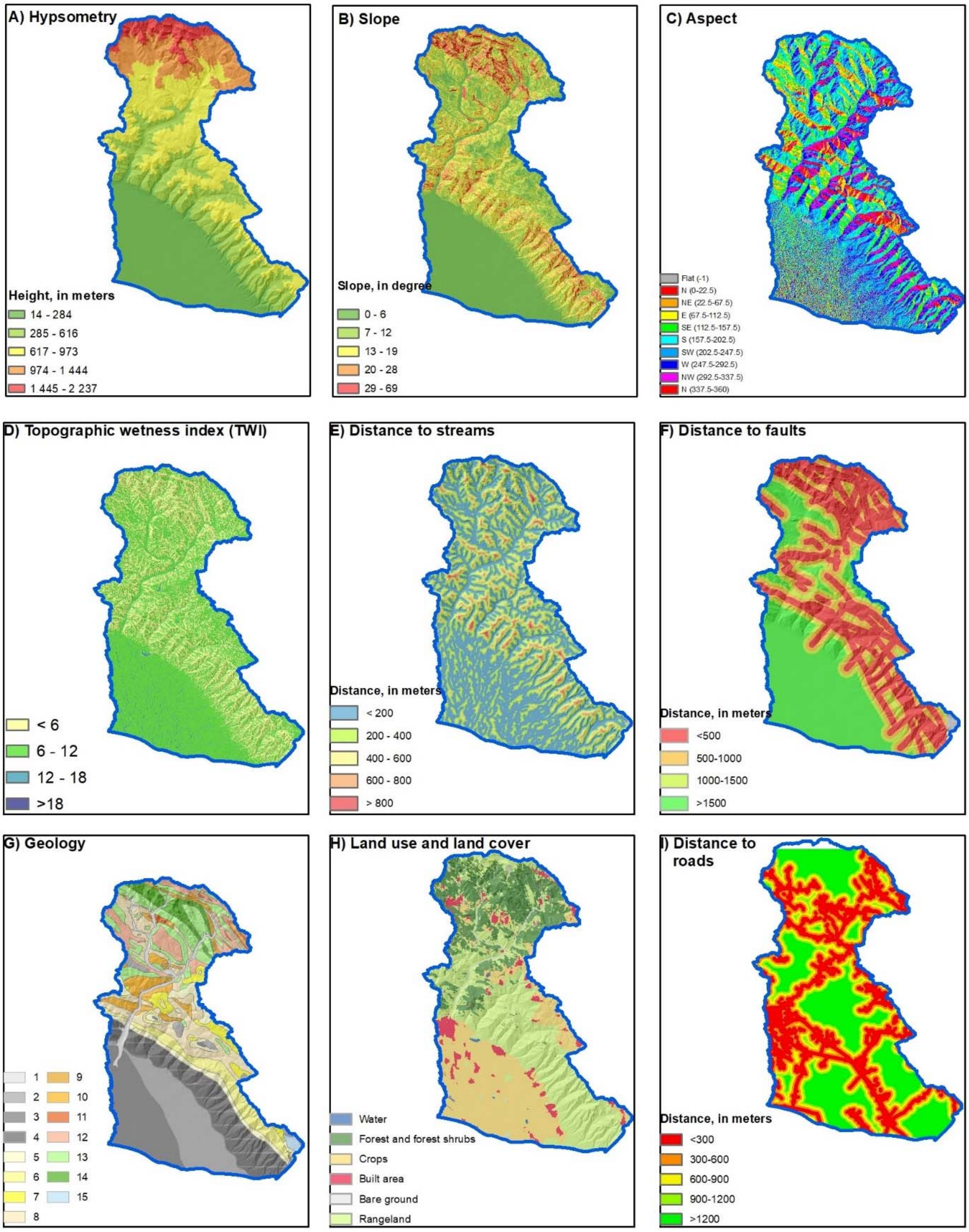

Fig. 5. Maps of landslide factors in the basin of the Agsuchay river

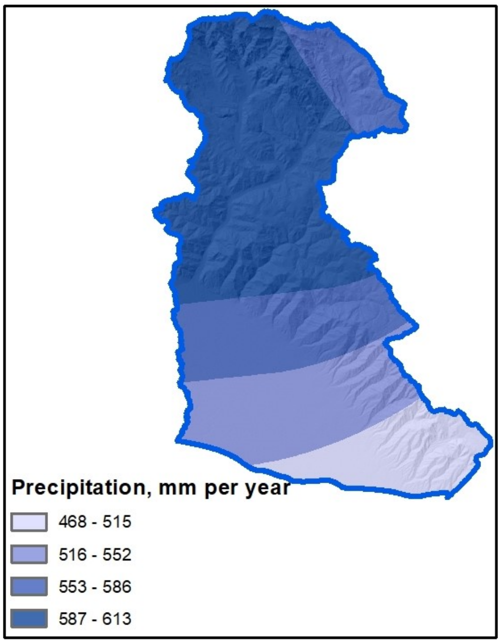

Fig. 6. Distribution map of annual precipitation in the basin Agsuchay river

Table 2

Analysis of the relationship between factors causing landslides and landslide distribution

Factor Name	Factor classes	Class area, Pi	Landslide area, Ni	FR_{ij}	Weight factor a, W_i
Hypsometry, in meters	14-284	306323400	4993,08222	0,005907426	3,83
	284-616	203414900	1314290,198	2,341629738	
	616-973	258086400	828851,6485	1,16391537	
	973-1444	117177100	49930,8222	0,154431429	
	1444-2237	54171620	393343,9215	2,631542192	
Slope, in degrees	0-6	330906600	66019,64268	0,072005394	3,32
	6-12	227688500	841611,7475	1,334037325	
	12-19	217790500	1162278,583	1,926054587	
	19-28	121181000	483219,4015	1,439153503	
	28-69	37695560	38280,29702	0,366507096	
Aspect	flat areas	50809610	74341,44638	0,528058947	1,00
	north	26740180	110957,3827	1,497576918	
	northeast	64591080	272955,1613	1,525162171	
	east	82213330	207490,3056	0,910862518	
	southeast	131276500	357282,7722	0,982250699	
	south	173426400	601389,014	1,251519271	
	southwest	184496600	494869,9267	0,968054829	
	west	131472300	309016,3107	0,848290108	
	northwest	90236100	163107,3525	0,652364743	
Geology*	1	29494140	97087,70982	1,193028445	2,86
	2	140260100	0	0	
	3	120623500	0	0	
	4	139786350	0	0	
	5	51286170	155895,1226	1,101677652	
	6	61790515	164216,9263	0,963204235	
	7	33116900	42718,59232	0,467508526	
	8	108513000	760612,8581	2,540412095	

	9	11266060	221914,7653	7,138984167	
	10	43814306	848269,1903	7,01681515	
	11	5965070	4438,295306	0,269663974	
	12	59204091,1	12760,09901	0,078113232	
	13	98113539,1	128155,777	0,473403567	
	14	31160724,2	155340,3357	1,806753797	
	Volcanic breccia	4806120	0	0	
Distance to faults, in meters	0-500	347749900	1543971,98	1,597895539	3,15
	500-1000	161212200	662415,5744	1,47879718	
	1000-1500	87413350	316783,3275	1,30424907	
	1500<	336260300	68238,79033	0,073035113	
Distance to streams, in meters	<200	469655500	1388076,857	1,067794446	2,61
	200-400	277143300	763016,9347	0,994679918	
	400-600	140608000	338604,946	0,870035199	
	600-800	44409040	101710,9341	0,827465345	
	>800	4429420	0	0	
Topographic wetness index (TWI)	<6	332261900	759503,2843	0,824985585	3,73
	6-12	563107100	1698757,529	1,088773744	
	12-18	36750760	133148,8592	1,307580313	
	>18	3142314	0	0	
Distance to roads, in meters	<300	278845400	242441,8811	0,310793604	2,28
	300-600	165115200	315673,7536	0,683406856	
	600-900	116582400	367823,7235	1,127806665	
	900-1200	84719300	378364,6748	1,596452995	
	>1200	281064000	1287105,683	1,636955589	
Land use and land cover	water	2350633	554,786913	0,085643955	5,26
	forests and forest shrubs	194466200	249654,111	0,46585411	
	crops	290814400	13869,67283	0,017306357	
	built area	50804620	21081,9027	0,150578142	
	bare ground	9854127	101526,0051	3,738647165	
	rangeland	392064100	2204723,193	2,040573919	
Precipitation, mm per year	468-515	120732192,2	0	0	8,77
	515-552	177959026	0	0	
	552-586	223405512,7	64355,28194	0,104399699	
	586-613	417074996,9	2527054,39	2,195883873	

** geological classes: 1 - Holocene, modern alluvial deposits - pebbles, gravel, sands, sandy loams, loams; 2 - Holocene, modern deluvial-proluvial deposits - pebbles, loams, sandy loams, clays; 3 - Middle and Upper Pleistocene, alluvial-proluvial deposits - clays, loams, sandy loams, pebbles with layers of volcanic ash; 4 - Eopleistocene, Absheron marine sediments - clays, sands, sandstones, limestones with layers of volcanic ash, loams, marls, conglomerates; 5 - Upper Pliocene, Akchagyl sedimentary deposits - clays, volcanic ash, breccias, sands, sandstones, pebbles, limestones; 6 - Lower Pliocene, Balakhani sedimentary deposits - clays, loams, sands, sandstones, pebbles, gravelstones, conglomerates; 7 - Upper Miocene, Pontian sedimentary deposits - sands, sandstones, clays, limestones, conglomerates, volcanic ash; 8 - Lower Miocene, Upper Maikop sedimentary deposits - shale clays with interlayers of clayey siderite nodules, volcanic ash, sands, sandstones, gravelstones, conglomerates; 9 - Oligocene and Lower Miocene Maikop sedimentary deposits - clays, mudstones, sandstones, marls; 10 - Eocene (Govundag Formation) sedimentary deposits - clays, marls, sandstones, clayey dolomites, volcanic ash, conglomerates; 11 - Middle and Upper Paleocene (Sumgait Formation) sedimentary deposits - clays, marls, sandstones; 12 - Lower Paleocene sedimentary deposits - limestones, sandstones, marls, argellites, clays; 13 - Upper Cretaceous volcanogenic-sedimentary and sedimentary deposits - tuff sandstones, basaltic andesites, porphyrites, limestones, sandstones, marls, mudstones, clays; 14 - Lower Cretaceous volcanogenic-sedimentary and sedimentary deposits - tuff sandstones, sandstones, marls, limestones, mudstones, tuff conglomerates, tuffs, tuffites, porphyrites, andesites.*

For the studied territory, the LSI values were determined using the following formula, when compiling maps of the landslide susceptibility index:

$$LSI = ((\text{Hypsometry} \times W_j) + (\text{Angle of gradient} \times W_j) + (\text{Exposure} \times W_j) + (\text{Geologic aspects} \times W_j) + (\text{Distance to faults} \times W_j) + (\text{Distance to watercourses} \times W_j) + (\text{Topographic Wetness Index} \times W_j) + (\text{Distance to roads} \times W_j) + (\text{Land management and vegetation cover} \times W_j) + (\text{Amount of precipitation} \times W_j)) \quad (7)$$

In this connection, a map of the landslide susceptibility of the Aghsuchay River basin was compiled in the ArcGIS software environment by summing up each landslide factor multiplied by its weights, using the Raster Calculator spatial analysis tool (Fig. 7).

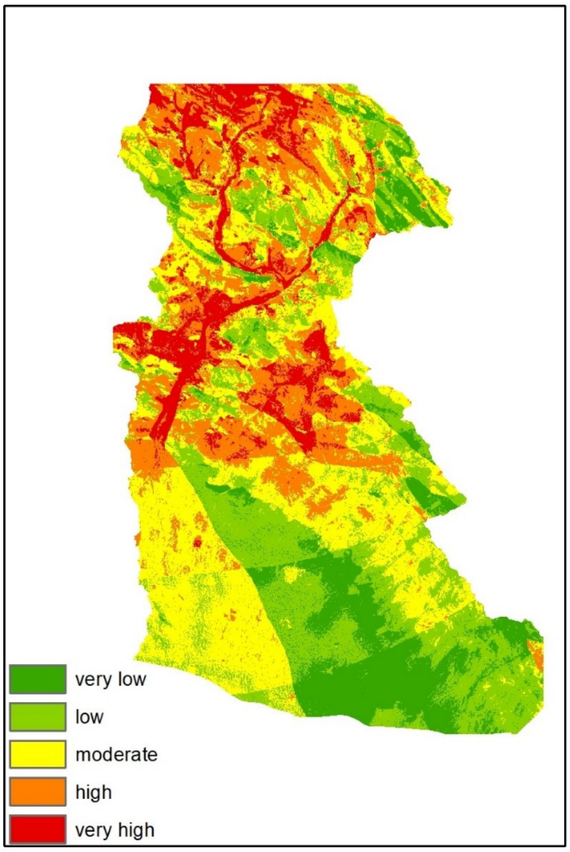

Fig. 7. Map of landslide susceptibility of the basin Agsuchay river

Using the natural boundary classification method in the ArcGIS software environment, the studied area was divided into five potential landslide zones: very low, low, moderate, high, and very high. The analysis result showed that zones with very low, low, medium, high, and very high landslide occurrence potential make 13.75; 24.48; 31.51; 20.51, and 9.74% of the study area, respectively. Areas with high and very high landslide susceptibility mainly cover the regions towards the Nialdagh Ridge, the slopes of the Steppe (tertiary) Plateau, and Langabiz Ridge. Almost the entire highland part of the basin is located in a zone of very high and high landslide susceptibility. The areas of low and very low susceptibility cover the flat part of the basin, as well as flat areas. The AUC value (from ArcSDM tool in ArcGIS Desktop) is 82%, showing the effectiveness of the method used for landslide susceptibility mapping and landslide development potential in the study area (Fig. 8).

The areas of distribution of Upper Cretaceous and Maikop clays, clay shales, and limestones have a high and very high potential for the development of landslides. Landslides are more common in areas with sparse vegetation, subalpine meadows, and partly in agricultural areas. Excavation work on the slopes, together with a large amount of precipitation, increases the risk of a landslide in the study area.

Conclusion. Landslide hazard assessment is an essential component of the national disaster prevention and mitigation strategy in Azerbaijan. The zoning of the territory, according to the potential for the development of a landslide process, is the basis for

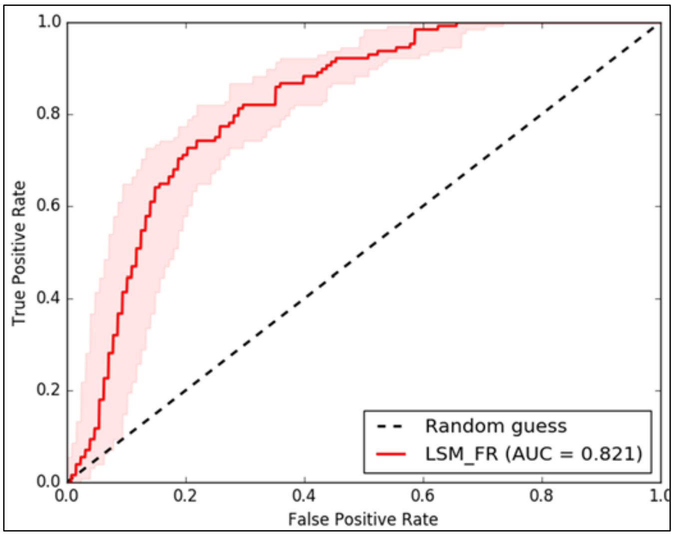

Fig. 8. Graph showing the validity of the model

assessing the landslide hazard associated with this risk and designing early warning systems.

Based on this idea, the study has made an analysis of the development potential of a landslide process in the Aghsuchay River basin on the southern slope of the Greater Caucasus. Landslide susceptibility mapping was compiled using statistical models (based on GIS), making it possible to determine the significance of each parameter influencing the development of landslide processes. Subsequently, susceptibility assessment was conducted by aggregating the result of the analysis of selected factors using spatial analytical equations. The study area was classified into five zones based on the degree of potential development of landslides: very low, low, medium, high, and very high. The accuracy of the obtained models was estimated using the AUC ROC (area under the error curve) analysis, which showed the high performance of the method used.

The results of the research conducted are of major importance for estimating landslide hazards and risks, planning sustainable land use, and reducing damage from landslides in the area under consideration. By virtue of its high reliability, the method can be used to assess the landslide susceptibility of various regions of Azerbaijan.

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Застосування кількісних методів для оцінки стійкості до зсувів басейну річки Агсучай

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Азербайджан робить багато зусиль для зменшення впливу небезпечних геологічних процесів на природні геосистеми, проте вони все ще завдають величезної шкоди. Більшою мірою до таких процесів схильний регіон Великого Кавказу, а саме південний схил, де зустрічається весь спектр небезпечних геологічних процесів: землетрус (7-8 б і вище), обвали, зсуви, осипи, селеві потоки та ін. Усі вони є масштабними за збитками процесами – впливають на значні площі, призводять до економічних втрат. Мета дослідження – виявити основні чинники формування та поширення зсувів у басейні однієї з найбільш селеносних річок не тільки Азербайджану, а й Південного Кавказу – р. Агсучай, виявити умови їх утворення, дати оцінку ризику вразливості території до зсувних процесів, а також способи запобігання та захисту. Для оцінки зсувної вразливості та створення карт потенційного розвитку зсувів у басейні р. Агсучай нами було використано метод співвідношення частотностей (Frequency Ratio method – FR). На прикладі басейну р. Агсучай для мінімізації збитків від зсувів було проведено детальне вивчення факторів (гіпсометрія, кути нахилу (крутість схилів), експозиція схилів, геологічна будова (літологія), відстань від розломів, середньорічна кількість опадів, відстань до ерозійної мережі, відстань до доріг та землекористування), що визначають розвиток зсувних процесів з урахуванням механізму їх розвитку, а також аналіз отриманих значень зсувної вразливості та потенційного їх розвитку. Для цього в програмному середовищі ArcGIS за допомогою інструменту просторового аналізу «Калькулятор растру» підсумувавши кожен фактор утворення зсувів, перемножені на свою вагу, була отримана карта зсувної вразливості басейну р. Агсучай. Використовуючи метод класифікації природних кордонів у програмному середовищі ArcGIS, район дослідження був поділений на п'ять зон за потенціалом розвитку зсувів: дуже низький, низький, середній, високий та дуже високий. В кінцевому підсумку достовірність отриманих моделей була оцінена із застосуванням AUC ROC (площа під кривою помилок) аналізу, який показав високу результативність (82%) методу, що використовується.

Ключові слова: *зсув, селеносна річка, геосистема, туристично-рекреаційний потенціал, збитки, зсувна небезпека, вразливість, кількісні методи*

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