Coğrafiya elmləri / Geographical Sciences

COMPREHENSIVE ASSESSMENT OF ECOLOGICAL AND GEOMORPHOLOGICAL HAZARDS IN AREAS DISTURBED BY MINING AT THE GADABAY GOLD–COPPER–PYRITE DEPOSIT

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Abstract. This study develops and applies a methodology for assessing ecological and geomorphological hazards associated with mining at the Gadabay gold–copper–pyrite deposit in Azerbaijan. The methodology integrates five criteria into an area-weighted composite hazard index: the extent of disturbed land, the geomorphological setting, the degree of topographic modification, the composition of surficial deposits, and the type of mineral resource extracted. Criterion weights were determined using the Analytic Hierarchy Process. The Normalized Difference Vegetation Index (NDVI) was derived from Landsat and Sentinel-2 imagery to assess changes in soil and vegetation cover within a 3 km buffer around the deposit between 1975 and 2025. The mapped area of the mining site expanded from 69.12 ha in 2015 to 84.12 ha in 2025, an increase of 15.00 ha. Field observations indicated that many mining landforms remained unreclaimed and had sparse or absent vegetation cover, leaving them susceptible to erosion. Surface runoff can transport sediment and contaminants from mine waste dumps into tributaries of the Shamkirchay River, while wind can disperse fine particles from exposed surfaces. The composite index brings together the extent of mining disturbance and the site characteristics that influence the potential transport of sediment and contaminants.

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Introduction

The Gadabay administrative district has been subject to substantial anthropogenic impacts for several centuries. High concentrations of copper, gold, and silver ores drove the expansion of mining activity from the nineteenth century onward. During this period, the German company Siemens carried out extensive geological exploration, discovered mineral deposits, and built industrial facilities. It also introduced technologies that were advanced for the time, including the first railway and hydroelectric power plant in the Caucasus. Mining continued during the Soviet period and expanded again in the twenty-first century, when international companies became involved in developing the remaining gold, silver, and copper reserves. The growth of the mining industry contributed to the development of road and railway networks and the emergence of large settlements near industrial sites. Mining, transport infrastructure, and settlement development, together with the construction of buildings and other structures and the extraction of mineral resources, substantially transformed the natural topography of the Gadabay district.

Anthropogenic transformation of topography encompasses the diverse effects of human economic activity on landforms. These effects alter natural ecosystems and often trigger adverse or potentially hazardous environmental processes. In the Gadabay district, human activity affects topography directly by creating artificial landforms and modifying natural ones, and indirectly by altering the conditions under which geomorphological processes occur and influencing other natural factors.

Assessing geomorphological hazards associated with anthropogenic changes to topography is important for conserving the district's unique natural ecosystems and maintaining their long-term functioning (Tarikhazer, 2020). A comprehensive assessment involves organizing, analyzing, and integrating diverse geographic data in successive stages and expressing the results as one or more composite indicators. Researchers in Azerbaijan and elsewhere have developed a wide range of approaches and methods for assessing natural systems and systems shaped by both natural and technological factors. These approaches include the assessment of topography in the context of

natural resource management. Research has focused primarily on potential hazards and risks, both in aggregate and for individual geomorphological and geological processes. Quantitative assessment of the extent to which human activity alters topography has received less attention (Gasimov, 2020, 2024).

Problem Statement

Since the second half of the twentieth century, comprehensive assessments have been widely used in geographic research to characterize systems, objects, and processes using qualitative and quantitative indicators (Eremenko et al., 2021). These assessments can examine the condition of natural systems and systems modified by human activity, as well as the relationships among their individual components (Krasheninnikova, 2006; Kruzhalin, 1997). The results are typically presented as a map showing the spatial distribution of a composite indicator.

This study applies the comprehensive assessment approach to examine environmental conditions, the level of environmental stress, and the state and degree of stress of the geomorphological system in the Gadabay administrative district. It examines the interaction between topography and economic activity within the district and in adjacent areas from two perspectives.

1. Analysis of ecological and geomorphological hazards and the associated risks for mining development.
2. Assessment of the impacts of mining activities on natural topography.

The study considers natural topography and ongoing geomorphological processes as potential sources of hazards for mining operations and local residents. It also examines how economic activity and the resulting changes to topography can give rise to both potential and existing threats to people and the environment.

Research Objective

This study aims to develop a methodology for comprehensively assessing ecological and geomorphological hazards in areas disturbed by mining at the Gadabay gold–copper–pyrite deposit.

Materials and Methods

The proposed methodology maps anthropogenic changes to topography in areas disturbed by mining and identifies their adverse and potentially hazardous environmental effects.

The methodology comprises five steps.

1. **Delineate disturbed land.** Delineate the boundaries of disturbed areas at active mineral deposits using boundaries derived from the interpretation of satellite imagery acquired at different dates and from field survey data.
2. **Define the assessment criteria.** Characterize each mapped area by its size, geomorphological setting, type of anthropogenic topographic modification, composition of surficial deposits within the affected zone, and type of mineral resource extracted.
3. **Assign scores.** Assign a score to each mapped area, whether it covers an entire deposit or part of one, for each criterion. Where criterion values vary among sections of the same deposit, use the score corresponding to the least favorable condition.
4. **Calculate the composite hazard index.** Multiply the score for each criterion by its weight and sum the weighted scores. The relative weights of the criteria were determined using the Analytic Hierarchy Process (AHP) (Saaty, 1980, 1990, 2008).
5. **Weight the index by area.** Multiply the resulting hazard index by the area of the corresponding disturbed land unit, whether it covers the entire deposit or part of it.

The extent of disturbed land within the Gadabay gold–copper–pyrite deposit over the 1975–2025 period was also refined by interpreting freely available multispectral imagery from Sentinel-2A and Sentinel-2B, Landsat 2 MSS, and Landsat 8 OLI/TIRS. The imagery was selected for its continuous coverage of the study area, relatively frequent repeat acquisitions, and the availability of Sentinel-2 data at a spatial resolution of 10 m per pixel.

Geological and Geomorphological Setting of the Study Area

The Gadabay administrative district includes the Shahdag horst–synclinorial ridge, which is composed of Upper Cretaceous and Eocene carbonate and volcanic rocks. The Shahdag Ridge watershed is deeply dissected, with river valleys incised at least as deeply as those of the Murovdag Ridge. Nivation, frost action, and gravity-driven processes dominate the area and contribute to substantial slope reshaping (Figures 1 and 2) (Tarikhazer, 2024a).



Fig. 1. Landslide activity



Fig. 2. Rockfall activity

The drainage divides in the middle- and low-mountain belts are generally level and only rarely form distinct ridges. In some areas, they are mantled by a relatively thick layer of unconsolidated eluvial deposits. Erosion and denudation are the dominant processes shaping the present-day topography (Tarikhazer, 2024b).

River valleys are the principal landforms in the study area. Drainage density increases with elevation, ranging from 0.4 to 0.5 km/km² in the low-mountain belt and reaching 0.9–1.0 km/km² along the drainage divide of the Shahdag Ridge. The morphology of the Shamkirchay River valley is controlled by the regional orographic configuration, the orientation of the valley relative to the strike of geological structures, the lithology of the rocks forming the valley slopes, and other factors. In its upper reaches, the river flows through a deep gorge with characteristically convex slopes. At its source, the river drains a steep-sided, amphitheater-shaped headwater basin. The size of this basin is largely controlled by the lithology of the rocks forming its slopes, which convey rainfall runoff and meltwater to the river. In the middle-mountain and foothill belts, valley morphology is governed primarily by bedrock lithology and by neotectonic and ongoing tectonic movements. The Shamkirchay River valley is incised into limestone and exhibits a stepped morphology. The influence of the direction of neotectonic movement on valley morphology is evident in the contrast between areas of recent uplift, where low terraces have high bedrock bases, and areas of relative subsidence, where depositional terraces are widespread. Both depositional and erosional terraces occur along the valley slopes. Their surfaces are narrow and extend discontinuously along the valley (Figure 3).



Fig. 3. Shamkirchay River valley

Ancient glacial landforms are well preserved near the drainage divide of the Shahdag Ridge at elevations above 2,400 m. In the upper reaches of the Shamkirchay River, a series of glacial cirques occurs at two distinct elevations, approximately 2,400 and 2,600 m. In the high-mountain zone of the Shahdag Ridge, remnants of planation surfaces cut into Eocene rocks are preserved at elevations of 2,400–2,800 m. Antonov (1993) regarded these remnants as counterparts of the Goychay planation

surface identified in the Lesser Caucasus. The surfaces formed through low-level erosion and denudation and are of different ages.

Neotectonic movements are reflected in several types of deformation of the planation surfaces. The most common is monoclinal tilting toward intermontane depressions.

Earthquakes have played a significant role in shaping the present-day topography of the Gadabay administrative district. Seismic intensity in the district can reach IX.

Overview of the Deposit

The Gadabay gold–copper–pyrite deposit is located in the Magara area on the eastern slope of Mount Misdag, approximately 1 km northwest of the administrative center of the Gadabay district. The deposit contains polymetallic ores with copper, gold, silver, sulfur, and other associated constituents in commercially significant concentrations.

High-grade sulfide ores were discovered in the 1850s, when the Mekhov brothers' company began the first commercial extraction. Mining was subsequently suspended and resumed only after the German company Siemens acquired the deposit in 1864. A copper smelter was built and a narrow-gauge railway was laid shortly thereafter. Copper remained the main commodity extracted until the outbreak of World War I. Total copper production from 1867 to 1914 amounted to approximately 58,000 tonnes.

The expansion of mining in Gadabay and the nearby settlement of Galakand, where a second copper smelter was later built, led to the construction of a branch of the Baku–Batumi railway in 1883. As firewood and coal were phased out and petroleum products were difficult to transport, an oil pipeline was laid from Dallar to Gadabay in 1894. In 1900–1901, additional ore reserves were identified at the mine, which had previously been considered nearly depleted.

Following the outbreak of World War I in 1914, German entrepreneurs were ordered to leave the Russian Empire. The rights to the deposit were formally transferred to Russian citizens, allowing mining to continue until Soviet rule was established. From 1922 to 1936, pyrite was extracted from stockworks discovered by Fedorov. Mining was then temporarily suspended again. In the subsequent period, the Aztsvetmed Trust operated the deposit until the dissolution of the Soviet Union. The operation involved underground leaching and copper recovery from mine waters.

A new phase of development began in 1997 with the signing of a production sharing agreement between the Republic of Azerbaijan and Anglo Asian Mining PLC covering gold and silver extraction. Azerbaijan International Mining Company (AIMC) resumed mining in 2009. As of 2009, the deposit's recorded reserves were estimated at 22 tonnes of gold, 192 tonnes of silver, and 37,000 tonnes of copper. A gold recovery plant was commissioned in Gadabay in 2013.

Results of the methodology, evaluation and discussion

The assessment showed that waste rock removal and ore extraction have substantially altered the topography of the mining site. The resulting anthropogenic landforms remain largely unreclaimed. The active mining site comprises extensive areas of disturbed land characterized by an open pit, ditches, waste dump fields, and spoil heaps (Figures 4 and 5).



Fig. 4. Spoil heaps at the mining site



Fig. 5. Mining operations at the Gadabay deposit

The unconsolidated material forming these anthropogenic landforms is generally bare or only weakly stabilized by herbaceous vegetation. As a result, surface runoff can carry contaminants from mine waste dumps into tributaries of the Shamkirchay River. In addition, channelized erosion, slope wash, landslides, and scree movement within disturbed areas increase the supply of loose sediment to streams, thereby increasing water turbidity. Recently formed

anthropogenic landforms are particularly susceptible to erosion because vegetation cover on waste dumps and open-pit walls takes several decades to establish.

In parts of the mining site, the disturbed ground consists of fine-grained material. Wind erosion and aeolian transport therefore contribute to the dispersal of fine particles, including contaminants. These processes make disturbed land at the deposit a source of environmental contamination. The assessment indicated that the potential total contaminant load carried by runoff increases as the area of disturbed land expands and the area of reclaimed land decreases. The type of mineral resource extracted primarily determines the composition of the contaminants. At this site, the extraction of silver, gold, and pyrite is associated with the widest range of hazardous contaminants. We used imagery from Sentinel-2A and Sentinel-2B, Landsat 2 MSS, and Landsat 8 OLI/TIRS to map NDVI within a 3 km buffer around the Gadabay gold–copper–pyrite deposit for the period 1975–2025. The NDVI maps revealed changes in soil and vegetation cover (Figures 6–8). Between 2015 and 2025, the mapped area of the deposit increased from 69.12 to 84.12 ha, an increase of 15 ha over ten years.

Figures 9–11 show changes in soil and vegetation cover within the 3 km buffer for 1975–2015, 2015–2025, and 1975–2025. Tables 1–3 summarize the corresponding results.

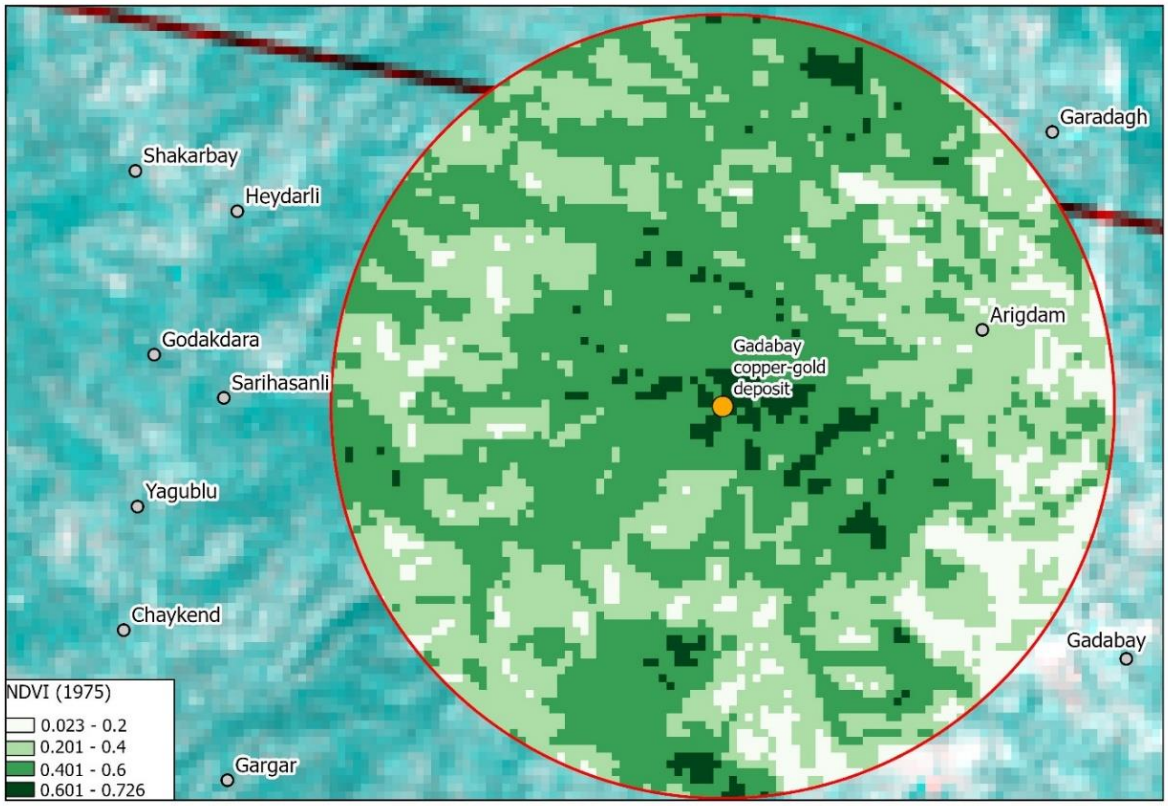


Fig. 6. NDVI within the 3 km buffer around the Gadabay gold–copper–pyrite deposit in 1975

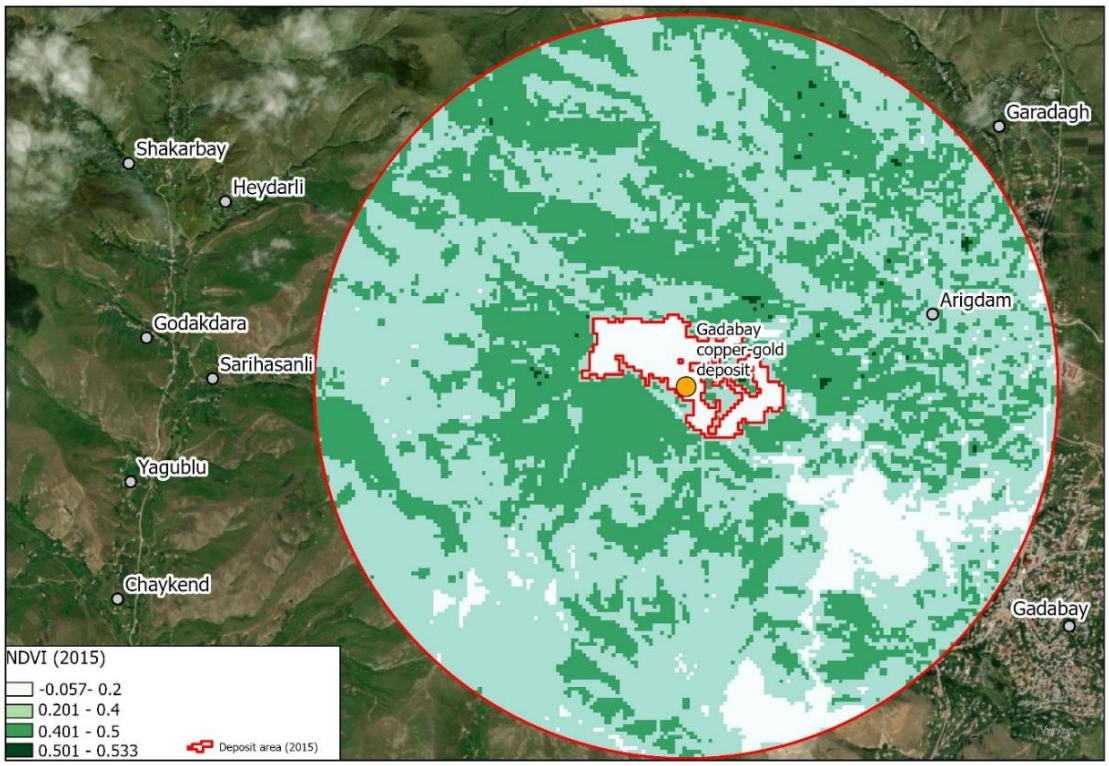


Fig. 7. NDVI within the 3 km buffer around the Gadabay gold–copper–pyrite deposit in 2015

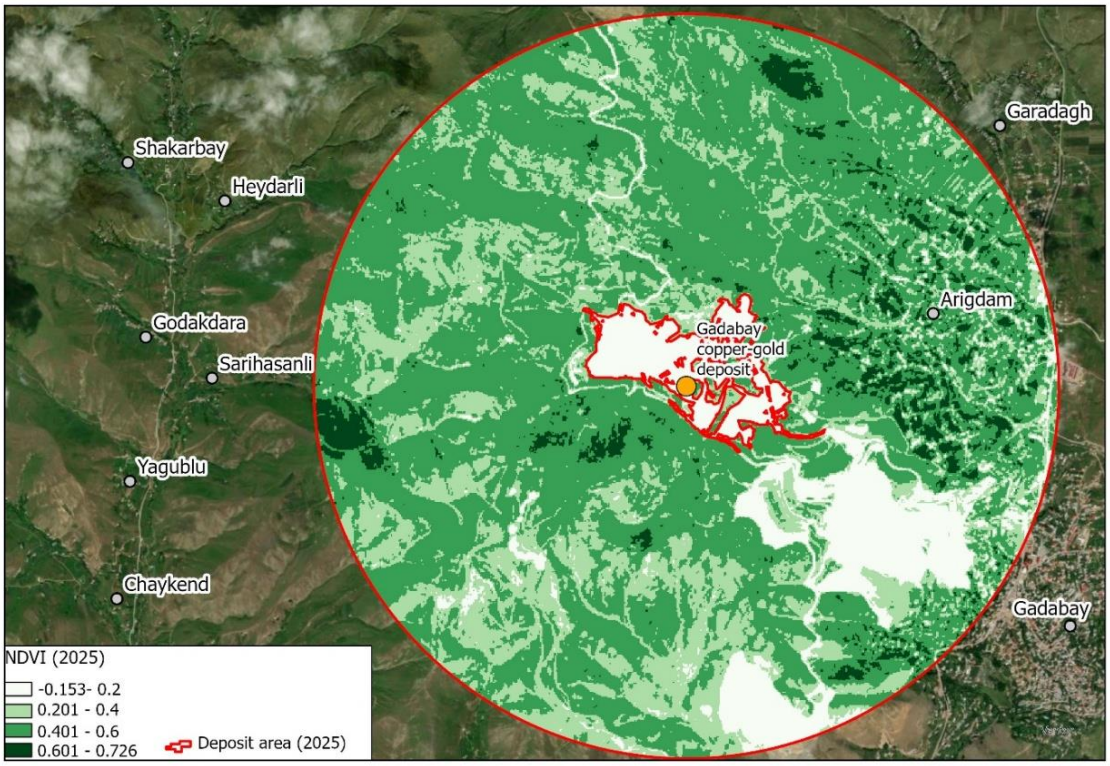


Fig. 8. NDVI within the 3 km buffer around the Gadabay gold–copper–pyrite deposit in 2025

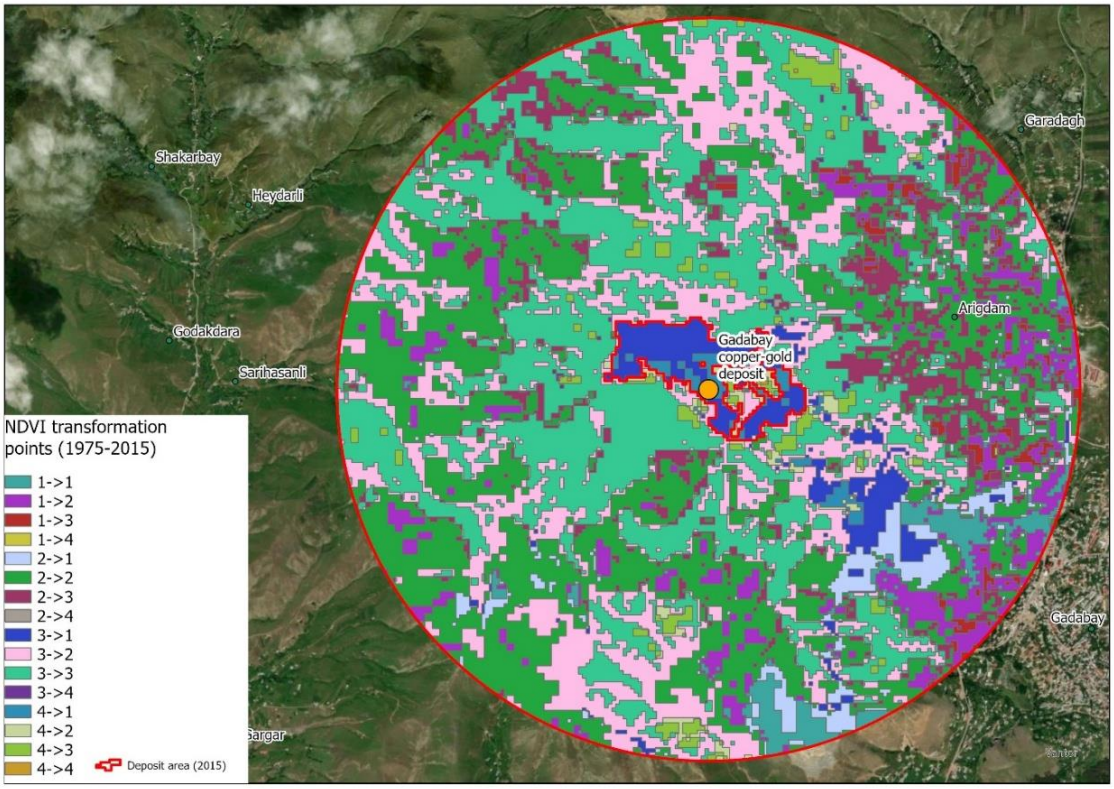


Fig. 9. Changes in soil and vegetation cover within the 3 km buffer around the Gadabay gold–copper–pyrite deposit, 1975–2015

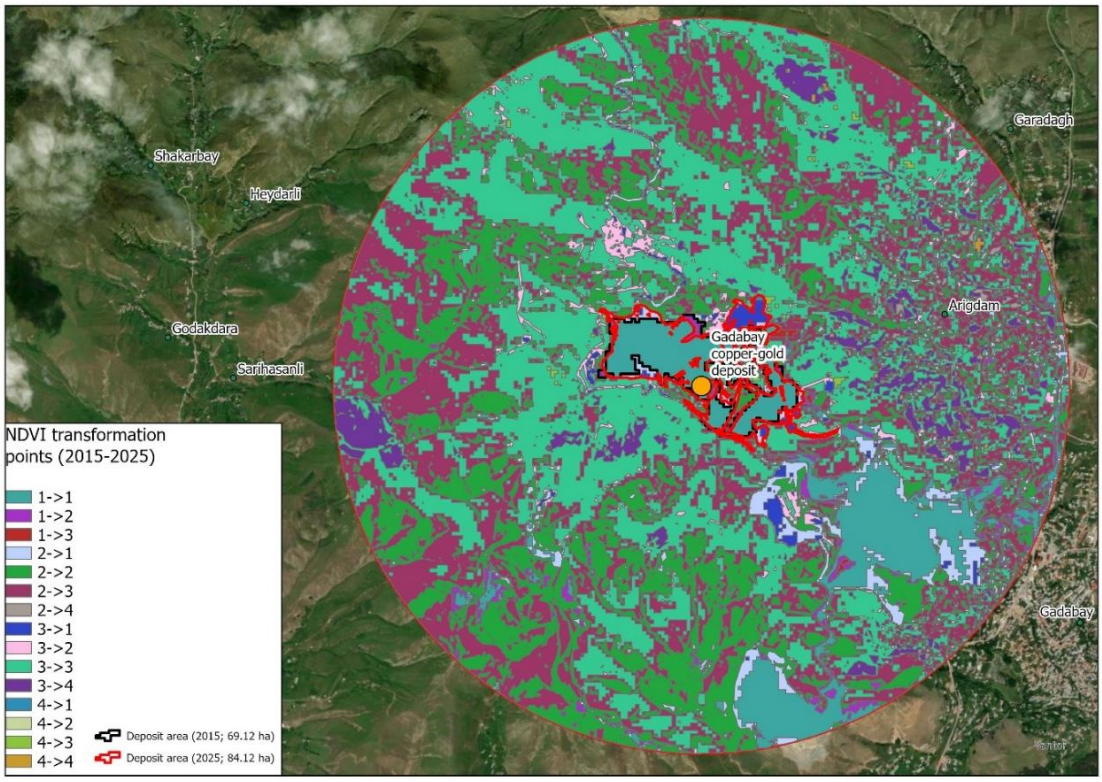


Fig. 10. Changes in soil and vegetation cover within the 3 km buffer around the Gadabay gold–copper–pyrite deposit, 2015–2025

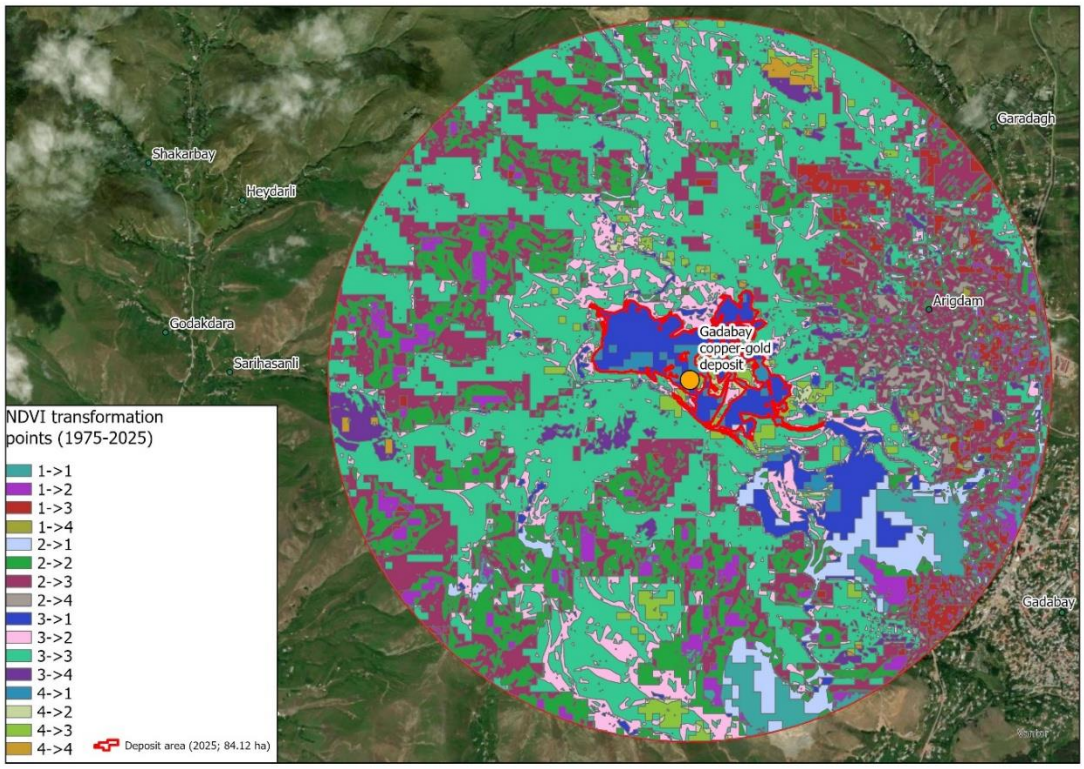


Fig. 11. Changes in soil and vegetation cover within the 3 km buffer around the Gadabay gold–copper–pyrite deposit, 1975–2025

Table 1.

Analysis of NDVI indicators (1975-2015) within a 3 km radius of the Gadabay copper-gold deposit

NDVI 1975 Area (S), sq.km (%)	NDVI 2015 Area (S), sq.km, (%)	Evaluation, point	Transformation and stability values (1975=>2015)	Area (S), sq.km	Area (S), %
0.023-0.2 2.5 (8.85)	-0.057-0.2 2.5 (8.86)	1	1=>1	0.59	2.09
			1=>2	1.59	5.63
			1=>3	0.31	1.11
			1=>4	0.0018	0.0063
			$\sum S_{Transformation+}$	1.9018	6.7463
0.2-0.4 10.72 (37.91)	0.2-0.4 15.1 (53.39)	2	2=>1	0.69	2.44
			2=>2	7.69	27.22
			2=>3	2.31	8.19
			2=>4	0.02	0.05
			$\sum S_{Transformation-}$	0.69	2.44
			$\sum S_{Transformation+}$	2.33	35.41
			$\sum S_{TransformationΔ+}$	1.64	32.97
0.4-0.6 14.1 (49.87)	0.4-0.5 10.62 (37.56)	3	3=>1	0.98	3.46
			3=>2	5.56	19.68
			3=>3	7.52	26.62
			3=>4	0.03	0.11
			$\sum S_{Transformation-}$	6.54	23.14
			$\sum S_{Transformation+}$	0.03	0.11
			$\sum S_{TransformationΔ-}$	-6.51	-23.03
0.6-0.726 0.95 (3.38)	0.501-0.533 0.05 (0.19)	4	4=>1	0.2421	0.86
			4=>2	0.2399	0.85
			4=>3	0.46	31.44

			4=>4	0.01	0.02
			$\sum S_{Transformation-}$	0.942	33.15

Table 2.

Analysis of NDVI indicators (2015-2025) within a 3 km radius of the Gadabay copper-gold deposit

NDVI 2015 Area (S), sq.km, (%)	NDVI 2025 Area (S), sq.km, (%)	Evaluation, point	Transformation and stability values (2015=>2025)	Area (S), sq.km	Area (S), %
-0.057-0.2 2.5 (8.86)	-0.153-0.2 3.13 (11.09)	1	1=>1	2.01	7.11
			1=>2	0.43	1.53
			1=>3	0.06	0.22
			1=>4	-	-
			$\sum S_{Transformation+}$	0.49	1.75
0.2-0.4 15.1 (53.39)	0.2-0.4 7.52 (26.61)	2	2=>1	0.86	3.04
			2=>2	6.39	22.59
			2=>3	7.69	27.2
			2=>4	0.15	0.55
			$\sum S_{Transformation-}$	0.86	3.04
			$\sum S_{Transformation+}$	7.84	27.75
			$\sum S_{TransformationΔ+}$	6.98	24.71
0.4-0.5 10.62 (37.56)	0.4-0.6 16.4 (58.0)	3	3=>1	0.26	0.93
			3=>2	0.70	2.48
			3=>3	8.61	30.46
			3=>4	1.04	3.7
			$\sum S_{Transformation-}$	0.96	3.41
			$\sum S_{Transformation+}$	1.04	3.7
			$\sum S_{TransformationΔ-}$	0.08	0.29
0.501-0.533 0.05 (0.19)	0.6-0.726 1.22 (4.3)	4	4=>1	0.002	0.007
			4=>2	0.001	0.004
			4=>3	0.035	0.12
			4=>4	0.017	0.06
			$\sum S_{Transformation-}$	0.038	0.33

Table 3.

Analysis of NDVI indicators (1975-2025) within a 3 km radius of the Gadabay copper-gold deposit

NDVI 1975 Area (S), sq.km (%)	NDVI 2025 Area (S), sq.km, (%)	Evaluation, point	Transformation and stability values (1975=>2025)	Area (S), sq.km	Area (S), %
0.023-0.2 2.5 (8.85)	-0.153-0.2 3.13 (11.09)	1	1=>1	0.66	2.35
			1=>2	0.99	3.51
			1=>3	0.77	2.73
			1=>4	0.071	0.25
			$\sum S_{Transformation+}$	1.831	6.49
0.2-0.4 10.72 (37.91)	0.2-0.4 7.52 (26.61)	2	2=>1	0.87	3.07
			2=>2	4.01	14.2
			2=>3	5.4	19.1
			2=>4	0.43	1.53
			$\sum S_{Transformation-}$	0.87	3.07
			$\sum S_{Transformation+}$	5.83	20.63
			$\sum S_{TransformationΔ+}$	4.96	17.56
0.4-0.6 14.1	0.4-0.6 16.4	3	3=>1	1.34	4.73
			3=>2	2.36	8.34

(49.87)	(58.0)		3=>3	9.77	34.59
			3=>4	0.63	2.22
			$\sum S_{Transformation-}$	3.7	13.07
			$\sum S_{Transformation+}$	0.63	2.22
			$\sum S_{TransformationΔ-}$	-3.07	-10.85
0.6-0.726 0.95 (3.38)	0.6-0.726 1.22 (4.3)	4	4=>1	0.26	0.93
			4=>2	0.16	0.57
			4=>3	0.45	1.58
			4=>4	0.08	0.3
			$\sum S_{Transformation-}$	0.87	3.08

Note. The tables were compiled by J. Y. Gasimov.

Conclusions

The comprehensive assessment of ecological and geomorphological hazards associated with mining-disturbed land in the Gadabay administrative district yielded three main findings.

1. The composite hazard index provides a more detailed assessment of the environmental consequences of mining by combining the area of disturbed land with factors that influence material transport and the associated ecological hazards. These factors include the type of mineral resource extracted, the geomorphological setting of the deposit, the extent of anthropogenic changes to topography, and the composition of mining-related deposits.

2. As of 2025, the Gadabay gold–copper–pyrite deposit had one of the largest areas of mining-disturbed land in the Gadabay administrative district, covering 84.12 ha.

3. NDVI maps derived from Sentinel-2A and Sentinel-2B, Landsat 2 MSS, and Landsat 8 OLI/TIRS imagery revealed changes in soil and vegetation cover within the 3 km buffer around the Gadabay gold–copper–pyrite deposit between 1975 and 2025. The mapped area of the deposit increased by 15 ha between 2015 and 2025.

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GƏDƏBƏY QIZIL–MİS–KOLÇEDAN YATAĞINDA DAĞ-MƏDƏN FƏALİYYƏTİ NƏTİCƏSİNDƏ POZULMUŞ ƏRAZİLƏRDƏ EKOLOJİ VƏ GEOMORFOLOJİ TƏHLÜKƏLƏRİN KOMPLEKS QİYMƏTLƏNDİRİLMƏSİ

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Xülasə. Tədqiqatda Azərbaycanın Gədəbəy qızıl–mis–kolçedan yatağında mədən istismarı ilə əlaqəli ekoloji-geomorfoloji təhlükələrin qiymətləndirilməsi metodikası hazırlanmış və tətbiq edilmişdir. Metodikaya əsasən, sahə üzrə çəkiləndirilmiş kompleks təhlükə indeksinin hesablanmasında beş meyar nəzərə alınmışdır. Bunlara pozulmuş ərazinin sahəsi, geomorfoloji mövqeyi, relyefin dəyişmə dərəcəsi, səthi çöküntülərin tərkibi və çıxarılan faydalı qazıntının növü daxildir. Meyarların çəki əmsalları iyerarxiyaların təhlili metodu ilə müəyyən edilmişdir. Yatağın ətrafındakı 3 km-lik bufer zonasında 1975–2025-ci illər ərzində torpaq və bitki örtüyündə baş verən dəyişiklikləri qiymətləndirmək üçün Landsat və Sentinel-2 peyk təsvirləri əsasında normallaşdırılmış fərq bitki örtüyü indeksi (NDVI) hesablanmışdır. Xəritələşdirmənin nəticələrinə görə, mədən ərazisinin sahəsi 2015-ci ildə 69,12 ha-dan 2025-ci ildə 84,12 ha-ya yüksəlmiş, on il ərzində 15,00 ha artmışdır. Çöl müşahidələri göstərmişdir ki, mədən fəaliyyəti nəticəsində yaranmış relyef formalarının çoxu rekultivasiya edilməmişdir. Bu sahələrdə bitki örtüyünün seyrək olması və ya ümumiyyətlə olmaması onların

Açar sözlər: *mədən istismarı nəticəsində pozulmuş ərazilər, ekoloji-geomorfoloji təhlükələr, kompleks təhlükə indeksi, iyerarxiyaların təhlili metodu, NDVI, Gədəbəy*

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