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THE IMPACT OF NATURAL FACTORS INTERACTION ON THE MANIFESTATION OF HAZARDOUS GEOLOGICAL AND GEOMORPHOLOGICAL PROCESSES IN THE CHARYN STATE NATIONAL NATURAL PARK: ASPECTS OF SAFE NATURAL RESOURCES MANAGEMENT

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Abstract: Charyn State National Natural Park (SNNP), located in the Sharyn River basin of southeastern Kazakhstan, is characterized by unique geomorphological landscapes and increasing tourist activity. The combination of complex natural conditions and intensive recreational use creates a heightened risk of hazardous geological and geomorphological processes, necessitating effective risk management strategies. The primary aim of this study to assess the impact of interacting natural factors on the manifestation of hazardous geological and geomorphological processes to ensure sustainable and safe natural resources management. The methodological framework integrates geoinformation analysis and remote sensing data within a Multi-Criteria Decision Analysis (MCDA) approach. The Analytic Hierarchy Process (AHP) was applied to assign weights to heterogeneous natural factors, enabling a quantitative assessment of their relative contribution to hazard development. Seven spatial indicators were analyzed: probability of precipitation, lithological composition, slope gradient, vertical dissection of terrain, drainage network density, Topographic Wetness Index (TWI), and Normalized Difference Water Index (NDVI). These datasets were processed, normalized, and combined using a weighted overlay technique in Geographic Information System (GIS) to generate an integral map. The application of multivariate analysis using remote sensing data and GIS enabled the creation of an integrated map reflecting the interactions of key natural factors. This integrative, multi-parameter spatial approach allowed for the objective identification and classification of areas according to the degree of manifestation of geological and geomorphological processes, thereby delineating zones with varying levels of risk. According to the results, the largest portions of the territory fall into the moderate (27.1%, 346.8 km^2) and high (26.5%, 339.6 km^2) categories, indicating widespread areas with elevated geodynamic activity. Very high degree zones account for 10.9% (139.9 km^2) of the study area and represent localized sites requiring targeted monitoring and risk mitigation. Relatively safer areas include those with a low degree (22.5%, 288.1 km^2) and a very low degree (12.9%, 165.7 km^2). Slope steepness, lithology, and terrain dissection were found to be dominant factors, while vegetation cover and moisture conditions acted as significant modifiers of hazard potential. The accuracy of the obtained data has been validated through field verification, ensuring the study's high practical relevance for environmental management planning and vulnerability assessment of the area.

Keywords: natural factors; geological and geomorphological processes; AHP, MCDA, GIS; safe environmental management; Charyn state national natural park

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INTRODUCTION

Since 2023, a scientific project No. AP19677559 titled "Instrumental and methodological assessment of hazardous natural phenomena and processes in Charyn State National Natural Park" has been implemented on the territory of Charyn SNNP, which is funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan. As part of the project, comprehensive studies are being conducted aimed at monitoring hazardous natural phenomena and processes using high-precision field equipment, as well as modern geoinformation and remote sensing methods. As a result of a reconnaissance survey of the Charyn SNNP territory, 12 monitoring sites were identified, characterized by the highest intensity and frequency of hazardous climatic and hydrological phenomena, as well as geological and geomorphological processes. These areas cover the most vulnerable natural systems, including river valleys, foothill slopes, and zones of tectonic faults. The Charyn SNNP, located in an arid and seismo-tectonically active zone of southeastern Kazakhstan, is characterized by a high rate of geomorphological transformations. The most common processes

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include planar wash, gully and lateral erosion, landslide and rockslide processes, as well as mudflow phenomena, which significantly impact both natural ecosystems and the tourism and conservation infrastructure of the park. In a number of existing studies, attention is primarily focused on individual aspects of geological and geomorphological processes, while their comprehensive analysis in relation to various natural factors of different origins remains insufficiently developed. Meanwhile, the activation of these processes is determined by the combined influence of climatic conditions, lithological and morphometric features of the terrain, hydrological characteristics, as well as soil and vegetation cover parameters.

The lack of an integrated approach using modern geoinformation technologies limits the capabilities of spatial analysis and natural risk forecasting. Consequently, this reduces the effectiveness of nature conservation measures and hampers the implementation of sustainable natural resource management principles, particularly within specially protected natural areas. This study is dedicated to a comprehensive assessment of the impact of natural factors on the activation of geological and geomorphological processes within the Charyn SNNP. The analysis is based on considering the interactions among five primary groups of factors: climatic, geological, geomorphological, hydrological, and biotic. Each of these factors can act independently or in conjunction with others to serve as a trigger for hazardous geological and geomorphological processes.

Climatic conditions are one of the key factors initiating the development of geological and geomorphological processes. Variations in precipitation levels, snowmelt, and temperature fluctuations contribute to soil over-saturation and a reduction in soil strength, thereby increasing the likelihood of landslides, erosion, and mudflow phenomena (Harris et al., 2008; Peiro et al., 2024). The greatest hazard in arid conditions is posed by intense precipitation events with a low probability of occurrence (e.g., ≥10 mm within 12 hours) that exceed the climatic norm (Chelariu et al., 2023; Miklin et al., 2022), since it is the exceeding of threshold precipitation levels, rather than their total annual amount, that most frequently initiates active geodynamic processes (Rosi et al., 2023). According to Heo et al. (2024), precipitation ranks third in significance among natural factors, following only soil characteristics and slope. The importance of the precipitation regime, along with accompanying climatic parameters such as temperature background and snow cover, has been emphasized in various studies (Piroton et al., 2020; Rom et al., 2023; Yuniawan et al., 2022; Zúñiga et al., 2020; Hidayat et al., 2019; Karmakar et al., 2023; Zhanibek et al., 2025; Chelariu et al., 2023; Miklin et al., 2022; Rosi et al., 2023).

The lithological composition of rocks (including their mineralogy, structure, mechanical properties, and stability) is determined by the intensity of weathering, erosion, landslides, and ravine formation. The study by Yanites et al. (2017) demonstrated that lithological heterogeneity influences erosion rates and landform development, thereby driving local variations in morphological evolution. Similarly, Yunus et al. (2016) emphasizes the role of lithological differences in erosion activity and watercourses morphology. Weakly cemented and porous deposits (loess, sands) are susceptible to intensive erosion, whereas stable rocks (granites, quartzites) provide relative slope stability (Ott, 2020; Arabameri et al., 2020). Under arid climate conditions, as demonstrated in the work of Yu et al. (2024), erosion activity significantly increases in areas dominated by loose sedimentary rocks and characterized by poorly developed vegetation, which limits the natural protection of slopes. Lithological variation of the rocks is a key factor in understanding the spatial heterogeneity in the nature and intensity of geological and geomorphological processes in arid climate conditions.

Key morphometric parameters of the relief – the surface slope and vertical dissection – determine the intensity of surface runoff and the activation of slope processes (Meghdad et al., 2021). An increase in slope steepness accelerates runoff and enhances erosion, particularly under conditions of heavy precipitation and weak soil cover. Vertical dissection serves as an indicator of relief maturity and tectonic activity, as evidenced by studies conducted in various regions, including the Sierra Nevada (Deng et al., 2019; Guzzetti et al., 2009). In the Charyn SNNP, as in other seismically active zones of Central Asia, slopes with inclinations exceeding 25° and high vertical dissection pose the greatest danger, especially in the presence of lithological heterogeneity and extreme precipitation events (Sharapkhanova et al., 2024; Abitbayeva et al., 2024). Hydrological characteristics of the terrain play a significant role in the formation of slope and erosion processes, particularly in mountainous and foothill regions. One of the key indicators is the drainage network density, which reflects the degree of terrain dissection by watercourses and indicates the potential intensity of water erosion. High drainage density values correlate with an increased capacity of water flows to washout and transport sediments (Sarkar & Kanungo, 2004; Makaya et al., 2019). Another important indicator is the TWI, which characterizes the landscape's capacity to accumulate moisture and predict areas with potential waterlogging. It is defined as a function of slope and catchment area and is widely used in modelling surface runoff and slope stability (Moore et al., 1991; Gómez-Gutiérrez et al., 2015; Tahmassebipoor et al., 2016). Elevated TWI values may indicate zones with an increased likelihood of water erosion and landslides, particularly when combined with lithological vulnerable rock formations.

Vegetation cover significantly influences slope stability and water erosion processes by serving as a protective barrier that reduces the impact of raindrop impact forces and slows surface runoff. The NDVI index is widely used in assessing vegetation density and its spatial variability (Uddin et al., 2018; Barakat et al., 2023). Low NDVI values generally indicate exposed areas that are more susceptible to erosion, landslides, and other geomorphological phenomena, whereas dense vegetation contributes to soil retention and slope stabilization. Vegetation cover also influences the infiltration properties of soil, evaporation, and biological activity, thereby indirectly affecting hydrological processes. Consequently, the biotic factor must be considered in the modeling of natural hazards, particularly in the context of climate change and landscape degradation.

Cimpoeșu et al. (2025) examined the relationship between natural hazards and tourism activities on the left bank of Lake Izvoru Muntelui (Romania). Based on field observations, surveys, GIS analysis, and statistical methods, the study found that landslides cause substantial damage to road infrastructure (73 affected sections) and increase the vulnerability of tourism facilities (from medium to very high), with most operators perceiving landslides and floods as serious threats.

Gacu et al. (2025) conducted a study in Odiongan, Romblon, using GIS and the AHP to assess building vulnerability to floods, landslides, and fires. A multi-hazard map was developed by integrating hazard exposure, building vulnerability, and spatial risk distribution. The analysis classified 4,043 buildings into five risk categories, identifying significant spatial variations in susceptibility, with certain barangays showing a higher concentration of high-risk structures. Previous studies in the Sharyn River basin, where the Charyn SNNP is located, have emphasized the importance of geomorphological and hydrological factors in assessing landslide susceptibility and demonstrated the effectiveness of GIS and remote sensing-based multi-criteria approaches (Kerimbay et al., 2025). The aim of this study is to quantitatively evaluate the influence of climatic, geological-geomorphological, hydrological, and biotic (vegetation) factors on the occurrence and spatial distribution of hazardous geological and geomorphological processes within the Charyn SNNP, in order to develop an integrated hazard map to support safe and sustainable natural resource management.

MATERIALS AND METHODS

Study Area

The study area encompasses the territory of the Charyn SNNP, located in the southeastern part of the Republic of Kazakhstan. The protected territory covers an area of 127,050 hectares and includes the administrative boundaries of Uigur, Yenbekshikazakh, and Kegen districts of Almaty Region (Kerimbay et al., 2019). The geological structure of the area is represented by Paleozoic sedimentary, volcanic, and intrusive rocks, overlain by Neogene-Quaternary deposits with a thickness of up to 150 meters. The relief exhibits a high degree of morphostructural contrast and encompasses a wide range of landforms from denudational and erosion-tectonic to accumulative-erosional and accumulative types. The most characteristic morphological features include outcrop cones, erosion terraces, canyon-like valleys, and alluvial plains (Medoyev, 1967). The hydrographic network is led by the Sharyn River, with the right-bank tributary Temirlik.

The rivers exhibit a mixed type of water regime, predominantly fed by snowmelt; the average annual water flow in the area is 49.4 m^3/s. The region's climate is characterized by a sharply continental, arid type. Annual precipitation varies from 125 to 325 mm. The average monthly air temperature at the hydrological station "Sarytogay Tract" ranges from –4.7 °C in winter to +21.5 °C in summer. Spatial heterogeneity of climatic conditions is determined both by latitudinal and altitudinal zonation, as well as by the influence of orographic barriers, which contribute to the formation of inversion thermal regimes within intermountain valleys (Kerimbay et al., 2019).

Justification of the methodology and selection of the AHP-MCDA approach

Assessment of the manifestation of hazardous geological and geomorphological processes within the Charyn SNNP requires the application of methodologies capable of accounting for the complex interactions of natural factors under conditions of limited reliable data. Contemporary spatial analysis approaches encompass a wide range of methods; however, not all of them allow for the integration of heterogeneous parameters into a unified analytical model. Heuristic methods based on expert evaluations are characterized by flexibility and ease of application, particularly in environments where archival information is scarce. Nevertheless, their subjective nature and limited reproducibility constrain the ability to obtain verifiable and comparable results (Sandić et al., 2023; Huang et al., 2020). Among statistical methods, the Frequency Ratio (FR) has gained the most widespread use – being a simple and widely employed approach based on the analysis of the spatial distribution of observed events (Sandić et al., 2023; Addis et al., 2024; Tadesse et al., 2024). Its primary advantages include objectivity, reproducibility, and the capacity for quantitative assessment of the significance of individual factors (Sandić et al., 2023; Yuan et al., 2020). At the same time, the FR assumes independence of factor influences, which does not reflect the complex interaction structures present in natural systems. Moreover, its application requires extensive and reliable archival data, which complicates its use in operational environments such as protected areas (Alamrew et al., 2024; Leoni et al., 2015; Melese & Gashure, 2024; Shano et al., 2020; Demisie et al., 2024). Nevertheless, the FR remains an effective tool for analyzing large volumes of spatial data with minimal subjective bias (Renza et al., 2022; Bezie et al., 2024; Kassa, 2024; Swain et al., 2023).

Deterministic approaches, such as the Limit Equilibrium Method and Finite Element Method, provide high predictive accuracy in local slope stability assessments. However, they require detailed geotechnical data and substantial computational resources, which limit their applicability for regional mapping (Renza et al., 2022). Machine learning techniques, including Random Forest and Support Vector Machine, enable the identification of complex nonlinear relationships between factors and offer high forecasting accuracy (Swain et al., 2023). Nonetheless, these methods demand large volumes of training data and are characterized by low interpretability, constraining their use in scenarios with limited observational data (Kassa, 2024). Considering the objective of this study – to assess the extent of influence and interactions of natural factors on the development of hazardous geological and geomorphological processes within protected areas – the most appropriate approach appears to be the AHP within the framework of MCDA.

This method provides a structured and systematic representation of the research problem, allows for the incorporation of expert knowledge, facilitates pairwise comparisons of factors, and enables weighted evaluation of their significance with subsequent consistency verification of judgments (Addis et al., 2024; Tadesse et al., 2024; Alamrew et al., 2024; Melese & Gashure, 2024; Shano et al., 2020; Saaty & Vargas, 2001; Pellicani et al., 2014). The AHP method is particularly effective under conditions of limited statistical data, especially when field observations and expert assessments are available, making it a relevant tool for monitoring natural processes in protected areas (Kassa, 2024; Al-kordi et al., 2025). Thus, the application of AHP-MCDA within the framework of assessing the hazard of geological and geomorphological processes in the Charyn SNNP enables a formalized, reproducible, and comprehensive interpretation of interacting natural factors. This, in turn, facilitates the development of scientifically justified recommendations for sustainable natural resource management and the conservation of protected areas.

Initial data and methods for acquiring spatial data using GIS

For the implementation of the AHP-MCDA methodology, the following spatial and thematic data were used, reflecting key natural factors that contribute to the activation of geological and geomorphological processes within the Charyn SNNP.

Climatic Factor

The probability of precipitation ≥10 mm within 12 hours was calculated based on data from the Charyn automatic weather station (AWS) operated by the Republican State Enterprise Kazhydromet and two temporary AWSs established as part of the project at the sites Ash Grove and Ulken Bugyty. This indicator reflects the likelihood of extreme rainfall events and serves as one of the key climatic triggers.

The probability of precipitation is calculated according to formula (1) (Brier & Panofsky, 1956) of an empirical or frequency-based probability estimate: $\mathrm{P(E)} = f/\mathrm{N}$ (1) P(E) – the probability of event E, f – the number of cases when event E occurred, N – total number of cases (sampling size).

The values of the calculated probabilities for each observation point were normalized to the interval from 0 to 1 using the formula (2) (Magalhães et al., 2023): $\mathrm{I_i} = (\mathrm{v_{obs}} - \mathrm{v_{min}})/(\mathrm{v_{max}} - \mathrm{v_{min}})$ (2)

Normalized data ($\mathrm{I_i}$) calculated based on observed ($\mathrm{v_{obs}}$), minimum and maximum values of the sample. The unit is based on the maximum probability of precipitation within the specified range and, accordingly, the maximum impact of precipitation as a trigger. Zero is taken as the minimum probability for the area under study (Magalhães et al., 2023). For the construction of the map, the precipitation assessment results across the Charyn SNNP were divided into intervals (Table 1), each assigned a score ranging from 1 to 3, with 3 indicating areas with the highest likelihood of precipitation according to the specified criterion. The number of classes (K) was determined based on the total number of disasters (*f*) (3) (Magalhães et al., 2023): $\mathrm{K} \approx 1 + 3{,}33 \log f$ (3)

Amplitude (A) calculated according to Number of classes (K), maximum ($\mathrm{v_{max}}$) and minimum ($\mathrm{v_{min}}$) value of rain probability (4) (Magalhães et al., 2023): $\mathrm{A} = (\mathrm{v_{max}} - \mathrm{v_{min}})/\mathrm{K}$ (4)

Geological Factor

To assess the stability of rocks against geological and geomorphological processes, a lithological map at a scale of 1:200,000 (Medoyev, 1967) was used. The lithological composition of the rocks, as depicted on this map, is a key factor in understanding the territory's resilience to natural processes.

The classification of rocks is based on their susceptibility to erosion and destruction (Yermolovich et al., 2018). The rocks were divided into three main groups depending on their stability:

1) weak stability – this group includes rocks that have low resistance to erosion processes, washout, and other destructive effects: gravelly soils, sands, and loess-like loams;

2) moderate stability: this group includes rocks that have medium resistance to washout and mechanical impacts. These rocks are less susceptible to degradation compared to rocks from the first group: boulder-aggregate, conglomerates, sandstones, clays, granosyenites, quartz syenites;

3) high stability – this category includes rocks that are most resistant to washout, erosion, and other geomorphological processes: tuff sandstones, shales, quartzites, granites (Table 1).

Geomorphological factors

To assess the geomorphological conditions influencing the stability of the study area, digital elevation models (DEMs) reflecting both macro- and mesoforms of the terrain were used. The primary source of spatial data was the AW3D30 model with an approximately resolution of 30×30 meters, derived from satellite observations by ALOS, enabling a quantitative analysis of morphometric parameters relevant to evaluating geodynamic activity. One of the key parameters is the slope of the surface, which impacts water erosion processes, slope stability, and soil cover degradation conditions. The slope was calculated using the Slope tool in the Spatial Analyst extension within ArcGIS 10.8, based on the processed DEM. The slope values were classified into three hazard levels (Table 1):

1) up to 8° – low erosion risk; areas resistant to degradation (weak hazard degree);

2) 8–35° – areas with moderate risk, susceptible to erosion and vegetation changes (moderate hazard degree);

3) over 35° – high risk of erosion and geodynamic processes that contribute to ecosystem degradation (severe hazard degree). The second significant parameter is the vertical dissection of the relief, which reflects the complexity and activity of geomorphological features. Its calculation is based on the analysis of relative surpassing within 1 km^2 grid cells, allowing for the consideration of both absolute and local morphometric differences. A high degree of dissection correlates with an increased likelihood of processes such as landslides, rockslide, and debris flows. The classification of vertical dissection (Table 1) was carried out as follows:

1) 6.4–48.3 m/km^2 – low degree of dissection, characteristic of stable areas;

2) 48.4–130.5 m/km^2 – average indicator indicating zones of potential geodynamic activity;

3) 130.5–451.6 m/km^2 – high degree, reflecting the presence of intense geomorphological processes and risks.

The applied methodology for the classification and interpretation of geomorphological parameters is based on the approaches of Pozachenyuk & Petlyukova (2016) and Spiridonov (1970). A comprehensive analysis of slope and vertical dissection within a geospatial environment provides an objective assessment of landscape stability and the spatial distribution of natural risks. This approach facilitates the accurate identification of potentially hazardous zones and supports reasonable decision-making in environmental protection and infrastructure planning.

Hydrological factors

Drainage density is an important morphometric parameter that characterizes the degree of development of the erosion-hydrological network within the studied area. In this research, this indicator was calculated based on a DEM using Flow Accumulation and Line Density tools within ArcGIS 10.8 environment. Since the same DEM was used for analysis, the obtained values reflect differences in the erosional dissection of the landscape and the potential activity of surface runoff. According to approaches described in references (Sarkar & Kanungo, 2004; Makaya et al., 2019), drainage density was classified into three categories: low (0.2–1.8 m/km^2), medium (1.8–2.7 m/km^2), and high (2.7–5.2 m/km^2), as presented in Table 1. This classification allows for the identification of areas with varying susceptibility to the formation of erosion processes and the development of gully networks. Additionally, the TWI was calculated as an integrated indicator assessing the likelihood of soil waterlogging and moisture accumulation depending on slope morphology. The TWI considers both the catchment area (As) and the slope gradient (β) (Moore et al., 1991) (formula 5): $TWI = \ln(A_s / \tan\beta)$ (5)

For the calculations, tools such as Hydrology and Raster Calculator in ArcGIS 10.8 were used. The TWI values within the study area ranged from 2.9 to 30.1, indicating significant heterogeneity in moisture conditions. Following the methodology accepted in works (Gómez-Gutiérrez et al., 2015; Tahmassebipoor et al., 2016), the index was classified into three groups: low (2.9–7.8), medium (7.8–11.3), and high (11.3–30.1) values, allowing for the identification of zones with varying probabilities of surface water accumulation and the formation of over humidified areas (Table 1). Comparison of the spatial distribution of drainage network density and TWI values allows for the identification of areas susceptible to intense surface runoff, erosion, and water accumulation. These parameters play a crucial role in modeling the vulnerability of territories to geological and geomorphological processes and serve as a basis for subsequent natural risk zoning.

Table 1. Parameters for assessing the degree of hazardous geological and geomorphological processes (Source: Modified by authors from Yermolovich et al., 2018; Yegemberdiyeva et al., 2020; Leontyev & Rychagov, 1988; Sharapkhanova et al., 2024; Abitbayeva et al., 2024)

Factor	Parameter	Hazard manifestation degree		
		Weak (1)	Moderate (2)	Strong (3)
Climatic	Rainfall	<0.3	0.3 – 0.6	>0.6
Geological	Lithology	Tuffaceous sandstones, shales, quartzites, granites	Boulder and pebble deposits, conglomerates, sandstones, clays, granosyenites, and quartz syenites	Gravelly deposits, sands, and loess-like loams
Geomorphological	Slope, °	Up to 8	8 – 35	more than 35
	Vertical Dissection, m/km^2	6.4 – 48.3	48.4 – 130.5	130.5 – 451.6
Hydrological	TWI	2.9 – 7.8	7.8 – 11.3	11.3 – 30.1
	Drainage density, m/km^2	0.2 – 1.8	1.8 – 2.7	2.7 – 5.2
Vegetation cover	NDVI	–0.07 – 0.1	0.1 – 0.4	more than 0.4

Biotic factor

To assess the vegetation condition in the study area, the NDVI index was used, calculated from a multispectral Landsat-8 OLI (spatial resolution 30×30 meters) image dated April 26, 2025. The data were obtained from the USGS Earth Explorer open geospatial portal, which provides access to archival and real-time satellite imagery. NDVI calculation was performed using the well-known formula 6 (Rouse et al., 1973): $NDVI = NIR - R / NIR + R$ (6) where NIR – near-infrared band, R – red band. NDVI is an important biophysical indicator widely used in remote sensing for quantitative assessment of vegetation condition, density, and productivity. NDVI values range from –1 to +1. Negative values (less than 0) typically indicate the absence of vegetation and correspond to open soils, urbanized areas, or rocky surfaces. Positive values (greater than 0) reflect varying degrees of vegetative cover development. The higher the NDVI value, the greater the vegetation productivity and ecological stability (Table 1) (Uddin et al., 2018; Barakat et al., 2023). Based on NDVI data, vegetation cover was classified into three categories reflecting varying levels of biotic activity and, consequently, vulnerability to natural impacts: areas with minimal or no vegetation cover (–0.07 to 0.1) (indicating high vulnerability); zones with fragmented or degraded vegetation (0.1 to 0.4) (indicating medium vulnerability); and areas with dense vegetation cover (>0.4) (indicating low vulnerability). This classification aligns with the approaches proposed in references (Uddin et al., 2018; Barakat et al., 2023) and enables the application of NDVI data within an integrated assessment of environmental hazard and landscape stability. To ensure comparability of heterogeneous spatial data presented in various physical units (including climatic, geological and geomorphological, hydrological, and biotic factors), all indicators were normalized and converted into a unified scoring scale. A three-tier classification system was employed to assess the hazard manifestation degree: weak (1 point), moderate (2 points), and strong (3 points). This approach enables the qualitative integration of various parameters into a unified multi-criteria analysis system, which is critically important for a comprehensive assessment of the territorial resilience to dangerous geological and geomorphological processes. The consolidated classification of factors according to the severity of geological and geomorphological hazards and their corresponding scoring values are presented in Table 1.

Determination of weights and construction of vulnerability maps

AHP–MCDA is an effective decision-making approach that allows for the integration of various input parameters to achieve specified goals (Ziadi et al., 2025; Aher et al., 2013; Assefa et al., 2015). The method's effectiveness has been demonstrated through its successful application in different areas, including land suitability analysis for agriculture (Parihari et al., 2021), assessment of potential zones of groundwater distribution (Biswas et al., 2020; Çelik et al., 2024), evaluation of landslide susceptibility (Zhou et al., 2023; Liu et al., 2024; Demirel et al., 2025, Al-kordi et al., 2025), and identification of areas prone to soil erosion (Ziadi et al., 2025). In this study, the AHP–MCDA methodology within a GIS environment was used to assess the factors influencing the susceptibility of the territory to hazardous geological and geomorphological processes and to subsequently develop a map depicting the degree of manifestation of these processes (Figure 1). The AHP method enables the integration of expert assessments, field observation results, and statistical data. This semi-quantitative approach is based on constructing pair-wise comparison matrices and calculating weight coefficients for the factors affecting the spatial distribution of the phenomena under study (Saaty, 1990; 1994; Saaty & Vargas, 2001).

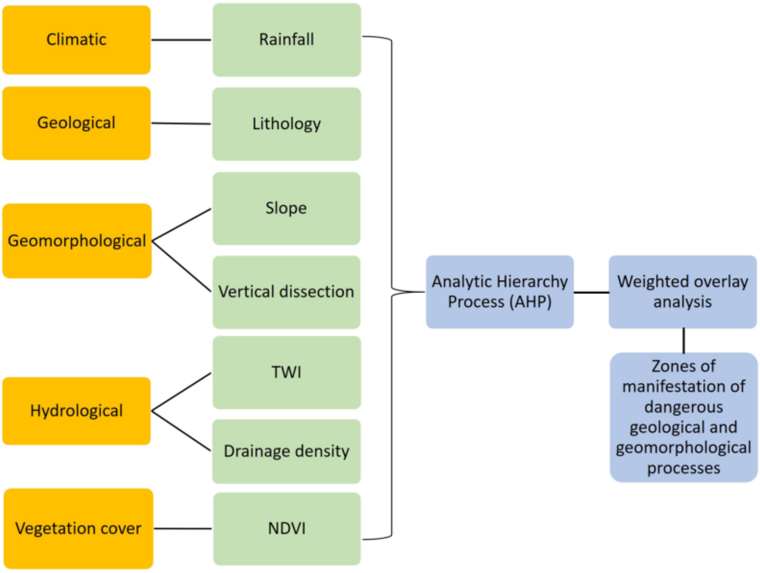

Figure 1. Flowchart of the method for the assessment of manifestation degree of hazardous geological and geomorphological processes using AHP-MCDA (Source: Modified by authors from Ziadi et al., 2025)

The AHP methodology involves a step-by-step process: formulating the objective, constructing a hierarchy of factors and parameters, performing pair-wise comparisons, normalizing the resulting values, calculating weights, and verifying the consistency of expert judgments. In the first stage, key factors potentially influencing the manifestation of hazardous geological and geomorphological processes were identified: precipitation, lithology, surface slope, vertical dissection of the terrain, drainage density, TWI, and NDVI. Each pair of factors was compared based on the Saaty nine-point scale, where values from 1 to 9 reflected the relative importance of one factor compared to another (Saaty, 1980). The results of pairwise comparisons were organized into a reciprocal matrix, which served as the basis for calculating the relative weights of the factors. To do this, the matrix was normalized using the following procedure: first, the sums of the values in each column were computed; then, each individual value was divided by the corresponding column sum, resulting in a normalized matrix where the sum of values in each column equals one. Next, the arithmetic mean of the normalized values in each row was calculated, allowing the determination of the relative weight of the corresponding parameter (Kebeba et al., 2024).

The obtained values form a priority vector that reflects the contribution of each factor to the overall susceptibility. The higher the weight, the greater the influence of the corresponding parameter on the resulting assessment. However, the interpretation of these weights is only valid if they are consistent with the judgments in the initial comparison matrix. Therefore, a crucial step is to verify consistency, ensuring the reliability and logical coherence of the expert evaluations.

The reliability of results obtained using the AHP method is largely determined by the consistency of expert judgments employed in pair-wise comparisons of factors. To quantitatively assess this consistency, the Consistency Ratio (CR), proposed by Saaty, is used as an indicator of logical coherence of the judgments.

The procedure involves calculating the maximum eigenvalue (λmax) of the pair-wise comparison matrix, which is a critical parameter for verifying the correctness of the weight distribution. This is achieved by first determining the priority vector (the eigenvector), then computing λmax as the sum of the products of each normalized vector element and the sum of the corresponding column in the matrix. Based on this value, the Consistency Index (CI) is calculated using formula 7 (Saaty, 1990): $CI = (\lambda \max - n)/(n-1)$ (7) where, λmax – the largest or principal eigenvalue of the analyzed matrix, and n — the order of the square matrix. Next, the CR is calculated as follows (8) (Saaty, 1990): $CR = CI/RI$ (8)

where RI is the consistency index, it measures the concordance of a randomly generated pair-wise comparison matrix. It depends on the number of elements being compared. A CR value < 0.1 indicates an acceptable level of consistency, suggesting that the expert assessments are logically justified and suitable for further analysis. If this threshold is not met, the comparison matrix must be reviewed and revised accordingly (Saaty, 1980; Saaty, 2000; Saaty, 2008; Mengstie et al., 2024). After determining the weight coefficients for each factor, a spatial analysis was performed using a weighted summation procedure. As a result, an integral map illustrating the degrees of manifestation of geological and geomorphological processes (DMP) was produced based on Formula 9 (Ziadi et al., 2025): DMP $= \sum_{i=1}^{n} R_i * W_i$ (9) where R_i represents the evaluation classes for each layer, and W_i denotes the weight coefficients for each factor that influence the manifestation of geological and geomorphological processes. The resulting values were classified using the "natural breaks" method into five levels of process manifestation: very low, low, moderate, high, and very high.

Considering the spatial distribution characteristics of precipitation, an initial classification of the territory into three classes was performed based on the probability of rainfall ≥10 mm within 12 hours. However, when this layer was overlaid with other factors using the Weighted Overlay tool in the Spatial Analyst module, the resulting map exhibited blurred (coarse) boundaries between zones of different hazard levels. To improve the spatial analysis accuracy and obtain smoother gradients of values, the normalized precipitation data were visualized using a stretch mode, which allowed the creation of a raster with a continuous probability distribution within the specified spatial resolution. The resulting smoothed layer was then incorporated into a multi-criteria analysis, where it was integrated with other factors according to the established weights.

RESULTS

Climatic factor: classification of precipitation

To assess precipitation as a key trigger of geological and geomorphological processes – especially under conditions of water scarcity typical of desert environments – the Rainfall indicator was used. This indicator measures the probability of liquid precipitation ≥ 10 mm within a 12-hour period (based on data from AMS meteorological stations) (Figure 2).

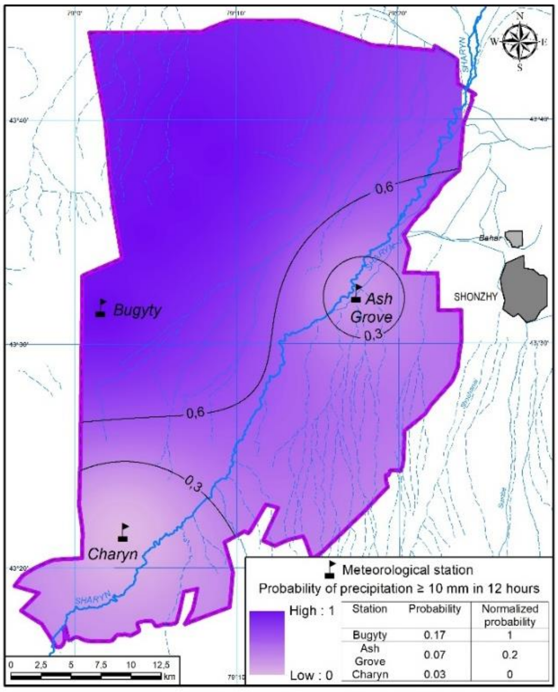

Figure 2. Probability of precipitation ≥10 mm in 12 hours;

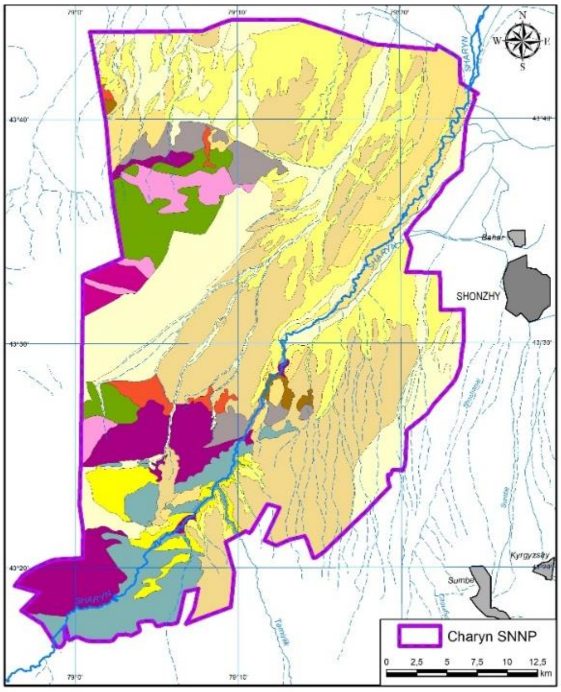

Figure 3. Lithological composition of rocks (Source: Geological maps, scale 1:200 000)

* Legend to the Figure 3

	Lithological composition of rocks
	Pebblestones, sands
	Pebblestones, sands and loess-like loams
	Boulders-pebbles, conglomerates
	Conglomerates, sands, clays
	Sands, clays
	Conglomerates, sands
	Tuff sandstones (variegated tuff lavas and tuffs of liparitic and dacitic porphyries, rare interlayers of tuffs of mixed composition and porphyrites, tuff sandstones)
	Tuff sandstones (tuffs and lavas of andesitic porphyrites, dacite, tyrachydacite porphyries and mixed composition of effusives)
	Shales (chlorite-sericite and phyllitic shales)
	Shales, quartzites (chlorite-siliceous, micaceous-quartz shales, silica and quartzites)
	Shales (sericite-quartz, chlorite-siliceous, chlorite-sericite and phyllitic shales)
	Granite syenites, quartz syenites
	Coarse-grained granites

Rain events with low probability can nevertheless initiate geomorphological changes and hydrological phenomena (Miklin et al., 2022; Rosi et al., 2023; Piroton et al., 2020). The highest likelihood of intense precipitation occurs predominantly in the northeastern part of the Charyn SNNP, which is influenced by the presence of an orographic barrier. It should be noted that, during west-to-east airflow, the ridge promotes precipitation on the windward side; that is, west of the Bugyty station, precipitation events are more frequent during both winter and summer. In the Ash grove, the recurrence of precipitation in the 5.0–9.9 mm range is higher than ≥ 10 mm or more. This can be explained by increased moisture availability in the area due to dense vegetation and more intensive transpiration compared to the Charyn AMS. Spatial analysis of extreme precipitation within the Charyn SNNP indicates a decreasing likelihood of heavy rainfall from the northeastern area toward the west and south, where the probability is lowest. However, this does not exclude the possibility of river water level rises and debris flow formation due to more intense precipitation events typical of the Northern Tien Shan mountains (near the eastern foothills of the Ili River and Kungei Alatau, Uzynkara ridge). Precipitation amounts of 35 mm or more are particularly critical and should be considered when forecasting hydrological phenomena.

Geological factor: lithology and erodibility of rocks

The lithological composition of rocks is a key factor controlling slope stability against erosion, landslides, and other destructive processes. The properties of the rocks determine the landscape features, the type of soil-forming processes, and sensitivity to external influences (Mushtaq et al., 2023). The results indicate that areas composed of rocks with a high degree of erodibility include valley-upland hills and proluvial-sloping plains around the Ulken Bugyty mountains, the floodplains and the first alluvial terraces of the Sharyn River (from the Sarytogay locality to the northeastern part of the SNNP), as well as the southeastern part of the national park (Figure 3). Regions exhibiting a strong degree of erosion cover an area of 429.7 km^2, which is approximately 31.4% of the park's total area (1 368.6 km^2). Areas with a moderate rock erosion degree occupy a significant portion of the studied territory, stretching from the north to the southeast of the national park. These areas are situated on valley-terraced hills on the right and left banks of the Sharyn River, as well as on secondary floodplain terraces and erosion hills known as "bedlands" (on the right bank). Territories exhibiting a moderate level of manifestation of geological and geomorphological processes cover an area of 603.6 km^2, accounting for 44.1% of the park's total area. Territories with a weak rock erosion degree include the Toraigyr and Ulken Bugyty mountains, the hilly ridges between them, and the southwestern part of the national park. These areas encompass 335.3 km^2, or 24.5% of the park's territory.

Geomorphological factors: slope and vertical dissection of the relief

To analyze the influence of geomorphological factors on the formation and spatial distribution of hazardous geological and geomorphological processes, key morphometric parameters of the terrain were utilized, including the slope angle and the degree of vertical dissection of the surface (Conforti et al., 2011; Achour et al., 2017; Rahmati et al., 2017).

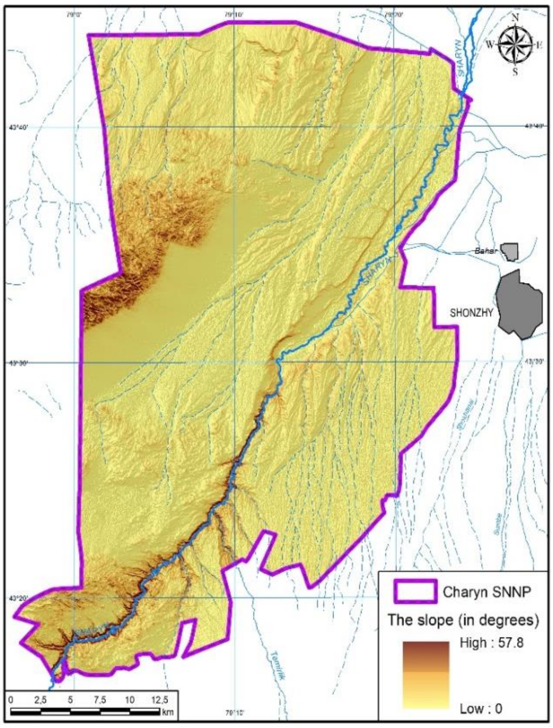

Figure 4. Curvature (Slope)
(Source: Based on AW3D30, 2024);

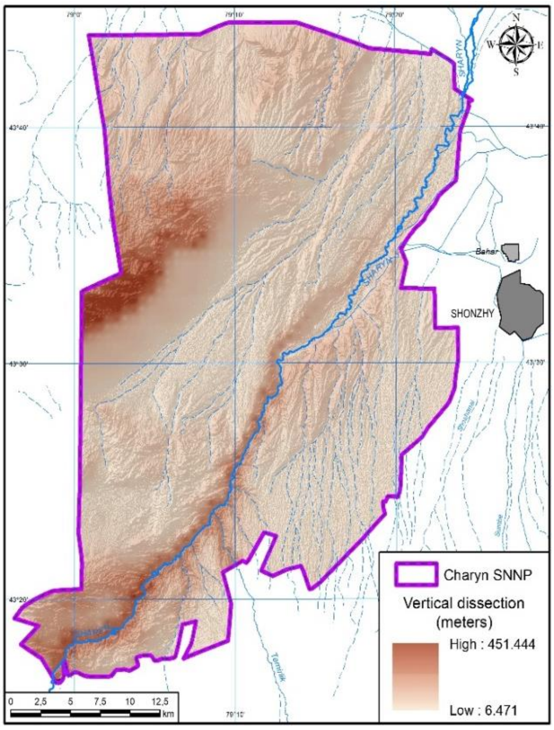

Figure 5. Vertical dissection of the relief
(Source: Based on AW3D30, 2024)

The slope angle is traditionally regarded as a fundamental parameter in geomorphological mapping, as it significantly affects surface runoff patterns and intensity, soil infiltration characteristics, the morphology of drainage networks, and the development of water erosion (Conforti et al., 2011; Arabameri et al., 2020; Chakrabortty et al., 2020). The character and intensity of slope processes, including landslides, falls, and erosion, are largely determined by the steepness of the slopes. In the Charyn SNNP, areas with the highest slope gradients (exceeding 35°, covering 12.2% of the park's area) are characterized by a high degree of hazardous process activity. These zones are predominantly localized within the Ulken Bugyty and Toraigyr mountain ranges, as well as in the upper section of the Sharyn River canyon before it transitions into the plains (Figure 4). Areas with slopes ranging from 8° to 35% (about 43% of the territory) are associated with denudationally inclined pediments, sloping and ridge-shaped hills southwest of the Toraigyr mountain, and with accumulative-erosional landforms in the interfluve between the Sharyn and Temirlik rivers. Additionally, such slopes are characteristic of erosion hills (badlands) south of Sarytogai and valley-rolling elevations north of the Ulken Bugyty mountains. The majority of the park's area (44.8%) features low slopes (less than 8°), which are generally linked to the development of planar wash processes (Zúñiga et al., 2020; Hidayat et al., 2019). The intensity of vertical terrain dissection, expressed through the amplitude of relative heights (the difference between the peaks of positive landforms and the nearest negative landforms), serves as an indicator of the activity of modern hazardous processes (Figure 5). According to morphometric analysis, 71.4% of the park's territory exhibits a weak degree of vertical dissection (up to 976.9 m/km^2), while moderate and high levels of dissection account for 20.6% (281.8 m/km^2) and 8% (109.9 m/km^2), respectively. Areas with pronounced vertical dissection and steep slopes - including the left and right banks of the southern part of the Sharyn River valley, as well as the Toraigyr and Ulken Bugyty mountains – are prone to active development of landslides and rockslides, as confirmed by both field observations and remote sensing data interpretation (Zúñiga et al., 2020; Hidayat et al., 2019).

Hydrological factors: the TWI and drainage network density

The hydrological variable of drainage density, calculated based on the AW3D30 DEM, is a key indicator of the development level of the watershed network and plays a crucial role in initiating erosion processes in mountainous regions (Makaya et al., 2019). Spatial analysis of hydrological characteristics revealed a pronounced dependence of erosion intensity on the morphometric parameters of the terrain in the study area. The values of river network density obtained from AW3D30 data range from 0.2 to 5.2 m/km^2. The maximal values (2.7–5.2 m/km^2), observed in areas with highly dissected terrain – characterized by low erosion and accumulative-erosive hills – are located southeast of the Bugyty mountains and in the southeastern part of the Charyn SNNP, on the right bank of the Sharyn River (Figure 6).

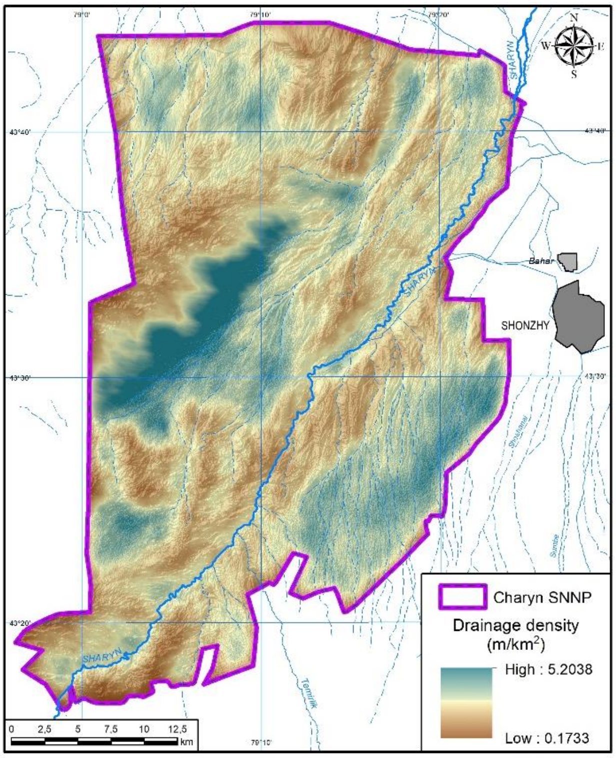

Figure 6. Drainage network density
(Source: Based on AW3D30, 2024);

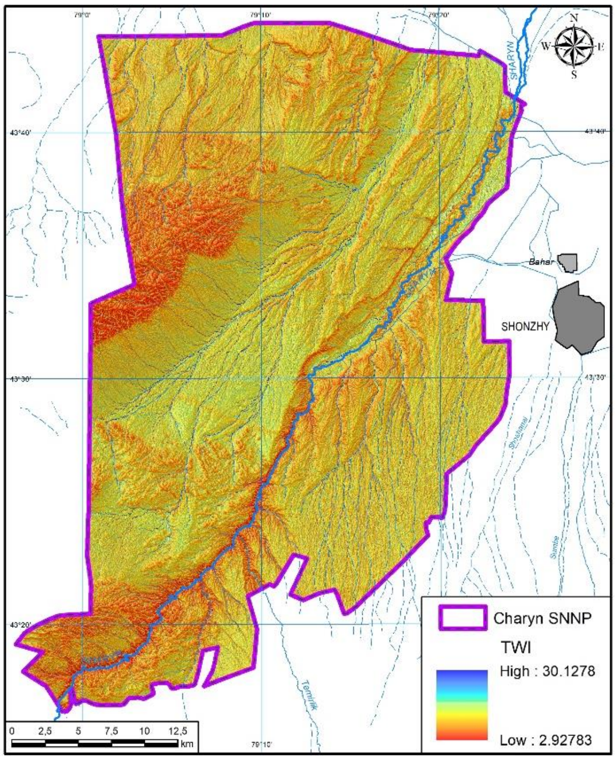

Figure 7. Topographic Wetness Index
(Source: Based on AW3D30, 2024)

This indicates a high degree of drainage and an elevated erosion potential in these territories. The spatial coincidence of areas with high drainage density and zones of intense terrain dissection confirms a strong relationship between watershed morphology and the development of erosion processes. The minimum values of river network density (0.2–1.8 km/km^2) are associated with the denudation-tectonic low mountains of Ulken Bugyty and Toraigyr, erosional hills (on both sides of the Sharyn River), and accumulative-erosional hills (in the northern part of the park). The TWI is widely used to assess the influence of landscape morphology on the spatial distribution and extent of zones experiencing soil saturation due to surface runoff accumulation (Moore et al., 1991). The obtained results indicate that the highest TWI values (11.3–30.1) are observed in the low-lying areas of the terrain, along the valleys of the Sharyn and Temirlik rivers, near the footslopes. This suggests that these zones are prone to moisture accumulation and saturation due to reduced surface runoff. This indicates potential areas of moisture accumulation and surface runoff processes (Figure 7). A joint analysis of drainage density and TWI distribution revealed an inverse correlation between these parameters in several areas: zones with a high density of river networks often exhibit lower TWI values, which may indicate more intensive drainage and minimal moisture accumulation, thereby promoting active linear erosion.

Biotic factor: NDVI classification

NDVI – the vegetation density index. NDVI is important for stimulating dangerous geological and geomorphological processes. The NDVI values range from –1 to +1. Negative values generally indicate the presence of water bodies, while values close to zero (from –0.1 to 0.1) point to areas with minimal or absent vegetation cover, which is typical for rocky, eroded, and strongly dissected slopes. Within the Charyn SNNP, such areas are predominantly found in the canyon zone, on steep slopes, and in regions with exposed bedrock, where the most intense forms of water and slope erosion occur. These areas are characterized by heightened geodynamic activity and pose potential hazards.

Moderate NDVI values (ranging from 0.2 to 0.4) correspond to areas with sparse herbaceous and shrub vegetation, typical of foothill and sloped regions prone to surface runoff and localized erosion (Figure 8).

Higher values (from 0.4 and above) indicate the presence of relatively dense vegetation cover, primarily located in floodplain zones along perennial and intermittent watercourses, including the Sharyn River valley and the channels of temporary streams within the Ulken Bugyty and Toraigyr mountains. The presence of dense vegetation in these areas signifies stable landscape conditions and a lower susceptibility to hazardous geomorphological processes. Thus, spatial analysis of NDVI enables the use of this indicator to differentiate areas based on the degree of their resilience to geological and geomorphological impacts. When combined with morphometric characteristics of the terrain, its application enhances the accuracy of assessing hazardous natural processes and facilitates the identification of zones with potential risk.

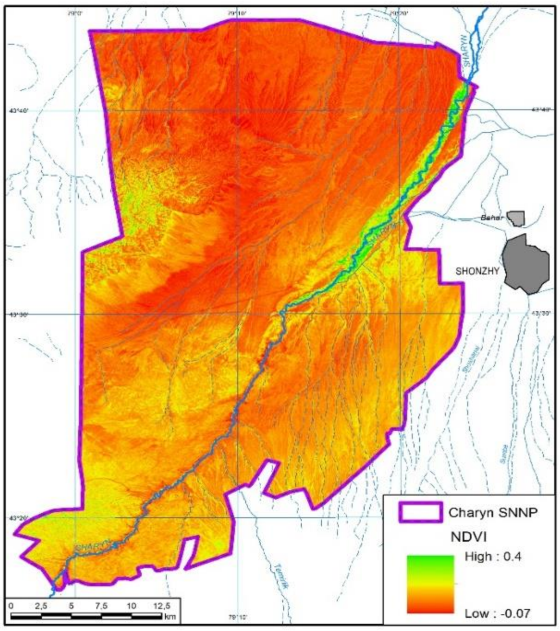

Figure 8. NDVI (Source: Based on Landsat-8, 2025)

Integral map

The results obtained are the outcome of calculations based on multi-criteria analysis and refined through expert assessments. During the study, a method integrating GIS with AHP was employed to identify and spatially delineate areas susceptible to hazardous geological and geomorphological processes.

The assessment was conducted using 7 key parameters that influence terrain stability: precipitation, lithology, slope inclination, vertical dissection of the terrain, drainage network density, TWI, and NDVI.

The AHP model is based on a multi-expert procedure, during which specialists collaboratively determined the significance of factors contributing to the emergence and development of geological and geomorphological processes. The assessments were refined at each stage until a consensus was reached on the weights of the parameters (El Jazouli et al., 2019). As indicated in the "Materials and Methods" section, the quantitative assessment of weight coefficients was carried out using a pair-wise comparison matrix constructed according to Saaty's methodology. The comparison matrix, which reflects the relative importance of normalized values, is presented in Tables 2 and 3. These matrices were used to determine the normalized principal eigenvector through an approximation method (Table 4). As a result of the analysis, the following indicators were obtained: the principal eigenvalue λmax = 7.68; the CI = 0.1132; with the number of parameters n = 7, the random consistency index (RI) = 1.32; and the CR = 0.085, which is below the acceptable threshold (< 0.1). This confirms the adequacy of the consistency level of the expert assessments and the validity of the obtained weights. Table 4 presents the normalized weight coefficients obtained through the application of the AHP method for seven factors influencing the degree of manifestation of hazardous geological and geomorphological processes in the Charyn SNNP. Each value reflects the relative importance of the corresponding criterion, determined based on expert assessments and pair-wise comparison procedures. The most significant contributors to the overall susceptibility index are surface slope (0.211), vertical dissection (0.178), and lithology (0.154), indicating the dominant influence of morphometric and geological parameters.

Table 2. Pairwise comparison matrix (Source: on materials from the analysis of AHP calculations)

Parameter	Rainfall	Lithology	Slope	Vertical Dissection	Drainage density	TWI	NDVI
Rainfall	1	0.33	0.2	0.5	3	1	1
Lithology	3	1	1	0.5	2	1	1
Slope	5	1	1	1	1	2	2
Vertical Dissection	2	2	1	1	2	1	1
Drainage density	0.33	0.50	1	0.5	1	1	1
TWI	1	1	0.5	1	1	1	2
NDVI	1	1	0.5	1	1	0.50	1

Table 3. Pairwise comparison matrix of the seven factors using the AHP method
(Source: on materials from the analysis of AHP calculations)

Parameter	Rainfall	Lithology	Slope	Vertical Dissection	Drainage density	TWI	NDVI	Normalized weight
Rainfall	0.075	0.049	0.038	0.091	0.273	0.133	0.111	0.110
Lithology	0.225	0.146	0.192	0.091	0.182	0.133	0.111	0.154
Slope	0.375	0.146	0.192	0.182	0.091	0.267	0.222	0.211
Vertical Dissection	0.150	0.293	0.192	0.182	0.182	0.133	0.111	0.178
Drainage density	0.025	0.073	0.192	0.091	0.091	0.133	0.111	0.102
TWI	0.075	0.146	0.096	0.182	0.091	0.133	0.222	0.135
NDVI	0.075	0.146	0.096	0.182	0.091	0.067	0.111	0.110

Table 4. Overall contribution of parameters (Source: on materials from the analysis of AHP calculations)

Rainfall	Lithology	Slope	Vertical Dissection	Drainage density	TWI	NDVI
0.110	0.154	0.211	0.178	0.102	0.135	0.110

Based on these values, an integrated map illustrating the degree of manifestation of hazardous geological and geomorphological processes (Degree of Manifestation of Processes – DMP) was created within a GIS environment. The calculation was performed on a pixel grid using the following formula (10) (Ziadi et al., 2025):

DMP = Rainfall ∗ 0.110 + Lithology ∗ 0.154 + Slope ∗ 0.211 + Vertical Dissection * 0.178 + TWI ∗ 0.135 + Drainage density ∗ 0.102 + NDVI ∗ 0.110 (10). According to the results of the spatial analysis (Figure 9), the distribution of areas with varying degrees of manifestation of processes is as follows: moderate – 27.1% (346.8 km^2); high – 26.5% (339.6 km^2); very high – 10.9% (139.9 km^2). Relatively safer areas include zones with low degree – 22.5% (288.1 km^2), and very low degree – 12.9% (165.7 km^2) of the total studied area (Table 5).

Table 5. Areas of degree of manifestation of processes (Source: on materials from the analysis of AHP calculations)

Degree of manifestation	Area (km^2)	Area (%)
Very low	165.7	12.9
Low	288.1	22.5
Moderate	346.8	27.1
High	339.6	26.5
Very high	139.9	10.9

The analysis of the integrated map of the degrees of manifestation of hazardous geological and geomorphological processes allowed for the identification of areas with varying degrees of hazard within the studied zone. The most vulnerable regions were found to be the high-altitude areas located on the left and right banks of the upper Sharyn River. These areas include the Toraigyr, Katu mountain ranges, as well as the Moyyntogai, Taskora, and Ulken Bugyty mountain ridges. These territories are characterized by highly dissected terrain, predominance of solid and semi-rocky rocks, and slopes exceeding 35°. Collectively, these morphometric and lithological factors justify classifying these zones as areas of high to very high hazard. The Valley of Castles area, one of the most popular tourist routes within the Charyn SNNP, particularly warrants attention. Due to the morphodynamic features of this region, there are potential hazards associated with geodynamic processes, such as landslide and rockslide activity, as well as gully and lateral erosion.

These factors necessitate careful consideration of natural risks when developing tourist infrastructure and organizing excursions. Conversely, areas classified as having moderate, low, or very low risk levels are predominantly characterized by sheet wash processes. Locally, there may be mild forms of gully erosion; however, these are limited in extent and typically observed in transitional zones between flat plains and hilly, ridged terrain.

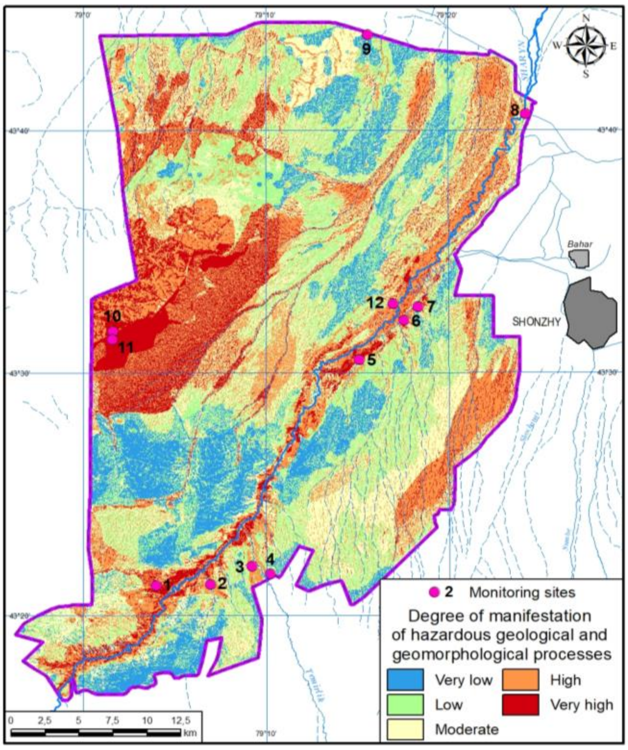

Figure 9. Integral map of the degree of manifestation of hazardous geological and geomorphological processes (Source: Developed by authors, 2025)

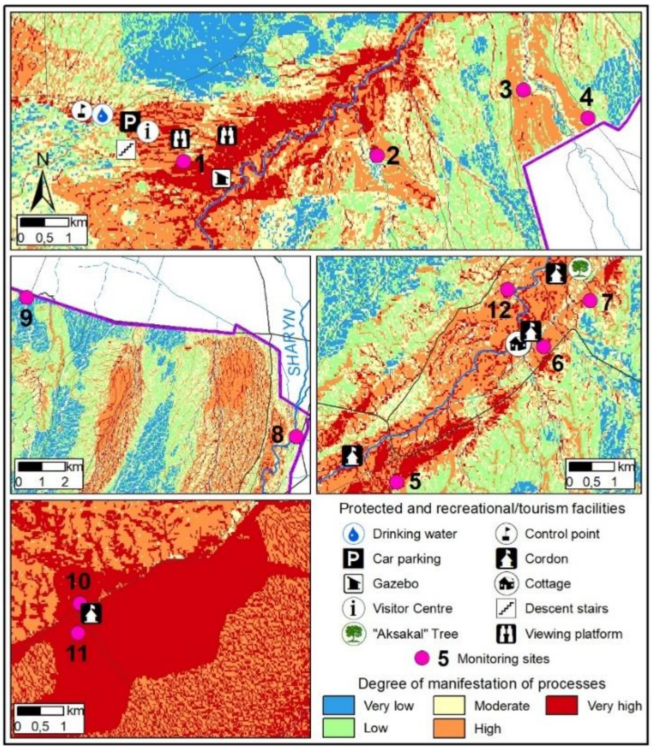

Figure 10. Placement of natural resource use facilities in the zone of manifestation of hazardous geological and geomorphological processes of the Charyn SNNP (Source: Developed by authors, 2025)

On the territory of the Charyn SNNP, the modern relief, characterized by a wide variety of geomorphological forms, is the result of long-term geological and geomorphological processes that developed during the Alpine tectono-magmatic era. Field studies have established that currently, the most widespread processes in the studied area are planar wash processes. At the same time, geomorphological processes such as landslides, rockslides, gully and lateral erosion tend to be localized and fragmentary, primarily occurring on steep slopes, areas with significant relief dissection, and specific lithological compositions of the rocks. To assess the adequacy of the model, field verification surveys were carried out at key sites of the study area. The verification included georeferencing of the observed processes, photo documentation, description of geomorphological forms, visual assessment of process activity (e.g., recent rockslides, signs of water erosion, soil cracks, etc.), as well as comparison with the model-derived integral map. At the same time, when interpreting the obtained results, it is necessary to consider a number of uncertainties related to the input data. For example, precipitation is represented by averaged long-term data that do not account for extreme weather events capable of triggering sudden geodynamic manifestations; the DEM with a 30 m resolution does not capture small-scale landforms typical of gully networks and slopes with micro-ridges, which reduces the accuracy of slope, TWI, and dissection calculations; NDVI and TWI may vary seasonally and also depend on the quality of satellite imagery (cloud cover, acquisition time, topographic shadowing); the lithological map was used at a 1:200,000 scale, which implies generalization of lithological units and omission of minor faults or lithological lenses. Despite the presence of certain sources of uncertainty, the combination of undertaken measures ensured the reliability and reproducibility of the integrated map, as well as its practical applicability for the assessment of geomorphological risks, natural resource management, and infrastructure planning within the Charyn SNNP.

It is important to note that natural resource use objects, including recreational and tourism zones, are situated within territories exhibiting a high to very high degree of activity of geological and geomorphological processes. This must be taken into account to ensure sustainable and safe natural resource management (Figures 10, 11).

DISCUSSION

This study is aimed at a comprehensive analysis of how interacting natural factors impact the activation of hazardous geological and geomorphological processes, with the goal of developing approaches for safe and sustainable resource management in the Charyn SNNP. The findings confirm that the activation of hazardous geological and geomorphological processes in the study area results from the complex interaction of multiple natural factors, each contributing to the spatial variability of risk. An integrated approach is of particular importance, as it allows for the identification of synergistic effects among climatic, geological and geomorphological, hydrological, and biotic components of the natural environment.

The uniqueness of the regional findings obtained for the Charyn SNNP lies in their association with a sharply arid climate and a complex orographic structure characterized by alternating canyons, mountain ranges, and intermontane basins. Similar studies in other arid and semi-arid regions of the world also emphasize the role of lithological vulnerability and relief; however, the degree of these factors' significance and their interactions varies.

a) zone of active landslide processes along the tourist route in the Charyn canyon (monitoring site №1)

b) slope with actively progressing rockslide processes in the area of the Charyn SNNP border checkpoint (monitoring site 10)

c) destruction of the roadway surface caused by a recent mudflow (monitoring site 9)

d) process of bank erosion of the Sharyn River caused by lateral erosion. The section is located in close proximity to a hydraulic structure (monitoring site 8)

Figure 11. Manifestations of hazardous geological and geomorphological processes within monitoring sites (Source: Photo taken by employees of the laboratory of geotourism and geomorphology of the JSC "Institute of Geography and Water Security")

For example, a study conducted in the upper reaches of the Minjiang River in China found that the combination of steep slopes and the loose composition of Quaternary deposits significantly increases the risks of landslides and erosion under monsoonal climate conditions (Wang & Bai, 2023). A comparison with the Charyn region shows that under a more arid climate, similar processes are activated mainly during extreme precipitation events, which are often of a torrential nature.

The identified patterns confirm that the most significant impact on the development of hazardous processes comes from the combination of extreme climatic conditions, lithological vulnerability of rocks, and morphometric parameters of the terrain. For example, areas with slopes steeper than 25°, located in zones with loose sedimentary rocks and high TWI values, exhibit the greatest susceptibility to slope processes, including erosion, falls, and mudslides. These findings are consistent with previous research, which emphasizes the vulnerability of arid regions when climatic and lithological factors are combined (Yu et al., 2024; Heo et al., 2024; Zhanibek et al., 2025). The comprehensive assessment revealed that biotic parameters, particularly NDVI values, play a mitigating role regarding geomorphological instability. Areas with high vegetation density are characterized by a relatively lower level of hazard. This is supported by previous findings emphasizing the role of vegetation in slope stabilization and reduction of runoff (Chelariu et al., 2023; Miklin et al., 2022).

It is especially important to highlight the significance of the river network density and its influence on erosion processes. Regions with high drainage density exhibit consistent correlations with increased water erosion intensity, necessitating additional measures for surface runoff management and hydrological monitoring, particularly during periods of intense precipitation. It is worth noting the comparison with a study conducted in the steppe regions of Romania, which established a direct relationship between erosion processes and river network density, particularly in areas with small elevation differences (Chelariu et al., 2023). In the Charyn SNNP, despite a more pronounced relief, a similar trend is observed: areas with high drainage density exhibit significantly increased water erosion intensity. This is especially relevant for canyon-like sections with ephemeral streams that, during extreme rainfall, transform into debris flows.

In South Korea an analysis of slope processes using GIS and remote sensing data revealed that high drainage density and lithological heterogeneity, under monsoonal rainfall conditions, act as catalysts for large-scale geodynamic phenomena (Lee et al., 2004). In contrast, within the Charyn SNNP, a similar drainage network configuration, combined with lower precipitation volumes, results in more localized manifestations of water erosion, highlighting the specific role of climatic conditions. The application of multivariate analysis using remote sensing data and GIS enabled the development of an integrated hazard map reflecting the interactions of key natural factors. This integrative approach, based on multi-parameter spatial analysis, allows for objective identification and classification of areas according to the degree of manifestation of geological and geomorphological processes, thereby highlighting zones with varying levels of risk. The largest portions of the territory are classified as moderate (27.1%, 346.8 km^2) and high (26.5%, 339.6 km^2) hazard, indicating widespread regions with increased geodynamic activity. Very high hazard zones cover 10.9% of the area (139.9 km^2), pointing to localized areas that require special attention. The most hazardous areas are located in the high-altitude regions along the upper reaches of the Sharyn River, where the Toraigyr, Katu mountain ranges, the Ulken Bugyty ridge, and the Moyyntogai and Taskora localities are situated. The Charyn Canyon also features complex geomorphological conditions characterized by a heightened risk of hazardous processes such as landslides, rockslides, gully formation, and lateral erosion.

Zones with moderate, low, and very low degree of hazard (collectively covering 62.5% of the area) are primarily affected by sheet wash and weakly expressed erosion. These processes are generally localized, occurring mainly in transitional zones between flat plains and hilly, undulating terrain, with limited spatial extent. Field observations confirmed that currently, the most widespread process on the studied area is surface runoff. At the same time, landslide and rockslide processes – primarily associated with steep slope sections and areas with significant vertical relief – along with ravine and lateral erosion, are localized and fragmentary in nature. The obtained data have practical significance for planning environmental conservation activities and for spatial zoning of the park territory, as well as for developing eco-tourism routes. The proposed approach can be adapted and scaled for other protected areas with similar natural and climatic conditions. Despite these significant findings, it is advisable in the future to expand the range of factors considered by including anthropogenic impacts, tectonic activity, and dynamic climate scenarios. This will not only improve the accuracy of spatial analysis but also lay the foundation for developing effective strategies for the safe and sustainable use of natural resources within the Charyn SNNP.

CONCLUSION

This study presents a comprehensive approach to assessing hazardous geological and geomorphological processes within the Charyn SNNP, based on the integration of field observations, remote sensing data, GIS analysis, and the AHP within the framework of MCDA. The findings indicate that the activation of geodynamical hazardous processes is driven by the combined influence of several natural factors, including extreme atmospheric precipitation, lithological vulnerability of rocks, slope steepness, vertical terrain dissection, drainage network density, TWI, and NDVI. Areas with slopes exceeding 25°, characterized by loose sedimentary deposits and high TWI values, exhibit the highest susceptibility to the development of hazardous processes, where erosion, landslides, and mudflows are most likely to occur. The AHP method provided a formalized integration of factors into a reproducible spatial assessment model.

The reliability of the model has been confirmed through field verification results. The developed composite map depicting the intensity of hazardous geological and geomorphological processes serves as an effective tool for risk zoning and decision-making within the framework of sustainable management of protected areas. The proposed approach can be adapted and applied to other arid and tectonically active regions with limited observational data.

The present study provides valuable insights into the influence of natural factors on the activation of geological and geomorphological processes within the Charyn SNNP; however, it has several methodological and informational limitations. The key constraints are associated with the insufficient spatial resolution of the input data, particularly the absence of high-resolution satellite imagery, detailed DEMs, and up-to-date soil maps. These limitations reduce the accuracy of topographic analysis and the comprehensive assessment of factors contributing to the development of hazardous processes. Overcoming these challenges could be achieved through the use of advanced remote sensing technologies, such as LiDAR, which would enhance the spatial detail and reliability of the input data. Future research could benefit from integrating hybrid approaches and machine learning methods capable of improving multi-criteria decision-making procedures and increasing the accuracy of geological and geomorphological process assessments. Expanding the model to incorporate anthropogenic factors, parameters of tectonic activity, and climate change scenarios would further improve forecast accuracy and the validity of adaptive management strategies for vulnerable natural systems.

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