DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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S.S. Chernomorets, K. Hu, K.S. Viskhadzhieva

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泥石流：

灾害、风险、预测、防治

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При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).

Conference logo is based on a figure from S.M. Fleishman’s book on Debris Flows (Moscow: Geografgiz, 1951, p. 51).

Debris flow phenomena and their assessment using geoinformation system technologies for the development of the tourist industry of Uzbekistan

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Abstract. The article, based on the requirements of the UN concept of the Sustainable Development, examines the dynamics of debris flows in Uzbekistan, which are the one of the most dangerous processes in the development of the tourism industry in the mountainous regions of the republic. A methodology for a step-by-step assessment of the physical-geographical factors of a debris flow based on the use of modern geographic information systems (GIS) technologies has applied in the example of the Shakhimardan exclave touristic-recreational-zone of the Fergana touristic subregion. The debris flow hazard of the research object was assessed on five scales of tourist comfortness and then zoning was carried out both according to individual and complex natural components that create the risk of a debris flow phenomenon. Effective and practical safety measures for conducting tourist routes are recommended.

Key words: *debris flow, Uzbekistan, tourism, Shakhimardan zone, GIS technologies, methodological assessment, comfort, zoning, safety measures and tourist routes*

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Селевые явления и их оценка с использованием ГИС-технологий для развития туристической отрасли Узбекистана

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Аннотация. В статье, исходя из требований концепции устойчивого развития ООН, рассматривается динамика селей в Узбекистане, которые являются одним из наиболее опасных процессов в развитии индустрии туризма в горных районах республики. На примере туристско-рекреационной зоны Шахимарданского эксклава Ферганского туристского субрегиона применена методика поэтапной оценки физико-географических факторов селя, основанная на использовании современных геоинформационных систем (ГИС) технологий. Селевая опасность объекта исследования была оценена по пяти шкалам комфортности для туристов, после чего было проведено зонирование как по отдельным, так и по комплексным природным компонентам, создающим риск селевого явления. Рекомендованы эффективные и практичные меры безопасности при проведении туристских маршрутов.

Ключевые слова: *сель, Узбекистан, туризм, Шахимарданская зона, ГИС-технологии, методологическая оценка, комфорт, зонирование, меры безопасности и туристические маршруты*

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Introduction

A set of measures is being gradually implemented to develop the tourism sector as one of the strategic sectors of the national economy, ensuring intensive development of regions, creating new jobs, increasing incomes and living standards of the population, and increasing the investment attractiveness of the country in the Republic of Uzbekistan. According to the 35th goal of the Development Strategy of New Uzbekistan for 2022–2026, within the framework of the "Travel in Uzbekistan" program, the number of domestic tourists should be at least 12 million people, and 9 million of them should be foreigners. The priority goal of the state Strategy in the field of tourism is to ensure safety trips.

Brief overview of the problem

One of the most dangerous natural phenomena in Uzbekistan is debris flows [*Uzhydromet, 2021*], because of the mountainous areas, where many types of tourism and recreational activities have been widely developed. There are complex relief conditions, a weak soil protective cover of vegetation, and intense rainfall (90%), a melting snow cover risk (4%) with DAM break, snow debris, and glacial bridges risks (6%). Debris flows cause material and social damage in 61% of cases, and in 17% of them are accompanied by human casualties [*Akhmedov, 2018*]. Therefore, there is an urgent need for accounting, assessment, monitoring and forecasting of debris flow processes using modern GIS technologies.

The purpose and objectives of the research – were to assess the debris flow hazard of the Fergana Valley of Uzbekistan using the example of the Shakhimardan exclave tourist-recreational zone using GIS technologies. The objectives of the research were to determine the dynamics of debris flows in the touristical recreational areas of Uzbekistan, to identify a methodology for assessing and mapping debris flow risk factors for tourism activities in a key area using GIS technologies, to outline measures for planning tourism services in debris flow risk areas.

Research methods

GIS in tourism, as a rule, includes six mandatory subsystems: data entry, storage and search, updating and adjustment, processing and analysis for estimating parameters, solving calculation and analytical problems, presenting data in various forms [*Kazakis, 2015*]. GIS give opportunity to quickly respond to any emerging situation in any territory with the receipt of all the necessary cartographic and thematic information on it. It is a cartometric study with the simultaneous construction of any maps, plans and diagrams [*Tehrany, 2017; Salimova, 2019*]. Based on GIS technologies, it is possible to simulate debris flow phenomena and study changes in their state over time. The structure and content of GIS technologies are determined by the scientific and applied problems solved in it, among which the most important is their assessment for making appropriate decisions [*Ajibade, 2021*].

Multi-criteria decision making (MCDM) is recognized as an important method for evaluating complex decision-making problems containing disparate data or criteria, such as identifying and mapping debris flow risk areas using multiple factors, and the Analytic Hierarchy Process (AHP) is the most commonly used decision-making method according to several criteria. Therefore, to organize the Shakhimardan exclave touristical recreational zone, taking into account debris flow risk, the approach of multi-criteria decision analysis based on GIS (GIS-MSDA) and the integration of the analytical hierarchy process (AHP) was used (Table 1).

Table 1. Data types and sources used for mapping debris flow risk areas

Data types	Data sources
Shuttle Radar Topography Mission (SRTM GL1) Global (30m spatial resolution)	High resolution topographic open data. https://portal.opentopography.org/
Sentinel 2A satellite images for May 27, 2023 (spatial resolution 10m)	Data from the Copernicus Open Access Centre. https://scihub.copernicus.eu/
Annual precipitation (2010–2020 years)	Data from the Worldwide Energy Outlook (POWER) https://power.larc.nasa.gov/

Research data

According to NIGMI and Uzhydromet in Uzbekistan, the area with debris flows exceeds 53.7 km^2, which is 12% of the total territory of the republic, and their number reaches more than 709 [*Dergacheva, 2017*]. The total number of debris flow days over 36 years of observations in the Fergana Valley was 372 days or 46% of the total number throughout Uzbekistan (Table 2). The stationary observations and in-depth studies of debris flows has stopped at the end of the 90s of the 20th century and the beginning of the 21st century in the republic.

Table 2. Dynamics of the number of days of mudslides in the regions of Uzbekistan*

Regions of Uzbekistan	Number of debris flow days			
	Number of days 1950–1986	in % of the total	Number of days 2010–2020	in % of the total
Namangan	180	22.2	60	8.9
Fergana	119	14,7	134	19.9
Surkhandarya	116	14,3	133	19.8
Samarkand	115	14,2	73	10.9
Kashkadarya	74	9.1	98	14.6
Andijan	73	9.0	11	1.6
Jizzakh	63	7.8	76	11.3
Tashkent	55	6.7	63	9.4
Navaiy	16	2.0	22	3.3
Total	811	100	672	*100*

*Debris flow events are not observed in the Syrdarya, Khorezm regions and the Republic of Karakalpakstan, and were not taken into account in the Bukhara region

Although the periodicity of the destructive debris flows themselves can span 40–60 years. The Shakhimardan natural crisis is the second most destructive among the 10 most destructive debris flows in Central Asia in the entire history of observations, which took place on 05/04/1927, 05/29/1997, 06/13. and 7.07.1997, 8.06.1998 [*Kadyrov, 1998; Aitamtov, 2012, Tulyaganov, 2020*]. As a result of the latest natural disaster, more than 100 people died, up to 600 people went missing, and 500 people lost their homes. A study of the consequences was not possible due to tensions in inter-ethnic relations, which were further aggravated by the disaster [*Petrakov, 2020*].

Latest published data on hazardous debris flow events in Uzbekistan for the period 2010–2020 years shows a slightly different picture [*Uzhydromet, 2021*]. The Fergana and Surkhandarya regions became the most debris flow risk areas of Uzbekistan. In the 21st century, the Namangan and Andijan regions of the Fergana Valley became less progressive debris flow phenomena. This is due to the implementation of complex debris flow protection structures in the Namangan region and less rainy seasons in the Andijan region, due to climate change. But over the past 11 years, the observation of the number of debris flows in average annual terms has increased from 23 to 61 debris flow days, or 2.66 times more without taking into account the melting of snow cover and the DAM breaks, snow debris, glacial bridges, i.e. 9/10 of all reported incidents.

Recorded debris flow activity in Uzbekistan in March-May of 2010–2020 years given in Fig. 1, and their total annual value is about 74% or ¾ of the total debris flows. Many tourist routes in these mountainous areas are planned specifically for the months of March-May, when it is important to take into account debris flows to ensure sustainable development of tourism. It is advisable to assess tourism risks, which, due to their geographical location, may be affected by debris flows. This allows for safe tourist routes while reducing damage from natural disasters.

Thus, debris flows in the Fergana region of Uzbekistan are an increasingly natural-anthropogenic process and the most dangerous factor affecting the tourism industry. The “Concept for the development of tourism in the Republic of Uzbekistan for 2019–2025,” approved by Presidential Decree No. 5611 of January 5, 2019, sets the task of diversifying the tourism industry of the Fergana region by increasing their safety. To implement this task, the assessment of debris flow hazard in tourist sites in the Fergana region becomes an urgent issue. Here it is necessary to take into account such principles of tourism as the discrepancy between natural and political-administrative boundaries, because the diversity of tourism policies in

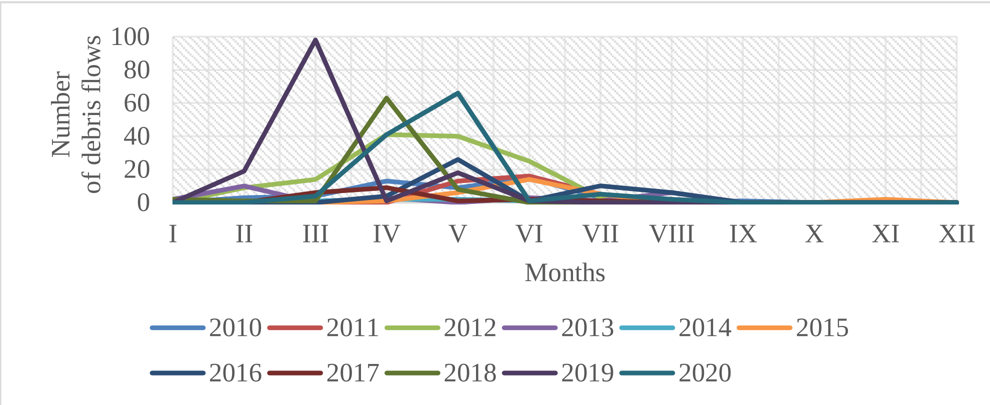

Fig. 1. Monthly number of debris flows in Uzbekistan from 2010 to 2020 (according to Uzhydromet, 2021)

Central Asian countries requires the researcher to assess debris flow hazards within administrative units. Therefore, the objects of all scientific research conducted in the field of tourism in Uzbekistan are countries or their administrative units. From the point of view of “Geographical tourism”, the object of our research is the Shakhimardan exclave touristical recreational zone, located on the territory of the Republic of Kyrgyzstan (Fig. 2), because in this key area, 1/3 of all registered debris flow events in the Fergana region occur [*Tobirov, 2021; Nigmatov, 2023*].

Research analysis

Spatial data layers of six factors influencing the occurrence of floods, such as absolute elevation (AE), slope (S), mean annual precipitation (MAP), vegetation density (NDVI), landuse and land cover (LU/LC) and flow concentration (FC) was prepared in raster format using GIS technologies and remote sensing methods in the case of research area.

All raster coefficient maps were reclassified using Spatial Analyst Tools to a common measurement scale of 1 (very low) to 5 (very high), and all classified data were resampled to 10 m using the raster data management tool → raster processing → tool Resample in the ArcGIS environment, converted to spatial dimensions. Then, reclassifying the debris flow hazard factor maps, the AHP model was used to determine the relative influence of each factor. The final debris flow susceptibility map of the study area was obtained by overlaying four spatial layers using the weighted overlay method in the ArcGIS environment. For this study, six factors closely related to debris flows were selected based on the analysis of previous studies and taking into account the availability of data based on the conclusions of the researchers, as well as the natural structure of the study area. The factors considered in this study and the methods used to map each factor are described below.

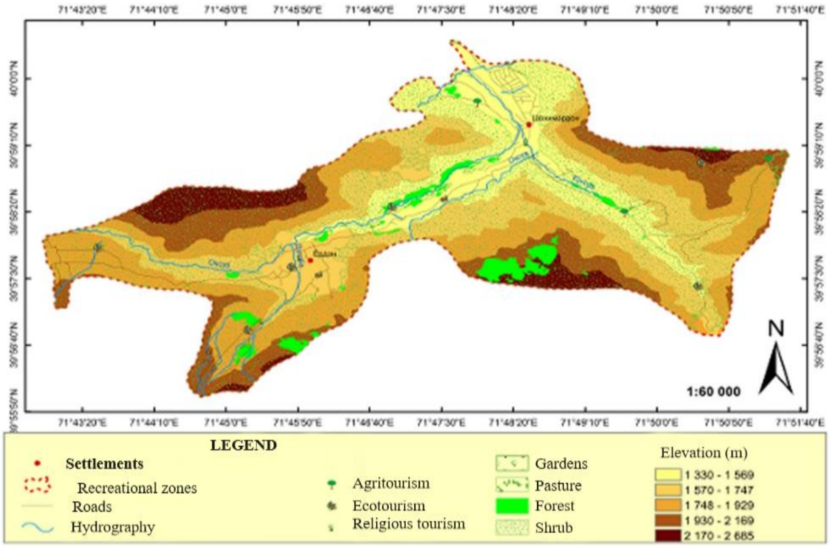

Fig. 2. Shakhimardan exclave tourist-recreational zone

The Digital Elevation Model (DEM) of the Shakhimardan touristical recreational zone was reclassified into five debris flow sensitivity classes and scaled to a spatial resolution of 10 m to create an elevation coefficient map. It was prepared from a DEM using the Spatial Analyst Tools of ArcGIS.

One of the debris flow map was created using DEM [*Ajibade, 2021*]. According to him, a flow direction map is created, then a raster flow concentration map is created. The calculation of flow direction and concentration was performed using hydrological tools – Fill, Flow Direction and Flow Accumulation, respectively, in the Spatial Analyst Tools ArcGIS program [*Kazakis, 2015*].

Precipitation data taken for 2010–2020 years from the World Energy Outlook (POWER) website, and was used to prepare a precipitation coefficient map for the study area. Mean annual precipitation was interpolated in ArcGIS10.8 using the interpolation method (IDW) with a cell size of 10 m and extracted using an area boundary shape file to create a precipitation map.

The area vegetation index (NDVI) map was prepared from the Sentinel 2A satellite image downloaded from the European Open Access Service Copernicus website using ArcGIS 10.8 software using the following equation.

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} = \frac{(Band8 - Band4)}{(Band8 + Band4)}, \qquad (1)$$

where: *NIR* is the spectral reflectivity of the surface in the near-infrared range (8 bands on the Sentinel 2A satellite image), *RED* is the spectral reflectivity of the surface in the red line (Sentinel 2A position 4 on the satellite image).

After all debris flow factors were prepared in raster format, they were reclassified into five groups of measurement scales from 1 to 5 at the same spatial scale (10 m). A high classified rating value (5) corresponds to territories with more advanced debris flows, a lower value (1) corresponds to less progressive debris flows. Since there is no single criterion for reclassifying mudslide warfare, classes of all factors were created based on the results of previous studies and taking into account local conditions.

The AHP process is the most commonly used and effective method in the multi-criteria decision making (MCDM) process for determining the relative importance of each criterion or factor [*Saaty, 1987; Tehrany, 2017*]. Factors used to map debris flow risk by using multi-criteria decision making included local natural features of the study area and impact indicators based on assessments of previous studies. The following steps carried out to establish the relative effects for each debris flow factor:

Step 1. Each factor was assigned a value from 1 (equal) to 9 (extreme) to construct a paired comparison matrix (Table 3).

Table 3. Matrix of paired comparisons by debris flow factors

Factors	Number					
	1	2	3	4	5	6
	NDVI	*LU/LC*	*S*	*FC*	*MAP*	*AE*
NDVI	1.00	1/3	1/5	1/7	1/9	1/9
LU/LC	3.00	1.00	1/3	1/5	1/7	1/9
S	5.00	3.00	1.00	1/3	1/5	1/7
FC	7.00	5.00	3.00	1.00	1/3	1/5
MAP	9.00	7.00	5.00	3.00	1.00	1/3
AE	9.00	9.00	7.00	5.00	3.00	1.00

Note: *AE* – absolute height, *FR* – landform, *UP* – surface slope, *MSD* – average annual precipitation, *NDVI* – vegetation density, *FC* – flow concentration).

Step 2. Created an optimized pairwise comparison matrix table (Table 4) by dividing each value in a column of the pairwise comparison matrix by the sum of the columns.

Table 4. Degree of influence of factors on debris flow processes

Factors	*NDVI*	*LU/LC*	*S*	*FC*	*MAP*	*AE*	Degree of influence of factors
NDVI	0.03	0.01	0.01	0.01	0.02	0.06	2.5%
LU/LC	0.09	0.04	0.02	0.02	0.03	0.06	4.3%
S	0.15	0.12	0.06	0.03	0.04	0.08	8.0%
FC	0.21	0.20	0.18	0.10	0.07	0.11	14.4%
MAP	0.26	0.28	0.30	0.31	0.21	0.18	25.6%
AE	0.26	0.36	0.42	0.52	0.63	0.53	45.2%

Step 3. The influence of each factor was calculated (Table 4) by dividing the sum of each row of the optimized table of paired comparison matrices by the number of factors according to the formula:

$$CI = \frac{\gamma_{max} - n}{n - 1}, \quad (2)$$

where n is the number of compared factors in the matrix, and γ_{max} is the maximum value of the pairwise comparison matrix.

After calculating the effects for each debris flow hazard factor, a stability check was carried out using equations. The maximum value (γ_{max}) of the comparison matrix was calculated using the following steps:

Step 1. Multiplying each value in the column by the influence of the criterion (Table 5).

Table 5. Significance rate for pairwise comparisons (CR = 0.005)

Factors	*NDVI*	*LU/LC*	*S*	*FC*	*MAP*	*AE*	Sum of factor impact values	Degree of influence of factors
NDVI	0.03	0.01	0.02	0.02	0.03	0.05	0.15	6.14
LU/LC	0.08	0.04	0.03	0.03	0.04	0.05	0.26	6.09
S	0.13	0.13	0.08	0.05	0.05	0.06	0.50	6.26
FC	0.18	0.21	0.24	0.14	0.09	0.09	0.95	6.60
MAP	0.23	0.30	0.40	0.43	0.26	0.15	1.76	6.88
AE	0.23	0.39	0.56	0.72	0.77	0.45	1.89	4.18

Step 2. Calculate the total effect value by adding the values in the rows.

Step 3. Calculation of the ratio of the total value of each impact to the influence of the corresponding criterion.

Step 4. Averaging the ratio of the total impact value to the impact criterion.

Checking the consistency coefficient (CR) is calculated by leveling:

$$CR = \frac{CI}{RI}, \quad (3)$$

where *CI* is the consistency index, *RI* is a random index that varies depending on the number of factors used in the paired comparison matrix. If *CR* is below 0.10, it means that the pair comparison matrix has optimal consistency. Greater than or equal to 0.10 this comparison is inconsistent. In this case, the comparison process should be repeated until the *CR* value falls below 0.10.

After preparing and classifying each debris flow management factor on a common scale (1–5) using ArcGIS and weighting the factors using the AHP approach, the spatial layers were merged. When creating debris flow risk maps using the equation below, the method of spatial analysis of the ArcGIS environment, scalable coverage was used.

$$FS = \sum_{i=0}^{n} x_i * w_i, \quad (4)$$

where *FS* is the sensitivity to debris flows, *n* is the number of decision criteria, x_i is a special optimized criterion, and w_i is the corresponding effect of the criterion.

The cell/pixel values of the raster layers were multiplied by the effects/percentage effects obtained from the AHP analysis, and the results were added together to obtain the total debris flow risks.

According to the country's law "On special economic zones of the Republic of Uzbekistan" dated February 17, 2020, the tourism industry of the economy began to develop in tourist and recreational zones and clusters, which should take into account the regional characteristics of the territory. Taking into account this need for a trend in economic development, we have proposed a new scientific and practical direction – "Geographic tourism", the object of study of which is precisely tourist areas, zones and clusters [*Nigmatov, 2023*]. It was classified the Earth's geosystems taking into account tourist zoning, where the Shakhimardan exclave touristical recreational zone was separately identified. In this zone, debris flows have been increasing over the past decades due to: widespread development of foothill lands for irrigated agriculture (60%), construction of road and communication networks in difficult terrain conditions without appropriate anti-erosion measures (15%), increased grazing of livestock on slope areas (12%), changes in precipitation patterns (11%) and other natural and man-made processes and phenomena (2%).

Using GIS technologies of terrain indicators, the determining risks of debris flow hazard in the territory of the key area were assessed (Fig. 3*a*). The absolute height of the area is classified on a 5-point scale, where low altitude areas (1.2), which are more prone to debris flows, are uncomfortable for tourism. Since in these areas of the zone the concentration of river flow is higher than in high-altitude zones. Areas with high debris flow hazard (ab.v. 1324–1500 m) are located in the northeastern part of the key area.

Flat landforms are very risk to debris flows, followed by concave and convex ones. In Fig. 3*b*, the terrain features areas with flat terrain are located on the southern slopes of the Alatau basin of the Aksu river.

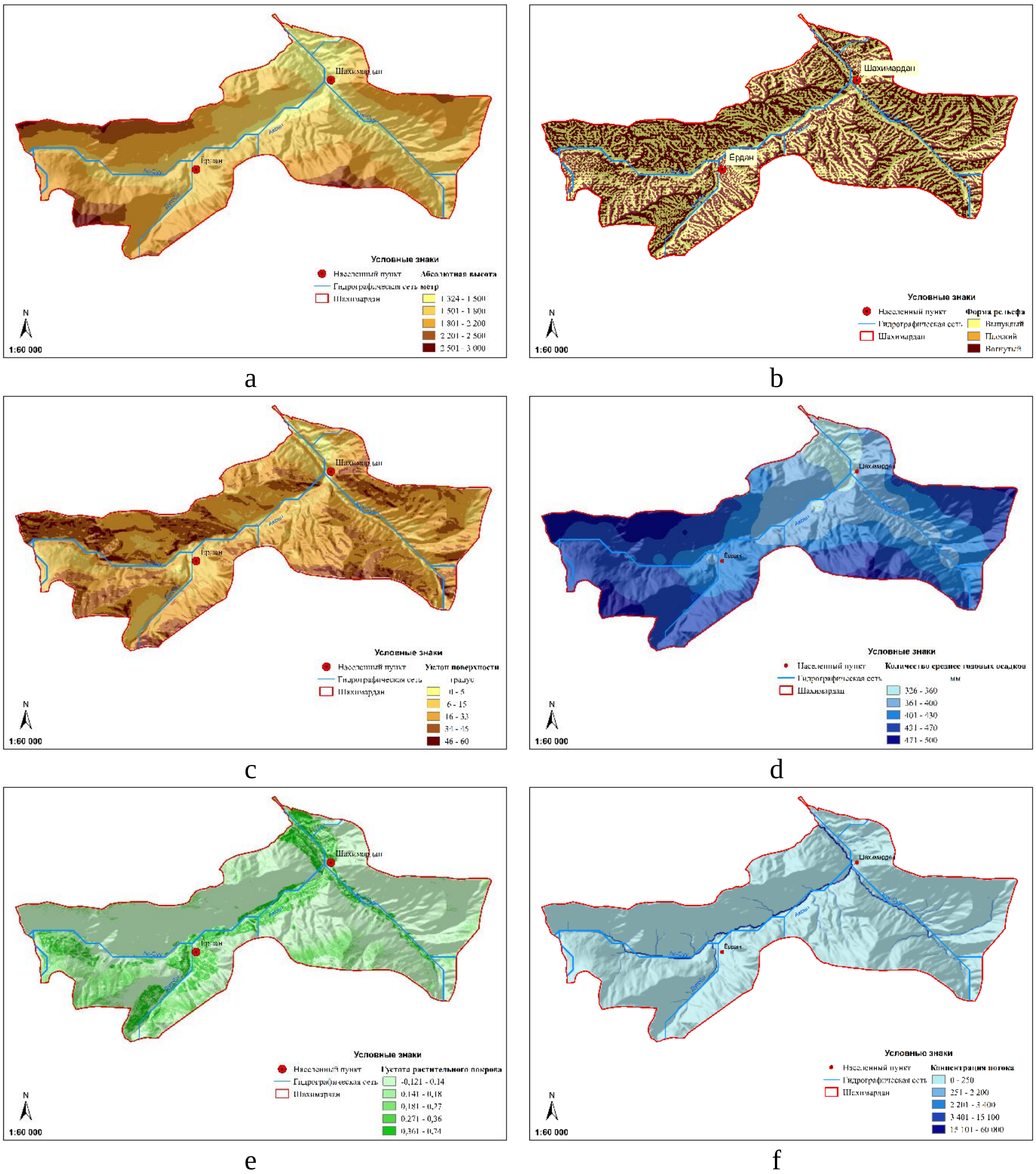

Fig. 3. Physico-geographical indicators that determine the debris flow hazard of the territory in the Shakhimardan tourist and recreational zone: a – absolute height, b – landform, c – surface slope, d – average annual precipitation, e – vegetation density, f – flow concentration)

The reclassified slope map (Fig. 3*c*) shows the territories with the most comfortable areas of the tourist and recreational zone. Debris flow-hazardous areas with a surface slope above 160 are located in the valleys of the Aksai and Kuk-Suu rivers, as well as in the area below the village of Shakhimardan.

The average annual precipitation ranges from 326–500 mm (Fig. 3*d*). They are too high for a storm debris flow on the watershed part of the Alaitau Mountains.

Vegetation cover is an index reflecting the density of vegetation per m^2 of area used to determine susceptibility to debris flow events (Fig. 3*e*). NDVI values in this study ranged from 0.14 to 74 m^2. The densest areas of vegetation cover are those where the annual average precipitation is the highest.

The runoff concentration was reclassified into five risk categories (Fig. 3*f*): very low (<250 pixel), low (250–2200), moderate (2200–3400), high (3415–15100), very high (>15100). The most concentrated flows are observed in areas with a large amount of average annual precipitation.

The debris flow risk map of the Shakhimardan touristical recreational zone (Fig. 4) was developed by combining the above-described thematic maps for the six debris flow hazard factors of the territory described above. It was integrated into three risk classes, according to the level of comfort – subcomfort, discomfort, subcomfort. The integrated use of multi-criteria decision making (MCDM) based on GIS and AHP technologies is more effective in identifying areas prone to debris flows for management purposes in the tourism industry [*Zimina, 2021*].

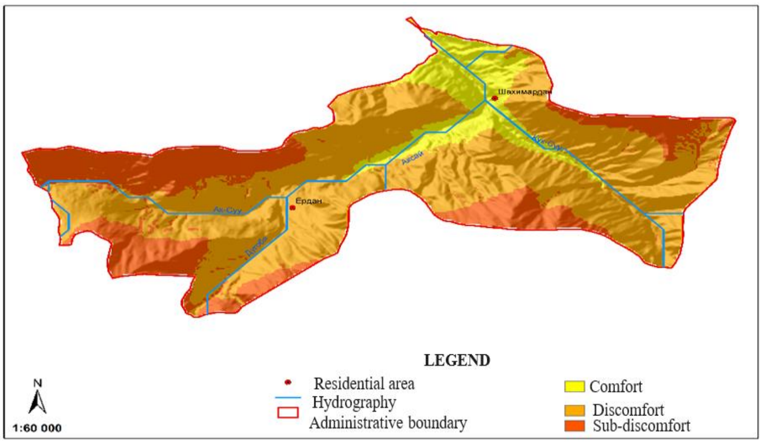

Fig. 4. Debris flow risk map of the Shakhimardan touristical recreational zone

Comprehensive detailed studies conducted by scientists from various countries [*Chernomorets, 2016, Viskhadzhieva, 2016*] revealed that climate warming in the Shakhimardan River catchment area contributes to the formation of dozens of lakes with a high breakthrough potential. In this case, for the safe development of tourism, systematic monitoring of the development of glacial lakes and the installation of early warning systems should be carried out.

To ensure the safety of tourists in areas at risk of debris flows, we have proposed measures that can be taken into account when planning tourist trips:

1. Providing tourists with access to information about debris flow risk zones, including maps and descriptions of debris flow-hazardous areas.
2. Development of methodological recommendations or instructions on the rules of conduct for tourists in debris flow-prone areas.
3. Introduction of assessment, monitoring and forecasting of debris flow events using sirens, sms messages and local media.
4. Providing travel companies with electronic information about weather conditions and river flow conditions.
5. Training travelers on the rules of responding to the threat of debris flows, including advice on safe places and evacuation procedures.
6. Installation of information and safety signs at tourist evacuation sites.
7. Creation of networks of hydrometeorological posts and a base for a unified information exchange system in tourist and recreational areas.
8. Providing tourists with a list of important contacts, including emergency services, medical institutions and organizations for assistance.
9. Recommendations for a set of necessary items (flashlight, water, canned food, documents, etc.).
10. Working with local authorities and emergency services to coordinate security measures.
11. Conducting joint exercises and training to prepare for emergency situations.

These measures will help ensure safety and reduce risk in tourist and recreational areas to reduce risks in the event of a debris flow.

Conclusions

Geographic tourism is a new direction in the tourism industry, the object of study of which is tourist and recreational taxonomic/inner units – regions, zones, clusters.

In the geographical and tourism classification, the Fergana Valley of Uzbekistan is an independent subregion, and the Shakhimardan mountain exclave is a separate tourist and recreational zone, where the economic development of valley bottoms leads to the activation of glacial debris flows, which must be taken into account when planning, constructing and operating tourist facilities and routes.

It is necessary to develop a consistent methodology for the digital collection and analysis of remote sensing data with the subsequent compilation of electronic web maps for six factors that determine the hazard of debris flow risk to assess the debris flow hazard of touristical recreational areas using modern GIS technologies in a laboratory conditions.

Integrated zoning was carried out by applying factor maps of debris flow hazard zones, taking into account five levels of comfort for tourists. These cartographic materials will serve as the basis for the development of a set of measures for the safety of tourist routes.

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