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ANALYSIS OF THE VULNERABILITY OF RECREATIONAL LANDSCAPES IN THE RIVER BASIN TO LANDSLIDES, CONSIDERING THE GEOMORPHOLOGICAL FACTOR (KAZAKHSTAN)

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Abstract: This study analyzes the vulnerability of recreational landscapes in the Sharyn River basin (Almaty Region, Kazakhstan) to landslides. The area, known for its tourism potential and geomorphological diversity, faces increasing threats due to slope instability. The aim of the research is to assess geomorphological and hydrological factors contributing to landslide risk and develop a comprehensive spatial model. Using GIS and remote sensing tools, a Digital Elevation Model (DEM) was created. The basin was divided into altitude zones, and slope gradient and exposure were analyzed. A landslide risk map was produced, classifying areas into low, medium, and high-risk zones. Slope stability was assessed using the Factor of Safety (FS), integrating soil type, moisture, and slope conditions. To enhance risk evaluation, the Analytic Hierarchy Process (AHP) was used to combine multiple spatial and environmental criteria. The Normalized Difference Water Index (NDWI) was derived from satellite imagery to map surface moisture and assess spatio-temporal humidity dynamics. NDWI helped refine FS results and indicated that high-risk areas were associated with steep slopes, north-facing exposures, and high soil moisture. Lower-altitude areas showed seasonal variability in humidity, influencing instability. The integration of NDWI and AHP improved the accuracy of landslide susceptibility mapping and the prioritization of vulnerable zones. The results confirm that geomorphological structure and hydrological factors jointly control landslide processes. This integrated approach supports early warning, spatial planning, and risk reduction in mountainous recreational regions. The findings are essential for sustainable tourism development and regional safety strategies. The methodology can be adapted for other vulnerable landscapes with similar natural and socioeconomic characteristics.

Keywords: tourism safety, high-altitude zones, landscape vulnerability, landslides, risk analysis, relief, factor of safety

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INTRODUCTION

The recreational landscapes of the river basin of the mountainous region represent a unique system of the natural environment. The Sharyn River is the largest left - bank tributary of the Ile River and belongs to the basin of Lake Balkhash, located in the semi-desert zone of the temperate climate zone. The basin area is 12,693 km2, with absolute heights ranging from 3,957 m at the source to 540 m at the mouth. The geographical coordinates of the basin are 42°40'-44°00' north latitude and 78°30'-80°35' east longitude. According to the hypsometric structure and macrorelief, the landscapes of the region belong to the class of flat and mountainous territories, the uniqueness of which opens up significant opportunities for the development of various forms of ecological tourism. Due to its physical and geographical location, geological and geomorphological features, and landscape diversity, the south-east of Kazakhstan, as noted by Nigmatova and co-authors, has sufficient natural resource potential for the development of recreation and such types of tourism as ecotourism and "green" tourism (agrotourism), water tourism and other types (Nigmatova et al., 2021). A physico-geographical mountainous region is a part of a continent that is characterized by the geomorphological unity of the territory, similar macroclimatic conditions, types of landscape diversity, and high-altitude zonation of landscapes. The relief is the main component of the this environment, which contributes to the development of the tourist potential of

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mountainous areas, which can be represented as tourist sites or resources that generate tourism. Tourism activities in mountainous areas bring many positive results, such as economic development, popularization of natural attractions and improvement of the standard of living of local communities (Dunets et al., 2019; Dunets, 2011; Ufimtsev, 2010).

However, the use of landforms for tourism purposes also has a number of disadvantages, including the threat of degradation of natural sites. In addition, mountainous areas are susceptible to various natural disasters, such as landslides, which requires special attention to ensure the safety of tourism activities and minimize environmental damage.

According to Sümeyra, giving conservation status to relief forms used for tourism is a key element of their sustainable use. This status contributes to the preservation of natural sites and the prevention of negative consequences associated with the exploitation of the territory for tourist purposes (Sümeyra, 2015). In mountainous regions, landslides represent one of the most severe natural hazards. Due to natural conditions or man-made actions, landslides have produced considerable human and economic losses. Individual slope failures are generally not so spectacular or so close as earthquakes or some other natural catastrophes. However, they are more widespread, and over the years, they may cause more damage to properties than any other geological hazards. The effects of these events have significant consequences for local communities, ecosystems, and infrastructure. With climate change and increased human activity, assessing the vulnerability of these areas has become a critical task (Van Westen & Castellanos, 2007; Kusainov, 2012; Baryshnikov, 2012).

The altitude and climate gradients in mountainous areas make geomorphic processes and relief evolution especially active. Slope movements are one of the main factors contributing to erosion and relief evolution. Landslides are catastrophic geological events that occur worldwide. Research on assessing their risk has only recently gained widespread attention among scientists (Redondo et al., 2005; Ovreiu et al., 2018; Castellanos & Van Westen, 2007).

Landslides in mountainous areas have a significant impact on the safety of tourism activities and the sustainable development of territories. Petley analyzes global trends in landslide losses, including their impact on tourism infrastructure and local communities (Petley, 2012). The study emphasizes the need to integrate risk assessment into tourism planning in order to minimize potential risks and ensure the safety of tourists and local residents. In the work of Media et al., data on mountain collapses and landslide in the Kungei Alatau, Terskei Alatau, and other ranges in southeastern Kazakhstan are presented. As a result of their research, more than 60 large seismogenic landslides were identified, with the volume of 25 ranging from 10 to 100 mln m^3, and the volume of the four largest landslides exceeding 100 mln m^3. In the mid-mountain and high-mountain zones of Zhetysu Alatau, Ile Alatau and Kungei Alatau, the density of seismogenic landslides ranges from 1/100 to 1/50 $км^2$, and the proportion of landslide-prone areas ranges from 1% to 1.5% (Medeu et al., 2018).

The geomorphological features of mountainous regions are an important factor in the formation of landscapes, their sustainability, and the development of tourism potential (Dunets, 2011). Many studies emphasize the role of geological structure and relief formation processes in creating attractive tourist resources, as well as the emergence of natural threats. In the work of Tserkashova et al., the influence of tectonic activity on the formation of complex reliefs and related geohazards is considered, and climatic factors play a significant role in the vulnerability of mountainous areas (Tserkashova et al., 2020). Changes in temperature conditions and precipitation can significantly increase the likelihood of landslides, especially in areas with high moisture content and intense erosion (Kalinin et al., 2019).

An important aspect is the study of the anthropogenic impact on mountain landscapes. In particular, urbanization, road construction, and mining activities can significantly increase the vulnerability of mountainous areas to landslides, as shown in studies. In addition, the sustainable development of mountainous areas requires taking into account natural threats, such as landslides, when developing tourist routes and infrastructure (Yakovleva et al., 2021; Froude & Petley, 2018).

For local communities located in areas with a high risk of landslides, the consequences can be catastrophic. Landslides threaten not only human lives, but also the destruction of infrastructure and agriculture. The assessment of the significance of the risks in this study showed that areas with high risks of landslides should receive special attention from local authorities. It is especially important to consider the impact of climate change, which can cause more frequent and severe precipitation, worsening the condition of slopes. The purpose of this work is to identify areas with a high risk of landslides based on an analysis of the terrain of the Sharyn River basin in the Almaty region, Republic of Kazakhstan.

This study is relevant due to the development of ecological tourism in this region, where natural hazards pose a serious threat to tourist routes and infrastructure sustainability. To achieve this goal, the following tasks were solved: creation of a DEM, analysis of slope maps to identify critical areas and areas at high risk of landslides, considering the geomorphological characteristics of the territory; use of satellite data to calculate NDWI to assess soil moisture; assessment of slope stability using FS calculation method and AHP multicriteria analysis, taking into consideration soil type and moisture content. The practical significance of identifying risk zones in terms of their impact on sustainable development and the safety of tourists is based on an integrated approach using GIS. This approach combines the protection of natural landscapes and infrastructure development to ensure the safety of visitors and the sustainability of the area.

GIS also allows for creating interactive educational programs that help raise environmental awareness among tourists and encourage them to interact with the environment more deeply (Seidualin et al., 2024; Krotova, 2003).

The results of the work have practical importance for planning sustainable development in the region, ensuring the safety of tourist routes, and minimizing damage from landslides. The findings of the study can be used as a basis for strategies to manage natural risks and promote environmentally sound tourism.

MATERIALS AND METHODS

The methodology of the work is based on the following steps, as shown in Figure 1. Firstly, using GIS and remote sensing technology to create a DEM and perform slope analysis. The DEM is created using topographic survey data and satellite imagery, and the ArcGIS PRO software is used to build the model. This allows us to determine key characteristics of slopes, such as height, slope, and exposure. The process includes collecting initial relief data, processing it, interpolating elevation points, creating slope maps, and exposures for further analysis (Kerimbay & Kerimbay, 2022; Zhensikbayeva et al., 2024).

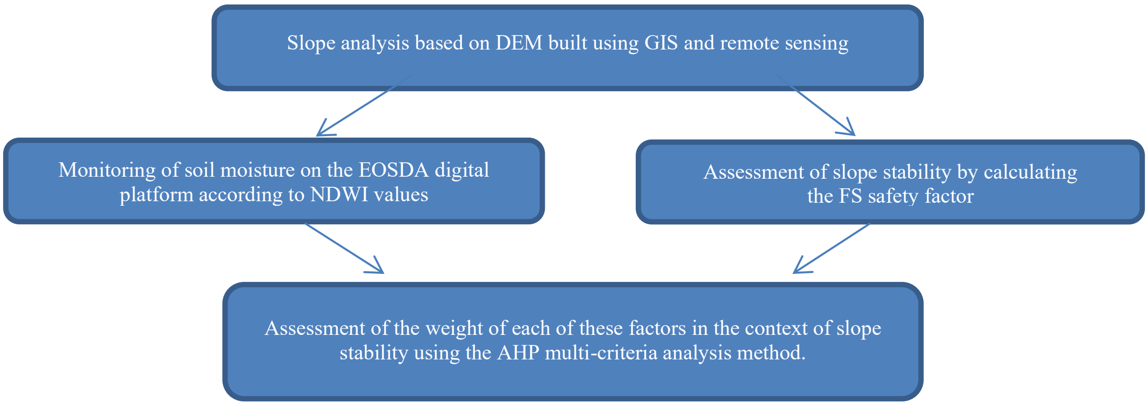


Figure 1. Methodology steps of our scientific research

Secondly, to increase the accuracy of assessing the vulnerability of territories to landslides, factors such as soil type and soil moisture were taken into account. These parameters play a key role in the formation of slope instability, which is confirmed by research (Fredlund & Rahardjo, 1993). The analysis included high, mid-mountain (3000-2200 m), and low-mountain (2200-1600 m) as well as the desert-steppe territories (below 1600m). Different types of soils in these zones have unique physical properties that affect slope stability: clay soils are prone to loss of stability in high humidity, while sandy and rocky soils are more stable. Soil moisture, which depends on climatic conditions (heavy precipitation and snowmelt), directly affects its density and particle cohesion. This, in turn, increases or reduces the risk of landslides.

The digital platform Earth Observing System Data Analytics (EOSDA, web service "Analytics-Time series") was used to monitor soil moisture in the Sharyn River basin (EOSDA, 2024). The method is based on the use of satellite data, where the green spectrum and the near-infrared zone make it possible to detect spatio-temporal changes in soil moisture and vegetation. NDWI values provide important information for classifying territories according to the degree of drought, humidity, and risk of landslide (Gao, 1996; Gu et al., 2007; Jackson et al., 2004). The integration of cartographic techniques and remote sensing data in a GIS environment forms the foundation for cartographic and remote monitoring of natural processes and events, which is essential at the regional scale (Sharapkhanova et al., 2024).

Thirdly, to assess the stability of slopes in mountainous areas, a safety factor calculation method was applied to FS, which makes it possible to identify landslide risk zones. Due to its versatility, this method is actively used in geotechnical and geomorphological analysis. Using the FS method, we obtained accurate data on potential threat areas and developed recommendations for minimizing them (Fell et al., 2005). Fourth, in order to assess the weight of each of these factors in the context of slope stability, the AHP method was applied, which provides a systematic approach to selecting and weighing multiple criteria, making it an ideal tool for geotechnical assessment. AHP is a method that allows you to make decisions when several criteria need to be taken into account (for example, soil type, soil moisture, relief, etc.). During the analysis, a hierarchy of factors is established, and then the weight of each one of them is determined using paired comparisons. The AHP in combination with GIS is widely used for spatial analysis and decision-making in various fields, such as risk management, sustainability assessment, environmental research and project management (Saaty, 1980; Malczewski, 1999; Saaty & Vargas,2001).

Geomorphologically, the Sharyn River basin is characterized by a high diversity of relief, including high-mountain, medium-mountain and low-mountain relief as well as desert-steppe plain territory. The mountain ranges bordering the basin have steep slopes and are heavily indented by deep river valleys. The watershed lines of the Ketmen Range and the Karatau Mountains run at an altitude of 2500-3000 meters, although some peaks reach absolute elevations of 3600-4200 m.

Similarly, in the northern spurs of the Central Tien-Shan and on the Kungei-Alatau ridge, the maximum heights are 3200-2100 m. The relief gradually decreases towards the mouth of the Karkara River, and the heights in the middle part of the basin do not exceed 1,800. The mountainous area is characterized by frequent rock outcrops, making this area particularly susceptible to landslide processes (Kerimbay, 2008; Kerimbay et al., 2024). The DEM analysis showed that more than 80% of the total basin area is mountainous (above 1,600 m). The rest falls on flat areas and counter (Figure 2). Based on this analysis, the territory of the Sharyn River basin was divided into high-altitude zones, which allowed us to characterize the slopes and their stability in detail (Table 1).

Table 1. High-altitude zones of the Sharyn River basin (Source: Authors' data processing)

№	Elevation Range (m)	Area (km²)	Percentage of Total Area (%)
1	up to 1000 m	724	8,7
2	1000-1600	979	11,8
3	1600-2500	4211	50,4
4	over 2500	2435	29,1

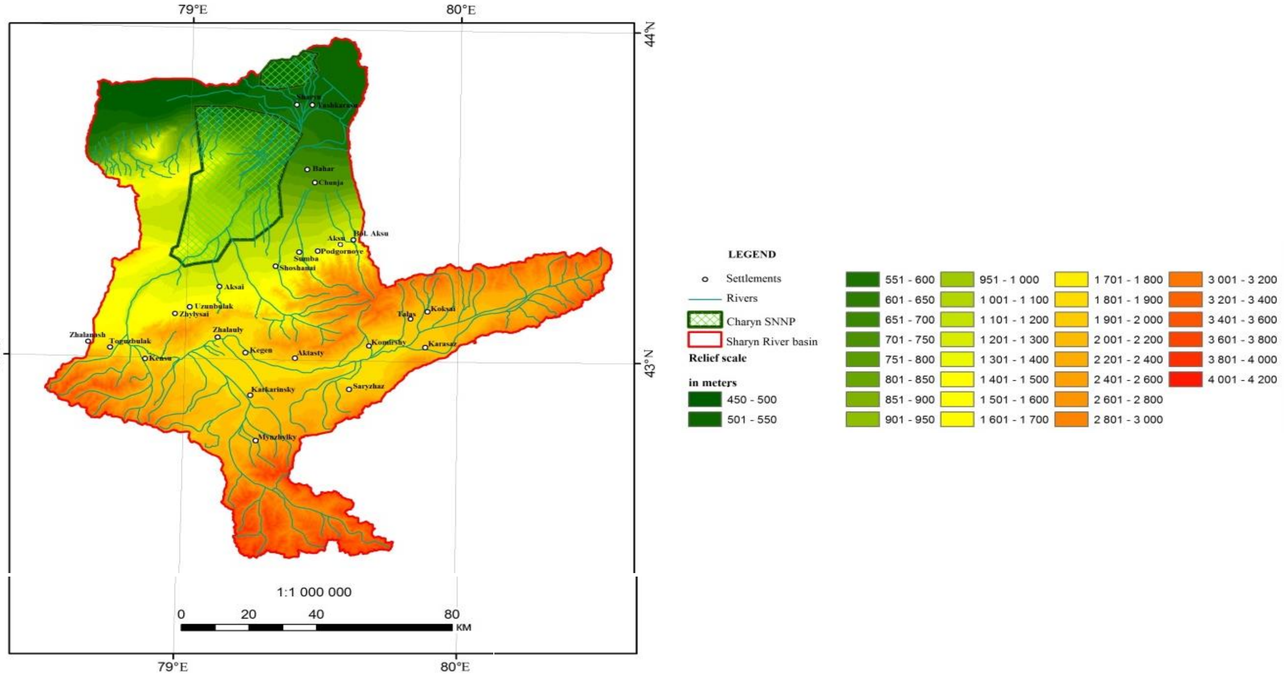


Figure 2. Digital Relief Model of the Sharyn River Basin (Source: compiled by the authors)

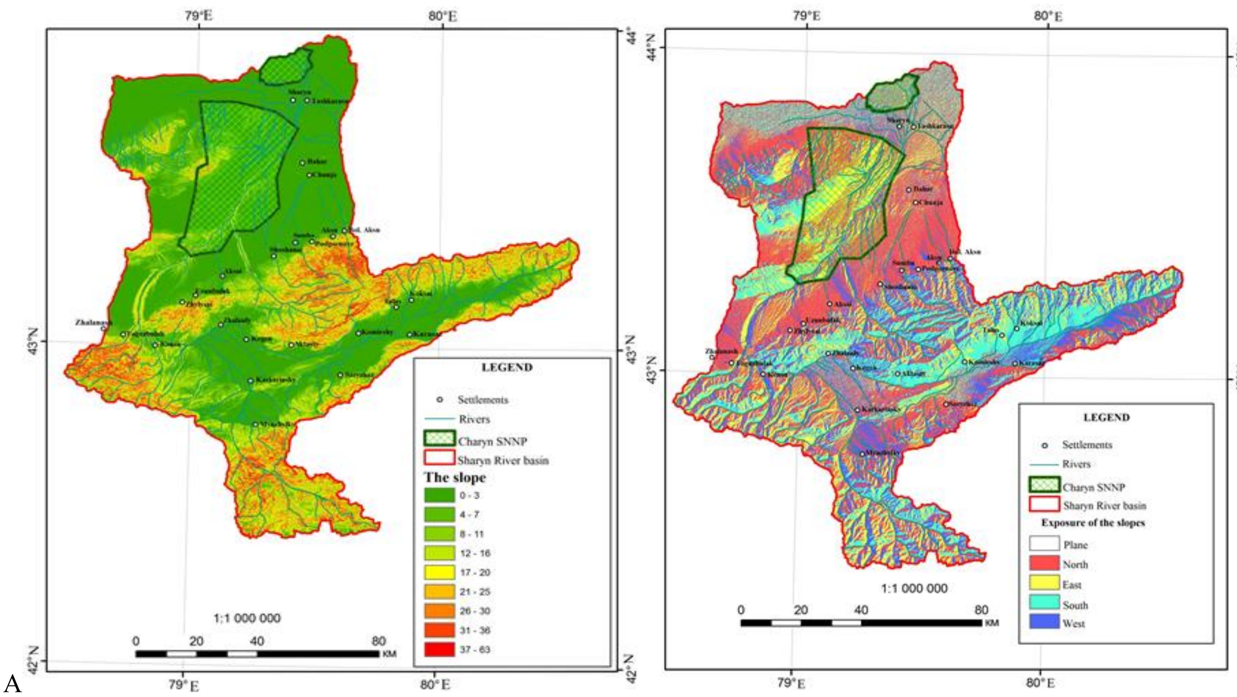
The main risk zones were identified based on an analysis of the geometry of slopes, their steepness and characteristics, as well as soil moisture data. This approach has made it possible to identify areas with a high potential for landslide processes, which require additional measures to minimize risks.

The territory of the Sharyn river basin is characterized by a latitudinal alternation of mountain ranges and large intermountain depressions, which is typical of the northern slopes of the Tian-Shan. Among the identified areas are the Terskei-Alatau and Kungei-Alatay highlands, the Shalkudusu-Kegen, Kuluktau-Temirlik and Ketmen mountains, the Turaigur lowlands, Zhalanash valley, as well as Aksay-Sogety foothills and lower delta of Sharyn. These areas reflect the significant diversity of the region's topography, which has an impact on landslide resistance. The main processes involved in the formation of the relief include glacial, tectonic, erosion-denudation, and accumulative types (Kerimbay et al., 2020).

RESULTS AND DISCUSSION

1. Analysis of the digital relief model to assess the slope resistance to landslides according to FS calculation

To determine the risk zone for landslides, it was necessary to perform an analysis of slopes and exposures from the original digital DEM file in tif (GeoTIFF) format (Figure 3).



A B

Figure 3. DEM of the Sharyn River basin: (A) map of slopes; (B) map of exposures (Source: compiled by the authors)

Steep slopes with a high risk exceeding the slope threshold of more than 30 degrees have been identified. The slope directions relative to cardinal directions have been analyzed and key areas with high risk of landslides have been identified based on overlap of slope data and exposure data.

To assess the stability of slopes, FS was calculated. The main results include:

- Areas with FS < 1 indicate steep slopes, unstable soil and high groundwater levels. This indicates a high probability of landslides.
- Areas where FS = 1 are in a state of borderline stability. Any slight changes in conditions could lead to landslides.
- Zones with FS > 1: are represented by more stable areas where the probability of landslides is significantly lower. To analyze the territories of landslide risk zones, based on data on slopes and exposure, a spatial assessment of risk zones has been performed (Figure 4).

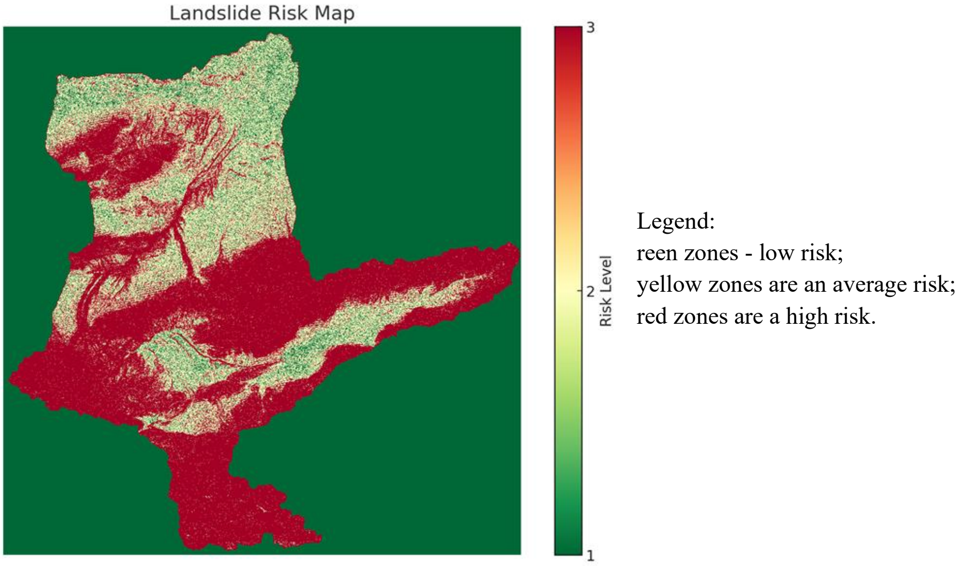


Figure 4. Landslide risk zones of the Sharyn River basin (Source: Authors' data processing based on calculations by FS)

Spatial assessment of the risk areas of landslides in the Sharyn River basin: green areas - low risk corresponding to gentle slopes; yellow areas - medium risk determined by transitional slope characteristics; red areas - high risk associated with steep slopes and unfavourable soil conditions. Summary of risk areas:

- Low risk covers approximately 2,835,159 cells (19.256 km²).
- Average risk is about 557,930 cells (3.789 km²).
- High risk is approximately 1.110.277 cells (7.541 km²). Each pixel of the map has a size of 82.41 mx 82.41m, which gives an area of about 6.793m^2 per pixel. This was used to calculate the total area of risk zones (Table 2).

The main results of the slope stability analysis performed using the FS method include: Zones with FS < 1 indicate a high probability of landslides. These zones are characterized by steep slopes and unstable soils, and have high groundwater levels. They are therefore the most dangerous areas. The high risk of landslides is concentrated on steep slopes, especially in highland areas such as the Terskei-Alatau and Kungei-Alataus. Zones with FS = 1: belong to border-stable territories. The slightest change in conditions (for example, heavy precipitation) can lead to the activation of landslides. The average risk is typical for foothills and mid-mountain areas with moderate slopes, such as Ketmen and Kuluktau-Temirlik. Zones with FS > 1 represent the most stable areas with a low risk of landslides, and a low risk was noted in the low-mountain and lowland areas including the Delta Sharyn. These results highlight the importance of taking into account geomorphological factors, such as slope steepness and exposure, when planning hiking trails and implementing conservation measures.

Table 2. Total area of landslide risk zones in the Sharyn River basin (Source: Authors' data processing based on calculations by FS)

№	The level of risk	The spatial assessment	Total area of risk zones (km)
1	Low risk	corresponds to gentle slopes with stable soils, with slopes of less than 15°. The lower reaches of the Sharyn River basin	19,256
2	Average risk	corresponds to the transitional characteristics of slopes with mixed exposures, ranging from 15 degrees to 30 degrees. It includes foothills and mid-mountains	3,789
3	High risk	corresponds to the steep slopes of the north-eastern exposure with unstable soils, slopes of more than 30° and watersheds in mountainous areas	7,541

2. Results based on AHP (Analytical Hierarchy Process) with additional factors: soil type and soil moisture NDWI

For more comprehensive and accurate results, we use additional factors such as soil type and soil moisture, based on the AHP, which is used to solve complex problems when it is necessary to take into account several factors or criteria that have varying degrees of importance (Hwang & Yoon, 1981).

So, the factors for assessing the resistance of slopes in the Sharyn River basin to landslides are:

Factor 1: Terrain - data on the digital terrain model, slopes, and exposures, as well as calculation of FS.
Factor 2: Soil Type - data on soil types, their properties, and resistance to landslides.
Factor 3: Moisture - data on moisture content.

Different types of soil in the Sharyn River basin have unique physical properties that determine their resistance to landslides. Clay soils are particularly susceptible to landslides during periods of high humidity, as their structure becomes less stable under the influence of water. At the same time, sandy and rocky soils demonstrate greater stability due to their drainage properties and mechanical strength. The diversity of soils in the Shari River basin is closely related to the altitude zone and the nature of geomorphological processes in the region. The high-altitude region (over 3000 m) is covered by modern glaciers. At lower elevations, there are deposits of gravel and loam formed on dark chestnut-colored mountain soils. Also, there are fragments of alpine meadows, typical of mountain meadow soils.

- The mid-mountain belt (3000–2200 m) is characterized by Alpine and subalpine meadows developed on dark mountain meadow soils. The peculiarity of this zone is the strong dissection of the relief and intense erosion processes. High moisture content and large hypsometric levels of soil create conditions for planar flushing development.
- Low-mountain (2200–1600m) includes temporary watercourse territories. The soils are represented by black mountain earth and chestnuts.

Desert-steppe plain (below 1600) covers foothills with drainless ecosystems. Gray-brown soils dominate in runoff dispersion zones. The NDWI space-time series, which was constructed for analysis between 2016 and 2024, includes high-altitude, medium-altitude (3000 - 2200m), low-altitude territories (2200 -1600 m) as well as desert-steppe plain territories (below 1600 m) (Tables 3-8). The results showed that NDWI values in high-altitude areas ranged from moderate drought (-0.6 to -0.3) to flooding (0 to 0.2). However, the area of flooded territory remained at all times. The average NDWI value indicated a trend towards moderate humidity between 2016 and 2024.

Table 3. NDWI values for the highland and mid-mountain belts (3000-2200 meters), 2016-2024 (Source: on materials EOS Data Analytics, authors' data processing)

NDWI	Humidity type	Area, km^2				
		2016	2018	2020	2022	2024
0.2-0.1	The surface of the water	0.00	0.00	0.00	0.00	0.00
0-0.2	Flooding, humidity,	0.34	0.015	0.00	00.82	0.00
-0.3-0	Moderate aridity, non-water surfaces	117.57	141.68	150.1	152.33	132.60
-0.6-0.3	Aridity	19.96	14.34	0.00	7.20	19.74
-1-0.6	Drought	12.57	14.10	0.00	0.78	17.80

Table 4. Minimum, maximum, and average NDWI values for high-altitude and mid-mountain zones (3,000–2,200 m), 2016-2024 (Source: on materials EOS Data Analytics, authors' data processing)

Years	NDWI mean	min	max
2016	-0.49	-0.74	0.16
2017	-0.39	-075	0.28
2018	-0.04	-0.08	0.03
2019	-0.09	-0.66	0.10
2020	-0.50	-0.74	0.04

Table 5. NDWI values for the low-mountain belt (2,200 - 1,600 m), 2016–2024 (Source: on materials EOS Data Analytics, authors' data processing)

NDWI	Humidity type	Area, km^2				
		2016	2018	2020	2022	2024
0.2-0.1	The surface of the water	0.015	0.010	0.066	0.066	1.29
0-0.2	Flooding, humidity,	0.43	0.40	0.51	0.27	0.70
-0.3-0	Moderate aridity, non-water surfaces	35.18	33.79	6.45	2.34	33.68
-0.6-0.3	Aridity	141.27	130.23	139.35	80.08	85.02
-1-0.6	Drought	19.25	17.09	5.15	68.78	32.10

Table 6. Minimum, maximum, and average NDWI values of the low mountain belt (2,200-1,600 m), 2016-24 (Source on materials EOS Data Analytics, authors' data processing)

Years	NDWI mean	min	max
2017	-0.49	-0.85	0.37
2018	-0.44	-0.75	0.30
2019	-0.47	-0.76	0.35
2020	-0.49	-0.85	0.36

The monitoring results showed that the territory with severe drought indicators (-1 to -0.6) significantly increased in 2022 and then decreased by 2024. At the same time, there was an increase in the area with a humidity index (0.2-0.1), indicating possible climatic or hydrological changes in 2024. The monitoring results showed that the territory with moderate aridity (from -0.3 to 0) demonstrated relative stability, occupying most of the region during the study period. No significant changes in the indicators (from -1 to -0.6) indicate the zone's resistance to extreme events.

At the same time, there was an increase in the area of wetlands (0-0.2), which may be due to local seasonal or climatic changes affecting the hydrological conditions in the region. The observed trends are related to the peculiarities of high-altitude zone. The observed trends are related to the peculiarities of high-altitude zones. Highlands with northeastern exposures and midlands with transitional slope characteristics and mixed exposures show a more balanced moisture level, which is related to their climatic characteristics. Low mountains and foothills with transitional slopes and mixed exposures are more susceptible to drought and arid conditions. The desert-steppe plain with stable soils has a moderate drought, but small changes in humidity indicate the influence of local climate factors or seasonality in some years. The areas of temporary watercourses have an increase in moistened areas in some years, while the territories of permanent watercourses remain unchanged

Table 7. NDWI values for the desert-steppe plain (below 1,600 m), 2016-2024 (Source: on materials EOS Data Analytics, authors' data processing)

NDWI	Humidity type	Area, km^2				
		2016	2018	2020	2022	2024
0.2-0.1	The surface of the water	0.00	0.00	0.00	0.00	0.001
0-0.2	Flooding, humidity,	0.076	0.013	0.016	0.00	0.217
-0.3-0	Moderate aridity, non-water surfaces	141.34	141.61	141.61	141.44	141.38
-0.6-0.3	Aridity	0.049	0.006	0.00	0.19	0.026
-1-0.6	Drought	0.00	0.00	0.00	0.00	0.00

Table 8. Minimum, maximum and average NDVI values for the desert-steppe plain
(below 1,600 m), 2016-2024 (Source: on materials EOS Data Analytics, authors' data processing)

Years	NDWI mean	min	max
2016	-0.17	-0.53	0.21
2017	-0.15	-0.40	0.13
2018	-0.09	-0.25	0.09
2019	-0.16	-0.56	0.12
2020	-0.13	-0.32	0.35

.Thus, soil types and soil moisture in the Sharyn River basin not only reflect the diversity of natural conditions, but also have a significant impact on slope stability. This is especially important when planning the use of these territories, as the moisture level in the soil directly affects its density and stability. Heavy rains or snowmelt can increase the water content, leading to a decrease in adhesion forces between soil particles and increasing the risk of landslides.To identify the relative importance of each factor, paired comparisons were made. For this purpose, a scale from 1 to 9 was used to indicate the importance of factors, with 1 being equal importance and 9 indicating that one factor is significantly more important than another. Based on the importance ratings, a matrix of pairwise comparisons was created (Table 9).

Table 9. Matrix of paired comparisons based on importance ratings (Source: on materials of the method Analytic Hierarchy Process)

№	Factor	Relief (1)	Soil (2)	Humidity (3)
1	Relief (1)	1	7	7
2	Soil (2)	1/7	1	5
3	Humidity (3)	1/7	1/5	1

The importance of slope stability factors can be assessed as follows:

- Relief (Factor 1): Relief plays a significant role in determining the stability of slopes. Steep slopes and exposed areas have a greater impact on the risk of landslides, so they will receive the highest weight. The terrain is more important than the type of soil and humidity (we will estimate the importance of the terrain compared to other factors on a scale of 1-10). Soil type and humidity also have an effect, although it is smaller than that of the terrain.
- Soil Type (Factor 2): The type of soil is important for slope stability, especially for clay soils, which are more susceptible to erosion and landslides. The importance of soil is greater than that of humidity, and the importance of terrain is also significant (let's assign a value of 5 for soil compared to humidity and a value of 3 for terrain).
- Soil moisture (Factor 3): While soil moisture can affect slope stability, its effect is likely to be less significant compared to the terrain and soil types. Humidity is considered less important than the soil and terrain factors, so its significance will be estimated at 1/3 of the importance of the soil factor and 1/7 of the terrain factor.

To obtain the weights for each factor, the values in the matrix are normalized (Table 10). This is done by dividing each value in a row by the total sum of all values in that row (Figure 5and Figure 6). According to the matrix of paired comparisons, relief has been identified as a significant factor, with a higher weight than other factors, as its value in the normalized table is greater. The type of soil and soil moisture are of medium importance. This may suggest that the terrain plays a more significant role in determining vulnerability to landslides in the study area.

Table 10. Normalized values of relief, soil, and humidity in the matrix (Source: on materials from the analysis of AHP calculations)

№	Factor	Relief	Soil	Humidity
1	Relief	0.067	0.453	0.453
2	Soil	0.140	0.162	0.815
3	Humidity	0.140	0.032	0.641

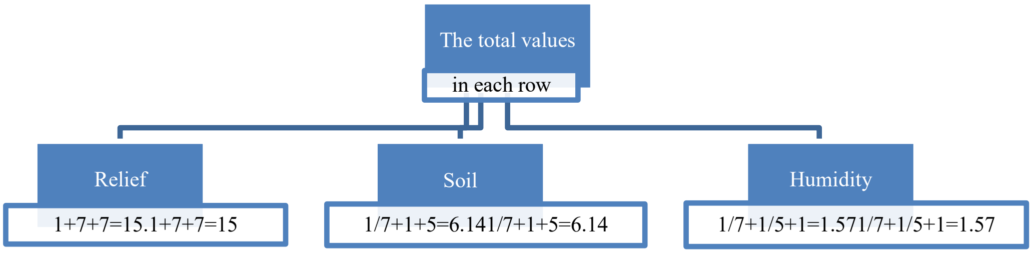


Figure 5. The total of the values in each row the matrix: Authors data processing

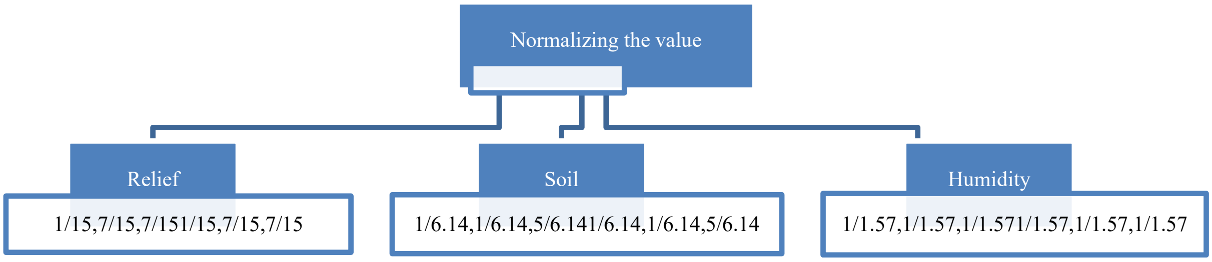


Figure 6. Normalizing the value: Authors data processing

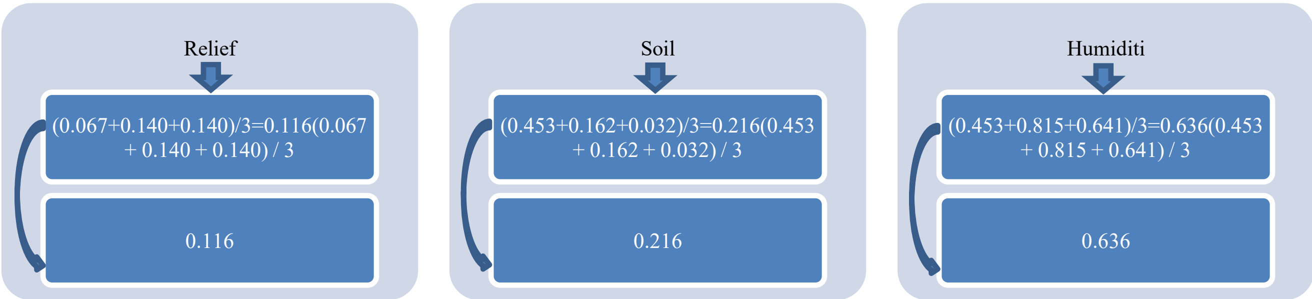


Figure 7. Calculation of weights and average values for each factor (Source: Authors data processing based on calculations by AHP)

The normalized values show the relative importance of each factor. For example, in the case of relief 7/15, a value of ≈ 0.467 indicates that relief contributes approximately 46.7%, when compared to other factors. Calculation of the final weights for the factors and the average values for each factor (Figure 7).

Thus, the results indicate that, although slope steepness remains an important factor in assessing the stability of slopes in the Sharyn River basin, soil moisture has a significant impact on the risk of landslides. Additionally, soil type also plays a role in determining the stability of the slopes. Therefore, it is essential to take into account both moisture and soil type when assessing the stability of a slope. These results emphasize the importance of considering the relief as the primary factor when planning sustainable hiking routes in mountainous areas. The relief has the greatest impact on landslide activity, making it a crucial consideration. While soil and humidity are also significant, their effects are likely to be secondary. Humidity may become more significant in the context of seasonal climate changes, for example.

3. Results of the analysis of the vulnerability of recreational areas in the Sharyn River basin to landslides

The results of the landslide resistance analysis, considering the geomorphological factors, soil type, and soil moisture, indicate that there is a wide variety of slopes with varying levels of stability within the Sharyn River basin. These areas with a higher risk of landslides tend to be concentrated in regions with steep slopes and unstable soil, as confirmed by the FS calculations, with values below 1 indicating a high probability of landslides. Special attention should be given to areas with high levels of soil moisture, as this significantly reduces the stability of slopes. Additionally, floods and heavy spring precipitation associated with snowmelt can increase the likelihood of ground movement. The most prone areas to landslides in the Sharyn River basin are located in the following geographical regions:

In the Terskei-Alatau, Kungei-Alatau, Shalkudysu-Kegen, Kuluktau-Temirlik, and Ketmen highlands and midlands, the constant effects of erosion processes and melting glaciers make the slopes extremely vulnerable to landslides. This is especially evident in the context of climate change, which increases glacial degradation and increases the intensity of surface erosion. Unstable soils formed on glacial deposits create a high potential for destructive processes. High erosion activity caused by slope and tectonic processes make the stability of landscapes extremely low, especially during periods of intense rain. The accumulation of loose material and changes in moisture regime increases the likelihood of landslides, especially in steep and actively collapsing areas (Kerimbay, 2008; Kerimbay et al., 2020).

Erosion processes that actively erode the slopes in the Turaigyr low-mountain erosion-denudation region contribute to the accumulation of sedimentary material in the lowlands. The slopes in this area are prone to landslides, especially during periods of heavy rainfall. Intensive processes of weathering and erosion in the Zhalagash and Aksai-Sogeti foothills form bedlands with weakened slope stability, which increases the likelihood of mass collapses due to the accumulation of loose material. Deposits of boulder-pebble strata and loess cover contribute to the formation of accumulative relief forms. These characteristics create dangerous conditions for landslides, especially in areas with insufficient soil consolidation. In the lower Sharyn desert-steppe plain zone, accumulative landforms formed by sedimentary material are vulnerable to soil displacement, especially under conditions of high humidity and sudden floods (Kerimbay, 2008; Kerimbay et al., 2020).

High-altitude zones, based on GIS analysis, open up opportunities for the localization of high-risk areas. GIS and remote sensing techniques make it possible to integrate data on soil types and moisture, providing a more comprehensive approach to slope stability analysis (Khromykh & Khromykh, 2007). The analysis of GIS data has allowed us to identify areas in the Sharyn River basin with different levels of vulnerability to landslides, which has been an important step in assessing and managing natural risks. Slope maps have proven to be especially useful in identifying areas with high slopes, which are a predisposing factor for landslide processes. Steep slopes, for example, have less soil stability, especially when exposed to moisture. This is confirmed by the results of our FS calculations. Additionally, the combination of slope maps and a slope exposure map has allowed us to establish a relationship between the orientation of slopes and their stability. Slopes facing the dominant sources of moisture are the most susceptible to landslides. In our work, it was important to develop measures to reduce the risk of landslides and increase safety in the region. Therefore, the use of GIS and remote sensing geotechnology became the main tool for assessing the vulnerability of slopes in the Sharyn River basin to landslides.

The use of the AHP method has made it possible not only to assess the importance of each factor, but also to integrate them into a comprehensive model that can be used to predict risks under various conditions. In particular, AHP helps identify those areas where each factor (for example, soil type or humidity) has the strongest impact on slope stability. This allows for more accurate targeting of efforts in areas with the highest risk. The study of the impact of landslides in the Sharyn River basin has shown the need for effective environmental and infrastructure measures. These measures include strengthening slopes, installing drainage systems, and improving monitoring. Additionally, it is important to create awareness programs for local residents about the risks and precautions associated with landslides. The study emphasizes the importance of having evacuation plans in place and strategies for quick response in case of emergency. This will help reduce damage and casualties in the event of a landslide. Despite the careful approach taken in this study, there are some limitations that need to be considered. Firstly, the data used for calculating the FS (factor of safety) is based on digital terrain models, which may contain some errors, particularly in areas with sudden elevation changes or complex geological structures. To improve accuracy, it may be beneficial to use higher-resolution data as information about groundwater levels and the geological characteristics of the area. Secondly, the FS method does not take into account all dynamic processes that can affect slope stability, such as earthquakes or changes in groundwater levels. In order to provide more accurate predictions of slope stability in the future, it would be helpful to develop more complex models that include these variables.

In addition, climate change and natural disasters, such as heavy rainfall and floods, can alter projected risks. This makes it necessary to regularly update data and use more sophisticated models to predict slope stability. Therefore, periodic monitoring and updating of data are important aspects of accurate forecasting of landslide risks.

CONCLUSION

The findings from the DEM analysis and FS and AHP calculations indicate that high- and mid-mountain areas with steep slopes and specific soil moisture conditions are the most susceptible to landslides. This information forms the basis for developing effective risk mitigation strategies, such as the construction of protective structures and water flow management, as well as the selection of safer routes for tourists. Additionally, the practical significance of these identified risk zones was considered in terms of its impact on the long-term sustainability of the region and tourist safety.

High risks of landslides in areas with steep slopes, such as the Terskei-Alatau Geomorphological Region, can lead to damage to infrastructure and increased restoration costs. This emphasizes the need for a sustainable approach to the construction and operation of tourism infrastructure. Sustainable development requires consideration of natural processes, such as slope stabilization and prevention of soil degradation, especially in areas with active tourism. Minimizing the risks of landslides helps attract tourists, create new jobs, and promote socio-economic growth in local communities. We have examined the impact of risk zones on tourist safety and developed measures to ensure tourist safety in risk zones (Table 11).

Table 11. Measures to ensure the safety of tourists in high-risk areas (Source: compiled by the authors)

№	Measures	Description
1	Identification of dangerous routes	Provides important information to adjust routes and strengthen safety measures
2	Warning and evacuation systems	In high-risk areas it is important to implement early warning systems and well-thought-out evacuation plans
3	Education and awareness	It is important to raise awareness among tourists and locals about natural hazards and necessary precautions through educational initiatives

The analysis has led to the development of an integrated approach that combines the planning of safe ecotourism routes, protection of the natural landscape, and ensuring the safety of tourists. This approach also ensures the sustainable development of infrastructure. This balance between environmental sustainability and the economic benefit of the region is reflected in Table 12. The results of the DEM and NDWI analyses, FS and HP calculations showed that high- and mid-mountain areas with steep slopes and unfavourable soil moisture conditions are most vulnerable to landslides. These data form the basis for developing effective measures aimed at minimising risks and ensuring the sustainable development of the region. We have devised risk minimisation measures:

1. Slope reinforcement and drainage system construction: The use of engineering solutions such as slope terracing, soil reinforcement with vegetation, and drainage system design helps reduce the risk of landslides.

2. Monitoring of terrain changes using GIS: Regular monitoring of changes in terrain and analysis of risky areas using GIS and satellite imagery allows you to quickly identify unstable areas.

3. Informing the public about possible risks: educational programs and alerts for local residents and tourists increase awareness of natural risks and recommend safety measures.

Table 12. Practical significance of recreational landscapes of the Sharyn River basin for the sustainable development of tourism (Source: compiled by the authors)

№	Recreational landscapes	Practical significance for the sustainable development of tourism
1	Landscapes Terskei-Alatau and Kungei - Alatau highlands	- Steep slopes and melting glaciers increase the risk of landslides, requiring constant monitoring of these areas to ensure the safety of tourists and local residents. - While the attractiveness of the region for mountain tourism, it is important to mark safe routes and install warning systems in potentially hazardous areas. - Monitoring the effect of climate change on glaciers and preventing their deterioration is essential for preserving the region's ecosystem.
2	Landscapes Ketmen Highlands	- Wide flat-topped ridges provide opportunities for the construction of tourist bases, but it is important to take into account possible erosion and take protective measures. - The creation of ecologically safe routes will minimize the load on the soil and preserve the natural heritage of the region.
3	Landscapes Shalkudysu-Kegen middle mountains	- Alluvial plains are convenient for tourist infrastructure, but lake plains with loose sediments require careful approach due to the risk of erosion. - Opportunities for organizing eco-routes that emphasize the uniqueness of ancient alluvial and lake forms. - Heavy precipitation can activate the processes of erosion and shifting of soils, which requires preventive measures.
4	Landscapes Kuluktau-Temirlik middle mountains	- Relief with hilly surfaces and relict denudation surfaces require consideration of their fragility when planning tourist routes. - Prolonged erosion processes can pose a threat to the stability of the landscape, especially with an intense tourist load. - The area can be used to organize easy routes with minimal risk, which makes it accessible for family tourism.
5	Landscapes The Toraigyr lowlands	- Low-mountain areas are favorable for the creation of recreation centers, given their moderate height and relative stability of the slopes. - Exposure to denudation increases the risk of erosion, so it is important to maintain natural balance and minimize human impact. Opportunities to get acquainted with the unique denudational forms of relief that can become a part of educational tourism.
6	Landscapes Zhalagash foothills	- Rolling terrain and badlands create interesting hiking routes. - Gully systems need special attention to avoid active soil erosion. - Accessibility of the area makes it suitable for recreation areas with minimal risk.
7	Landscapes Aksai-Sogeti foothills	- Terraced foothills with loose sediments need to be protected from destruction as tourist flow increases. - River valleys deeply embedded require the installation of warning signs and safe viewing platforms creation. - The promotion of ecological routes will help preserve natural characteristics of area.
8	landscapes lower Sharyn plain	- The flat terrain of the delta is favorable for the development of tent camps and recreational areas. - Areas that are prone to seasonal flooding may require monitoring and assessment of hydrological risks. - Preserving ancient alluvial deposits and maintaining the ecosystem of the region is important to sustainable development.

The identified risk areas and proposed measures emphasize the importance of an integrated approach to sustainable development. These combined measures can significantly reduce the risk of landslides, minimize damage and ensure the safety of the local population and tourists, here protection of natural landscapes and security are combined with economic and social growth. This will help preserve the natural beauty of the region and create safe conditions for tourism and employment.

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