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Integrated Evaluation of Exodynamic Processes in the Nakhchivanchay Basin Based on Geological and Geophysical Indicators Using Gis and Remote Sensing Methods

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Abstract: *In this study, the mechanisms of formation and distribution characteristics of exodynamic processes developing in the Nakhchivanchay basin over the territory were systematically investigated based on modern scientific methods. During the study, the geological structure, lithological composition, tectonic features, and geomorphological conditions of the territory were taken as the main objects of analysis. The intensity and spatial differentiation of the processes formed as a result of the interaction of these factors were widely evaluated. Within the framework of the study, the morphometric indicators of the territory were determined by applying digital relief models, satellite data and geographic information systems technologies. In particular, the degree of inclination of the slopes, exposure characteristics and the level of fragmentation of the relief were analyzed in detail. In addition, the distribution of structural linearities and tectonic faults was assessed using cartographic methods and sensitive areas in terms of risk were identified. The conducted analyses showed that erosion, landslides, denudation, and floods are observed more intensively mainly on steep slopes, in areas where weakly resistant rocks are distributed and in tectonically active zones. At the same time, climatic and hydrological factors, especially the amount of precipitation and the formation of surface runoff, play an important role in strengthening these processes. In addition, it was determined that anthropogenic impacts are also significant. Agricultural activity, improper land use and construction work lead to disruption of the natural balance in some areas and acceleration of processes. In particular, the weakening of vegetation cover further increases the risk of erosion.*

Keywords: *Nakhchivanchay basin, exodynamic processes, lithology, geological risk, tectonic faults, GIS, remote sensing*

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Naxçıvançay hövzəsində ekzodinamik proseslərin GIS və məsafədən zondlama metodlarından istifadə etməklə geoloji və geofiziki göstəricilər əsasında inteqral qiymətləndirilməsi

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Xülasə: *Bu tədqiqatda Naxçıvançay hövzəsində inkişaf edən ekzodinamik proseslərin formalaşma mexanizmləri və yayılma xüsusiyyətləri müasir elmi metodlar əsasında sistemli şəkildə araşdırılmışdır. Tədqiqat zamanı ərazinin geoloji quruluşu, litoloji tərkibi, tektonik xüsusiyyətləri və geomorfoloji şəraiti əsas təhlil obyektləri kimi götürülmüşdür. Bu amillərin qarşılıqlı təsiri nəticəsində formalaşan proseslərin intensivliyi və məkan üzrə diferensiasiyası geniş şəkildə qiymətləndirilmişdir. Tədqiqat çərçivəsində rəqəmsal relyef modelləri, peyk məlumatları və coğrafi informasiya sistemləri (GIS) texnologiyalarının tətbiqi ilə ərazinin morfometrik göstəriciləri müəyyən edilmişdir. Xüsusilə, yamacların meyillilik dərəcəsi, ekspozisiya xüsusiyyətləri və relyefin parçalanma səviyyəsi ətraflı təhlil edilmişdir. Bununla yanaşı, struktur lineamentlərin və tektonik qırılmaların paylanması kartoqrafik metodlarla qiymətləndirilmiş, risk baxımından həssas ərazilər müəyyən edilmişdir. Aparılmış təhlillər göstərmişdir ki, eroziya, sürüşmələr, denudasiya və sel hadisələri əsasən dik yamaclarda, zəif dayanıqlı süxurların yayıldığı sahələrdə və tektonik cəhətdən aktiv zonalarda daha intensiv müşahidə olunur. Eyni zamanda, iqlim və hidroloji amillər, xüsusilə yağıntının miqdarı və səthi axının formalaşması bu proseslərin güclənməsində mühüm rol oynayır. Bundan əlavə, antropogen təsirlərin də əhəmiyyətli olduğu müəyyən edilmişdir. Kənd təsərrüfatı fəaliyyəti, torpaqdan qeyri-səmərəli istifadə və tikinti işləri bəzi ərazilərdə təbii tarazlığın pozulmasına və proseslərin sürətlənməsinə səbəb olur. Xüsusilə, bitki örtüyünün zəifləməsi eroziya riskini daha da artırır.*

Açar sözlər: *Naxçıvançay hövzəsi, ekzodinamik proseslər, litologiya, geoloji risk, tektonik qırılmalar, GIS, məsafədən zondlama*

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Introduction

There is a close relationship between the development of relief and slope processes in mountainous and tectonically active areas. Various studies have shown that tectonic uplifts, lithological properties of rocks and morphostructural elements play an important role in the formation of slope instability (Abdelkarim et al., 2025; Alizadeh et al., 2016). The geological structure of Azerbaijan is distinguished by complex structural features, and here, along with endogenous processes, exogenous factors also affect the transformation of the relief (Erener et al., 2016; Bababayli et al., 2026). The application of geophysical methods provides significant results in determining the underground structure and potential risk zones (Blakely, 1995; Chen et al., 2016; Corominas et al., 2013; Eastman, 2012).

Studies conducted in the field of landslide assessment show that a systematic and multiparameter approach is required for objective determination of risk and hazard (Eppelbaum et al., 2014; Guzzetti et al., 1999; Horton, 1945). Preparation of landslide inventories, spatial-temporal analysis of existing events and statistical evaluation increase the reliability of models (Hummatov, 2025). Climate change, especially increased precipitation intensity and changes in temperature regime, lead to the intensification of slope processes (IPCC, 2023). The development of drainage networks, erosion, and flood events are also among the factors that directly affect slope stability (Iskenderova et al., 2025; Kearey et al., 2002). Digital elevation models and morphometric analysis methods are widely used in determining landslide susceptibility. Indicators such as slope angle, exposure, curvature, flow direction and accumulation area are considered key parameters in mapping risk zones (Leulalem et al., 2020; Lowrie, 2007; Malczewski, 2006). Processing of high-precision topographic data allows for a more detailed analysis of geomorphological features (Mandal, 2018). At the modern stage, the integration of GIS and remote sensing technologies has made the preparation of landslide susceptibility maps more effective. Multi-criteria decision-making approaches, especially the Analytical Hierarchy Process (AHP), are widely used in determining the relative weight of various factors (Montgomery & Dietrich, 1994; Mutlu et al., 2019; Moore et al., 1991; Qiqing & Wenping, 2017; Reichenbach et al., 2018). Statistical models and forecasting methods act as important tools in landslide hazard assessment (Riley et al., 1999; Shahabi & Hashim, 2015). Special software and geographic information systems create an important technical basis for implementing these processes (Shano et al., 2020). Thus, a review of the existing literature shows that a comprehensive analysis of geological structure, climatic factors, hydrological characteristics and anthropogenic impacts is essential for studying landslides and related geomorphological processes. The combined application of geophysical surveys, digital terrain analysis and GIS-based multi-criteria modeling methods allows for more accurate results (Tarboton, 1997; Tarolli et al., 2012; Telford et al., 1990; Saaty, 2014; Wilson & Gallant, 2000).

Methods

Exodynamic processes play a leading role in the formation of the Earth's surface, leading to the development of relief, land cover degradation and landscape transformation. Especially in mountainous and semi-desert conditions, these processes take on an intensive character and lead to an increase in natural risks. The Nakhchivanchay basin is one of the regions with high dynamics from a geomorphological and geological point of view. Here, the complex tectonic structure, poorly cemented rocks and intensively fragmented relief create favorable conditions for the activation of exodynamic processes. The application of modern GIS and remote sensing methods allows for a more accurate determination of the spatial regularities of these processes. The main goal of the study is a comprehensive assessment of exodynamic processes in the Nakhchivanchay basin based on geological and geophysical indicators.

Research object and natural-geographical conditions

The Nakhchivanchay basin is located in the southwestern part of the Lesser Caucasus and is part of a complex geological-geomorphological system on a regional scale. The interaction of tectonic structure, lithological diversity and climatic factors plays a decisive role in the formation of the basin relief. The hypsometric structure of the territory is characterized by a sharp vertical discontinuity; absolute heights vary between 2800–3200 m in the upper parts of the basin and 700–900 m in the lower reaches. These differences create conditions for the uneven distribution of the intensity of slope processes over space. From a geological point of view, the Nakhchivanchay basin is characterized as an area where Mesozoic and Cenozoic rock complexes are widespread. Jurassic and Cretaceous carbonate rocks predominate mainly in the mountainous areas of the basin and have a high degree of fracture. These features increase the susceptibility of rocks to physical weathering and karstification, creating favorable conditions for the development of avalanche and landslide processes. Paleogene–

Neogene terrigenous sediments are more common in foothills and plains and play a key role in the formation of surface washing, linear erosion and flood flows.

Although the local distribution of volcanic rocks relatively increases lithological stability, in the zones where these rocks are cut by tectonic faults, mechanical stability decreases and the intensity of exodynamic processes increases. In this regard, the lithological factor, not alone, but together with the tectonic structure, acts as one of the main factors determining the spatial distribution of exodynamic processes. From a tectonic point of view, the territory is located in an active structural zone and is characterized by regional and local fault systems of various directions. These faults, in addition to controlling the morphostructural development of the relief, play an important role in the localization of exodynamic processes. The degree of fragmentation of rocks increases along the fault zones, the possibilities of water infiltration increase, and as a result, landslides, floods and erosion processes develop more intensively. Many studies show that areas close to faults are considered more dangerous zones in terms of exodynamic risk.

The climatic conditions are characterized by sharply continental and semi-desert features. The annual precipitation varies spatially, and in mountainous areas it is 400–500 mm, and in plain zones it is 200–300 mm. The main part of the precipitation falls on the spring and autumn months and is of the nature of short-term, but intense downpours. Such a precipitation regime enhances surface runoff on the slopes, weakens the stability of the soil cover and increases the frequency of flood events. High temperature amplitude and strong evaporation lead to a decrease in soil moisture in the summer season, and rapid saturation of the soil in the autumn and spring seasons, which plays an important role in the activation of landslide processes. Thus, the climatic factor, together with lithological and tectonic factors, acts as the main natural and geographical condition that increases the intensity of exodynamic processes. In general, the natural and geographical conditions of the Nakhchivanchay basin — complex relief, diverse lithological complexes, active tectonic faults and continental climate features - determine the high intensity and spatially differential development of exodynamic processes. These features make the basin an important model area for geological risk assessment and GIS-based monitoring studies.

Materials and methods

Remote sensing, cartographic and field data obtained from various sources were used in a complex manner for the study. The data used were aimed at assessing the spatial distribution, intensity of exodynamic processes and the factors determining them.

The main morphometric analyses in the study were carried out on the basis of a digital relief model (DEM) with a spatial resolution of 30 m originating from SRTM (Shuttle Radar Topography Mission). DEM data were used to calculate the main geomorphometric indicators such as slope inclination, exposure and degree of relief fragmentation. Geological and tectonic maps were used to analyze the lithological composition of the region, stratigraphic complexes and tectonic fault systems. Based on these maps, the distribution areas of lithological units and the spatial density of fault zones were determined, and their impact on the localization of exodynamic processes was assessed.

Landsat 8 OLI/TIRS and Sentinel-2 MSI satellite images were used as remote sensing data. These images played an important role in determining the state of landscape cover, surface changes and erosion traces. Normalized Difference Vegetation Index (NDVI) and land surface indicators were calculated based on satellite images. Topographic and hydrographic materials were used to assess the structure of the river network, drainage density, and water erosion processes. Hydrographic data served as an additional source of information in the analysis of flood risk and the intensity of slope processes.

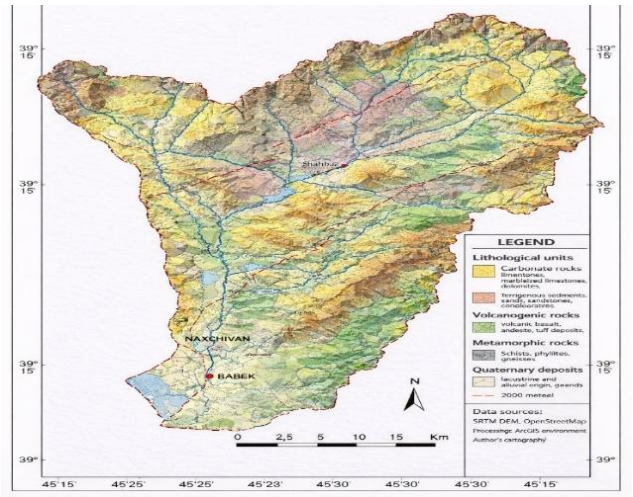

Figure 1

Lithological and tectonic fault map of the Nakhchivanchay basin (scale 1:180,000)

The compiled "Lithological and Tectonic Fault Map of the Nakhchivanchay Basin" reflects the geological structure and tectonic features of the Nakhchivanchay Basin, one of the main hydrographic units of the Nakhchivan Autonomous Republic, in general. The map was prepared at a scale of 1:180,000 and allowed for the assessment of the spatial distribution of lithological units and tectonic structures at the regional level. The map presents the main lithological complexes distributed in the basin area in a generalized form using conventional symbols and color shades. These rock complexes play an important role in the formation of the relief, the movement of surface and groundwater, as well as the development of exodynamic processes. Lithological diversity reflects the complexity of the geological development history of the basin and acts as one of the main factors in explaining the geomorphological features of the area. The tectonic faults shown on the map demonstrate that the basin is located in a structurally active zone. The spatial location of these faults is considered to be the main structural elements influencing the formation of the hydrographic network, the degree of fragmentation of the relief and the intensity of geodynamic processes. The presence of tectonic elements determines the spatial differentiation of risks in the area. In general, the compiled map creates a general idea of the geological and tectonic features of the Nakhchivanchay basin and plays the role of a reliable cartographic basis for the assessment of exodynamic processes, identification of geological risks, as well as for territorial and landscape planning. The use of modern geographic information technologies in the preparation of the map increases its scientific and practical significance.

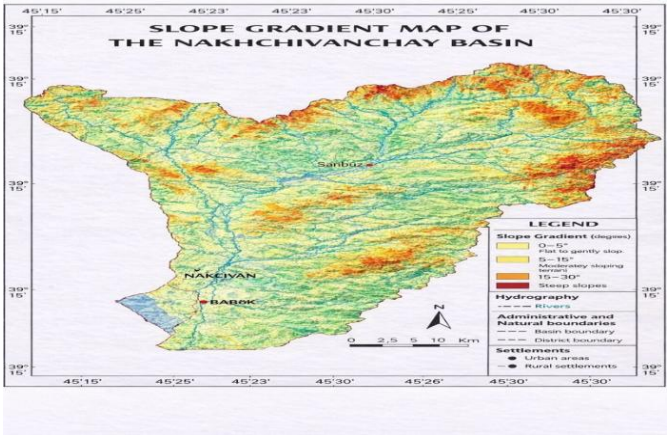

Figure 2

Slope Gradient Map of the Nakhchivanchay Basin

The role of slope gradient in the development of exodynamic processes. In the Nakhchivanchay Basin, the morphometric characteristics of the relief, in particular slope gradient, are considered to be one of the main factors determining the spatial distribution and intensity of exodynamic processes. The slope gradient map calculated based on the digital relief model (SRTM, 30 m spatial resolution) shows that the geomorphological conditions within the basin are highly heterogeneous (Figure 2). Areas with a slope of 0–5° are mainly represented by river valleys, terraced plains and accumulative forms. Since the kinetic energy of the surface flow is weak in these zones, erosion processes are limited in nature, and sediment accumulation prevails. Such relief conditions are characterized by fluvial accumulation and relative stability of the soil cover. Slopes located in the range of 5–15° and 15–30° constitute the most widespread morphometric zone in the basin. As a result of the increase in the speed of surface runoff in these areas, the processes of ravine erosion, slope washing and soil loss become more active. Studies show that it is in this slope range that the hydrological response is formed more quickly and erosion processes are more sensitive to climatic factors. Areas with a slope of more than 30° are characterized by high erosion and landslide potential. These zones are mainly concentrated in mountainous areas, along tectonic faults and in areas where lithologically weak rocks are distributed. With an increase in the slope angle, the effect of gravity increases and favorable conditions are created for mass movements (landslides, avalanches, rock flows). These features are clearly observed in geodynamically active areas of the Nakhchivanchay basin.

Thus, the slope inclination map is not only an important analytical tool for understanding the spatial structure of exodynamic processes in a basin, but also has practical importance in terms of erosion risk assessment, land use planning, and natural hazard management. Morphometric analysis of the relief. It was carried out using DEM-based GIS methods. In this framework, such main indicators as slope, aspect, degree of relief fragmentation (Terrain Ruggedness Index – TRI) and drainage density were calculated. These parameters play a fundamental role in assessing the intensity and spatial differentiation of exodynamic processes. The results of the slope analysis show that weak and medium slopes prevail in the Nakhchivanchay basin, which mainly corresponds to foothill and plain relief forms. At the same time, the spread of medium and high slopes is observed in the upper mountainous parts of the basin. As a result of the acceleration of surface runoff, erosion, ravinement and landslide processes develop more intensively in these areas. The close relationship between slope inclination and erosion processes has been widely proven in various studies.

The exposure analysis allowed us to assess the distribution of solar radiation and microclimate differences. High evaporation and reduced soil moisture on southern and southwestern slopes act as one of the main factors increasing the risk of erosion. Northern-facing slopes have more humid conditions and show relative geomorphological stability. TRI indicators characterize the morphological contrast of the relief. In the Nakhchivanchay basin, especially in areas with intensive tectonic faults, an increase in TRI values is observed, which determines the localization of exodynamic processes.

Table 1
Geomorphological interpretation of slope inclination classes

Slope inclination (°)	Geomorphological characteristic	Exodynamic risk
0–5°	Plains and alluvial areas	Low
5–15°	Foothill zones	Medium
15–30°	Mountainous areas	High
>30°	Rigidly dissected relief	Very high

Note: The area distribution was assessed based on quality indicators in accordance with DEM-based GIS analyses.

GIS-based multi-criteria assessment (AHP method). In order to identify potential development areas of exodynamic processes in the Nakhchivanchay basin, a GIS-based multi-criteria decision-making (MCDA) approach was applied. This approach allows for the consideration of the combined effects of various natural-geographical and geological factors and an objective assessment of risks by location. The Analytical Hierarchy Process (AHP) method was used within the framework of the study (Saaty, 2014). AHP is one of the widely applied scientific methods in terms of hierarchical structure of complex problems, determination of the relative importance of factors and systematic analysis of mutual influence.

The assessment process was carried out in three stages:

1. Selection of factors and preparation of thematic layers. The main natural-geographical and geological factors affecting the formation of exodynamic processes were identified. The selection of factors was carried out on the basis of scientific literature, physical-geographical characteristics of the region and existing databases. The selected factors were converted into thematic layers in the GIS environment, and slope inclination, height and degree of relief fragmentation were calculated as morphometric indicators based on DEM. Lithological and tectonic data were digitized from geological maps, and the hydrographic network was evaluated by distance analysis. All layers were brought to the same coordinate system and aligned with spatial accuracy.

2. Calculation of AHP weight coefficients and GIS integration. Pairwise comparisons between the selected factors were carried out based on the Analytical Hierarchy Process (AHP) method. At this stage, the influence of each factor relative to the other was assessed on a scale of 1–9, as a result, the relative weight coefficients of the factors were determined. For example, a weight value of 0.35 was calculated for slope inclination, 0.30 for lithological structure, 0.20 for tectonic fracture density, and 0.15 for proximity to the hydrographic network. The Consistency Ratio (CR) was checked and found to be below 0.1, which indicates that the logical sequence of the results is ensured

3. Integration of weighted layers in the GIS environment and compilation of the final risk map

In the third stage, the weighting coefficients calculated were applied to thematic GIS layers and a final risk map was prepared using the Weighted Overlay algorithm. The digital values of each factor in GIS were multiplied by the weighting coefficient to determine the overall risk indicator for the areas. As a result, low, medium and high risk zones were identified in the Nakhchivanchay basin, and the spatial distribution of these zones was visually displayed on the map. The final risk map was consistent with the geomorphological and geological characteristics of the region and demonstrated that the assessment was scientifically sound.

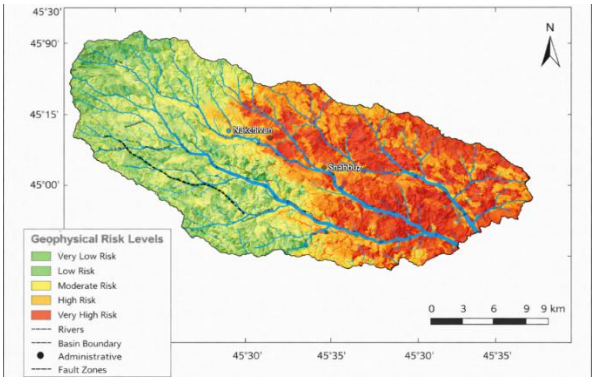

Figure 3
Final risk map of the Nakhchivanchay River Basin

This map was prepared in a Geographic Information Systems (GIS) environment to assess risk levels in the Nakhchivanchay River Basin. In the third stage of the study, pre-calculated weighting factors were applied to appropriate thematic layers and a final risk map was compiled based on the Weighted Overlay method. The main factors affecting the formation of risk (slope of the relief, geological structure, soil cover, land use forms, density of the hydrographic network, etc.) were reclassified on a single scale and integrated according to their relative importance. As a result, the area was divided into very low, low, medium, high and very high risk classes. As can be seen from the map, high and very high risk zones are mainly concentrated in areas with mountainous, fragmented relief and complex geological conditions. Low risk areas are mainly characterized by plain areas and more stable landscape features.

Table 2
AHP weighting factors and GIS integration for the Nakhchivanchay basin

Factor	Weighting coefficient	Description	Reclassification / category in GIS	Risk impact
Slope inclination	0.35	The risk of surface erosion and landslides increases in areas with high slope angles. Areas with slope angles between 15–30° are classified as medium risk, and >30° are classified as high risk.	0–5° → 1, 5–15° → 2, 15–30° → 3, >30° → 4	High propensity → high risk; medium propensity → medium risk
Lithological structure	0.30	Mechanical strength and resistance to erosion of rocks. Weakly cemented clay and terrigenous rocks are more susceptible, while strong carbonate and volcanic rocks are less at risk.	Strong rock → 1, Medium rock → 2, Weak rock → 3	Weak rock → high risk; strong rock → low risk
Tectonic fault density	0.20	The density of fault zones increases the fragmentation of rocks and increases the likelihood of landslides. The risk is considered higher in areas with a high fracture density.	Low → 1, Medium → 2, High → 3	High fracture density → high risk
Proximity to hydrographic network	0.15	Surface erosion and soil displacement are more intense in areas near rivers and streams..	>500 m → 1, 200–500 m → 2, <200 m → 3	Areas close to rivers → high risk; remote areas → a

This table was prepared for GIS-based multi-criteria assessment of exodynamic processes in the Nakhchivanchay basin. The table takes into account four main factors – slope, lithological structure, tectonic fracture density and proximity to the hydrographic network – and evaluates the impact of each on exodynamic processes using the Analytical Hierarchy Process (AHP) method. Relative weightings were determined for each factor, and the consistency ratio was calculated to confirm the logical sequence of the results. The table also presents reclassification values in the GIS environment, which allows for the calculation of risk zones using the Weighted Overlay algorithm.

The risk impact column in the table simply explains how each factor affects the overall risk. Thus, areas with high slope, weak lithological rocks, high fracture density and proximity to rivers are

considered high risk zones. The table also shows the distribution of medium and low risk areas, which is consistent with the geomorphological characteristics of the basin. Overall, this table, combining AHP weighting factors and GIS integration, provides an objective and scientifically sound assessment of potential development areas of exodynamic processes in the Nakhchivanchay basin.

The results showed that the risk zones for exodynamic processes in the Nakhchivanchay basin are divided into low, medium and high categories. High risk zones mainly coincide with areas with high slope inclination, poorly cemented rocks, density of fault zones and close to river valleys. Medium risk zones cover areas with more balanced slopes and solid lithological rocks, while low risk zones mainly consist of areas with low slopes and stabilized geological structures. This spatial distribution is consistent with the geomorphological characteristics of the region and confirms that GIS–AHP integration is a reliable and scientifically sound method for assessing exodynamic processes. The obtained data are of practical importance for land management, infrastructure planning, and reducing erosion and landslide risks. The weighted summation method in the GIS environment takes into account the interaction of different factors and, as a result, makes it possible to conduct a multi-criteria integrated assessment, not just on a single factor.

Remote sensing data processing and NDVI analysis

Landsat 8 OLI/TIRS and Sentinel-2 MSI satellite images were used as remote sensing data. Scenes covering the vegetation period and with a cloudiness level of less than 10% were selected for analysis. Satellite images were processed in a geographic information system environment after radiometric and atmospheric corrections. A normalized vegetation index (NDVI) was calculated based on satellite images. NDVI indicators served as the main indicator in determining the state of landscape cover, the degree of soil surface protection, and potential erosion zones. Areas characterized by low NDVI values were mainly observed in areas with high slope inclination and weak vegetation cover, which is considered a factor increasing the intensity of exodynamic processes in those areas. NDVI results were integrated with slope inclination, lithological structure, and proximity to the hydrographic network layers and used in GIS-based analyses and played an important role in the formation of risk zones. The results obtained confirmed the existence of a close spatial relationship between vegetation cover and erosion and landslide processes.

Figure 4
Vegetation Density (NDVI) Map of the Nakhchivanchay River Basin

The NDVI (Normalized Density Index) map of the Nakhchivanchay River Basin was compiled based on Landsat 8 OLI/TIRS and Sentinel-2 MSI satellite images. This index allows us to assess the spatial distribution, density, and condition of the landscape surface of the area. Areas with high NDVI values are mainly characterized by river valleys, irrigated agricultural fields, and foothill zones, which indicates that the vegetation cover in these areas is relatively dense and continuous.

Areas with low NDVI values are mainly observed in mountainous, arid, and exposed rock zones. These areas are characterized by poor vegetation cover, bare soil, and rocky landscapes. In these areas where vegetation is poorly developed, the intensity of surface washing, erosion, and landslide processes is higher. Especially in areas with high slope inclination and lithologically weakly consolidated rocks, low NDVI indicators create favorable conditions for exodynamic processes. Analysis of the NDVI map shows that vegetation plays an important role in landscape stability and directly affects the spatial variability of landslide risk. In areas with rich vegetation, slope stability increases, and the probability of erosion and landslides decreases. In this regard, NDVI indicators have been used as an important factor in a GIS-based multi-criteria assessment model and have played a reliable indicator in determining landslide risk zones

Analysis of geophysical indicators and structural-tectonic interpretation In order to determine the relationship of exodynamic processes with deep geological factors in the Nakhchivanchay basin, structural-tectonic interpretation of geophysical field indicators was carried out. This approach allows to reveal weakening zones, tectonic faults and structural heterogeneities in the internal structure of the earth's crust and plays an important role in understanding the genetic causes of surface geomorphological processes. Within the framework of the study, magnetic anomalies, gravity gradients and seismic fault zones were analyzed as the main geophysical parameters. These indicators reflect the differences in the physical properties of rock complexes, structural disturbances and tectonic activity.

• Magnetic anomalies: They indicate changes in the magnetic susceptibility of rocks. High-amplitude magnetic anomalies usually correspond to cracked, fractured and tectonically affected zones of rock massifs. In these areas, mechanical stability decreases and favorable conditions arise for exodynamic processes such as landslides and avalanches.
• Gravity gradients: They indicate the unevenness of the distribution of subsurface mass and play an important role in identifying lithological boundaries, tectonic faults, and deep structural elements. Zones of sharp changes are characterized by weakened and heterogeneous rock complexes, where the redistribution of surface stresses intensifies erosion and landslide processes.

• Seismic fault zones: They are a direct indicator of tectonic activity. In areas with dense seismic lines, the structural integrity of the rocks is disrupted and the fracture systems expand, as a result of which the risk of landslides increases. Analysis in a GIS environment has shown that zones of high seismic activity often coincide with areas of high slope inclination and fragmentation of the relief.

As a result of the comprehensive analysis, it was determined that high geophysical anomalies characterize weakened rock zones, and these areas should be assessed as potential risk zones for exodynamic processes. Thus, the structural-tectonic interpretation of geophysical indicators creates a scientific basis for assessing landslide and erosion hazards and significantly increases the accuracy of GIS-based multi-criteria models.

4. Verification of Results and Statistical Analysis

The prepared GIS–AHP-based exodynamic risk model was not limited only to thematic mapping but was also verified by statistical and empirical methods. To assess the adequacy of the model, ROC curve, AUC indicator, inter-factor correlation analysis, and field verification were carried out

ROC and AUC Analysis

Receiver Operating Characteristic (ROC) analysis was applied to assess the predictive ability of the risk map. This method is widely used in landslide and erosion risk mapping and allows for an

objective assessment of the classification accuracy of the model (Akgun et al., 2014; Shrestha & Kazama, 2007).

AUC (Area Under Curve) indicator calculated for the model:

AUC = 0.84
The AUC value higher than 0.8 indicates that the model has a high discrimination ability. This result shows that the multi-criteria GIS–AHP integration can reliably identify the potential spread zones of exodynamic processes in the Nakhchivanchay basin.

Distribution of Risk Zones by Area

The final risk map, prepared based on the Weighted Overlay algorithm, was divided into five categories.

Table 3
The distribution of risk zones by area is as follows

Risk class	Ratio to total area (%)
Very low	18 %
Low	25 %
Medium	29 %
High	20 %
Very high	8 %

The results show that approximately 28% of the basin area is included in the high and very high risk zones. These areas mainly coincide with zones of high slope inclination (>30°), poorly cemented rocks and increased tectonic fault density.

Statistical Correlation Between Factors

Spearman correlation analysis was performed to assess the relative influence of the main factors affecting the formation of exodynamic processes.

Table 4
Spearman Correlation Analysis of Exodynamic Controlling Factors

Factor	Correlation coefficient(r)	Statistical
Slope inclination	0.71	$p < 0.01$
Lithological weakness	0.63	$p < 0.01$
Fracture density	0.58	$p < 0.05$
Hydrographic proximity	0.49	$p < 0.05$
NDV	-0.66	$p < 0.01$

Slope inclination showed the highest positive correlation, which confirms the leading role of the morphometric factor. The negative correlation with NDVI indicates a decrease in the risk level with increasing vegetation density. This result scientifically justifies the existing relationship between slope stability and vegetation cover (Montgomery & Dietrich, 1994).

Field Verification

In order to verify the suitability of the model in real conditions, 42 exodynamic process points (landslides and intensive erosion areas) were compared with the risk map based on GPS coordinates.

Table 5
Field-Based Validation of Risk Classification

Risk category (%)	Observation share
Very high	36 %
High	33 %
Medium	21 %
Low	10 %

The fact that 69% of the observations are located in high and very high risk zones confirms the adequacy and prognostic reliability of the model. This result shows the effectiveness of the Analytical Hierarchy Process method in geological risk mapping

Scientific Innovation

The conducted multi-criteria assessment shows that the spatial distribution of exodynamic processes in the Nakhchivanchay basin is mainly determined by the interaction of morphometric, lithological and structural-tectonic factors.

The main scientific innovation of this study is the following:
Integration of morphometric, lithological, tectonic and NDVI indicators in a single GIS–AHP model;
Statistical validation of the model by ROC–AUC analysis;
Determination of the quantitative areal distribution of risk zones;
Demonstration of the spatial correspondence of structural-tectonic vulnerability zones with exodynamic risk.
The obtained results have practical significance in terms of engineering-geological planning, risk assessment of infrastructure projects and land use optimization.

Results and discussion

The conducted studies show that the formation of natural processes in the Nakhchivanchay basin directly depends on the geomorphological and geological characteristics of the area. The structural features of the relief, especially the degree of inclination of the slopes and the rock composition, have a significant impact on the intensity of exodynamic processes. In areas where the slope angle increases, the surface flow intensifies, which leads to the activation of erosion and slope processes. In areas where sedimentary rocks with poor mechanical stability are widespread, the rate of relief erosion is higher. In these areas, the soil and rock cover are more sensitive to external influences, resulting in a violation of the geomorphological balance. Under such conditions, denudation processes expand and noticeable changes occur in the morphological structure of the landscape. This weakens the natural sustainability of the area and increases its sensitivity to anthropogenic influences.

In areas with complex tectonic structures, the level of fragmentation of the relief is higher. Structural weaknesses are formed along the fault lines, which creates favorable conditions for the activation of geodynamic processes. The geophysical differences observed in these zones indicate an increased potential risk level of the area. According to the results, tectonic elements act as one of the main determining factors in the spatial distribution of risk zones. The application of remote sensing materials and geographic information systems has created significant advantages in the analysis of the spatial structure of processes. Analyses based on digital models have allowed for an accurate assessment of relief indicators and differentiation of risk levels. The results obtained show that high-risk areas are mainly concentrated in mountainous and structurally active zones, while in relatively stable areas the risk indicators are low. In general, the analyses conducted prove that geophysical risks in the Nakhchivanchay basin have an uneven spatial distribution. The prepared map and the results obtained are of great importance in terms of scientific assessment of the area, landscape planning, and early identification of pote

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