




Geo-information Modeling and Spatial Analysis of Environmental and Infrastructure Parameters in the Shusha Region Using Satellite Imagery and GIS Technologies

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Abstract. This article emphasizes the application of Geographic Information Systems (GIS) as a robust and modern tool for environmental monitoring and analysis. Through GIS-based methodologies, key ecological parameters—such as landscape transformations, land cover dynamics, vegetation health, and biodiversity—can be accurately mapped and evaluated. The complex topography and unique historical-geographical features of the Shusha region necessitate a spatially integrated approach to ecological assessment. Furthermore, the research aligns with Azerbaijan’s national priorities, which place ecological restoration, sustainable development, and the transition to a green economy at the core of post-conflict regional policy. The findings of this study aim to contribute both scientifically and practically to the development of informed strategies for ecological security and sustainable management of the liberated territories. The ecological assessment of the liberated Shusha area is of strategic importance for the post-conflict reconstruction and sustainable development of the region. Due to decades of neglect and war-related damage, reliable ecological data is essential for sustainable decision-making and natural resource management. This study aims to assess the current ecological status of Shusha district using Geographic Information System technologies. Its aim is to identify ecological threats and visualize ecological indicators to support restoration and policy planning. Various methods such as data collection, research, analysis, spatial analysis, cartographic modeling were applied in this study. In addition, the normalized vegetation index was used in the compositional analysis of the vegetation cover of the area, and the complex water balance method was used in the analysis of the dynamics of water resources.

Keywords: Environmental parameters, Satellite imagery, GIS technologies, Ecological indicators, Data collection, Cartographic modeling

1. Introduction

The Shusha District, with a historical legacy spanning approximately 270 years, was officially designated as an administrative district in 1930. Today, it holds the distinguished title of the cultural capital of the Republic of Azerbaijan. On May 8, 1992,

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States, Canada, Germany, Russia, and Turkey, GIS technologies have been extensively utilized to address environmental issues including soil erosion, biodiversity loss, and water resource management. In Azerbaijan, however, the use of GIS has predominantly been concentrated in geodesy, cartography, and agriculture, with its integration into ecological research still at an early developmental stage [8,9].

Therefore, a GIS-based assessment of the ecological condition of the Shusha region is both a timely and essential initiative. It seeks to address the existing scientific gap and to provide a data-driven foundation for the ecological rehabilitation of the area. Furthermore, the research is closely aligned with broader concerns of ecological security, sustainable environmental management, and post-conflict restoration, underscoring its multidisciplinary importance [10].

2. Research goals and objectives

The primary aim of this study is to assess the ecological condition of the liberated Shusha region through the application of Geographic Information Systems (GIS) technologies, with the objective of identifying and spatially analyzing existing environmental issues. To achieve this goal, the research employs modern spatial analysis tools and GIS-based methodologies to determine and visualize key ecological indicators [11, 12]. The specific objectives of the research are as follows:

- To analyze and synthesize the theoretical and methodological foundations for the application of GIS technologies in ecological research;
- To collect and examine ecological data related to the natural conditions of the Shusha region from previous periods;
- To conduct a spatial assessment of anthropogenic impacts, including soil degradation, changes in vegetation cover, and other forms of environmental disturbance;
- To analyze land cover and landscape structure changes using data derived from remote sensing (RS) and GIS;
- To develop spatial models for identifying ecologically sensitive areas and endangered ecosystems within the region;
- To present the findings through detailed cartographic visualizations and formulate scientifically grounded recommendations for ecological rehabilitation.

The successful implementation of these objectives will contribute to the establishment of an objective, accurate, and systematic information base on the ecological status of the Shusha region. Furthermore, the study will provide essential insights for the development of strategies aimed at the sustainable ecological management and restoration of the area. The object of the study is the natural environment of the liberated Shusha region, including its ecological components and the system of anthropogenic factors influencing them. This encompasses key environmental elements such as soil resources, vegetation cover, landscape structure, water bodies, and other significant ecological indicators [13,14].

The subject of the study is the application of Geographic Information Systems (GIS) technologies in assessing the ecological condition of the Shusha region, with a focus on the spatial-temporal analysis of ecological transformations using geospatial tools.

3. Research methods

This study employed an integrated methodological approach based on GIS and remote sensing (RS) technologies to evaluate the ecological state of the Shusha region. Normalized Difference Vegetation Index (NDVI) analysis was conducted using satellite imagery to detect changes in vegetation and soil cover. Spatial and temporal assessments were carried out through GIS software, enabling the visualization of anthropogenic impact zones and areas of ecological risk [15]:

In addition to geospatial analysis, statistical and comparative methods were applied to evaluate the dynamics of environmental changes over time. Experimental studies, expert assessments, theoretical-experimental comparisons, and cartographic techniques were also utilized to ensure the scientific rigor and objectivity of the analysis. Together, these methods facilitated a comprehensive and evidence-based assessment of the ecological conditions in the study area. A substantial portion of the Shusha region is characterized by extensive vegetation cover, which significantly contributes to the ecological and economic evaluation of the land. The analysis of the spectral properties of vegetation is crucial not only in geological surveys utilizing geophysical satellite data but also in the assessment of the health status of agricultural and forested areas. Furthermore, remote sensing technologies facilitate the monitoring of vegetation dynamics, enabling these processes to serve as key indicators in biosphere monitoring efforts. Such data are essential for detecting environmental changes, including the impacts of pollution and various stress factors [16,17,18].

Within this framework, spectral and hyperspectral vegetation indices constitute vital analytical tools for evaluating vegetation conditions. Vegetation indices, which are derived from the spectral reflectance characteristics of plant surfaces, represent important metrics for assessing vegetation attributes. These indices quantify the interaction between reflected energy at specific wavelengths relative to plant developmental stages and other influencing factors such as soil type and climatic conditions. To date, more than 160 vegetation indices have been developed empirically, primarily based on the spectral characteristics of soil and vegetation [19]

Among these, the Normalized Difference Vegetation Index (NDVI) is the most extensively utilized indicator for assessing vegetation vigor and development. Recent advancements have produced modified versions of NDVI that exhibit greater resistance to atmospheric interference, thereby enhancing the reliability of vegetation monitoring.

A principal advantage of these indices lies in their accessibility and versatility in addressing a wide range of environmental and agricultural challenges. NDVI, in particular, serves as a foundational tool in comprehensive analyses, enabling the generation of productivity maps for forests and agricultural lands, delineation of natural and landscape zones, and the creation of various other visual representations.

NDVI technology facilitates the remote observation of vegetation changes without necessitating physical field visits. Satellites capture electromagnetic responses from the Earth's surface across multiple spectral bands, which are subsequently processed to produce vegetation maps of specific regions. This methodology is particularly valuable for assessing plant density and health in inaccessible or otherwise challenging terrain, thereby providing critical insights into regional vegetation dynamics [20].

To assess the health status of vegetation, the absorption and reflection values of red (RED) and near-infrared (NIR) wavelengths are compared using the Normalized Difference Vegetation Index (NDVI). The NDVI is calculated according to the following formula:

$$\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED})$$

The resulting NDVI values range between -1 and $+1$. Values approaching $+1$ indicate the presence of dense and healthy vegetation, whereas values near -1 correspond to sparse or absent vegetation. In this study, satellite imagery from the Landsat series—including Landsat 8 Operational Land Imager (OLI), Landsat 5 Thematic Mapper (TM), and Landsat 4—were utilized for the years 1987, 2000, 2006, 2010, and 2018. Due to frequent cloud cover in the study region, acquiring fully cloud-free images spanning the period 1987–2018 was not feasible. Consequently, only satellite images with cloud coverage below 30%, totaling over 500 images, were sourced from the United States Geological Survey (USGS) archives [21,22].

Data processing was performed using several geospatial software packages, including ArcGIS 10.4, Erdas Imagine 2015, ENVI 5.3, Global Mapper, and Surfer 11.

To evaluate changes in forest cover between 2010 and 2020, an analysis based on mean NDVI values was conducted. NDVI values were normalized to a scale ranging from 0 to 1 and classified into five distinct intensity categories: very low, low, medium, high, and very high vegetation density. The temporal dynamics of these classes were analyzed and expressed as percentages relative to the total forested area. This classification approach primarily captures broad regional or national vegetation trends rather than detailed local-scale (pixel-based) variations. Figure 2 presents the geographical location of the study area, illustrated using Landsat 8 satellite imagery [23].

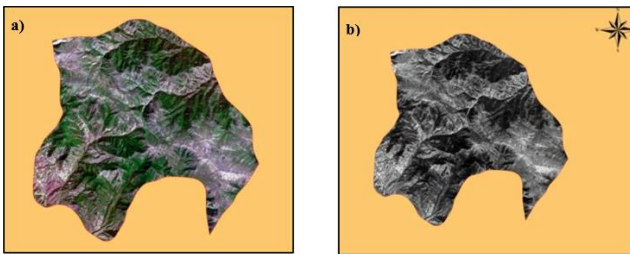


Fig. 2. Satellite image fragment of Shusha region: a) panchromatic b) multispectral

It is important to note that the forest cover mask employed in the NDVI calculations was derived exclusively from satellite imagery acquired in 2020. Consequently, this approach may create the impression that forest cover has remained static over preceding years. However, it is necessary to consider that land use within these areas may have varied historically, including uses such as cropland, shrub land, or zones designated for construction. In such instances, observed land cover changes could be temporary or marginal, potentially representing a transition towards forest or grassland ecosystems.

Landsat 8 satellite images from two distinct temporal periods encompassing the study area were orthorectified through a first-order polynomial transformation, utilizing ground control points obtained from Shuttle Radar Topography Mission (SRTM) elevation data and large-scale topographic maps. Multispectral data, with a spatial resolution of 1.5 meters, were acquired by integrating panchromatic and multispectral satellite images through pan-sharpening techniques. This multispectral dataset, combined with topographic indicators and satellite imagery, facilitated the classification of landscape components via multiband airborne spectrometry data spanning all seasons [24,25].

During this phase, a terrain elevation model (TIN model) and a three-dimensional (3D) model were generated using ArcGIS software. These models were constructed based on selected red and near-infrared spectral bands and georeferenced cartographic data (see Figure 3).

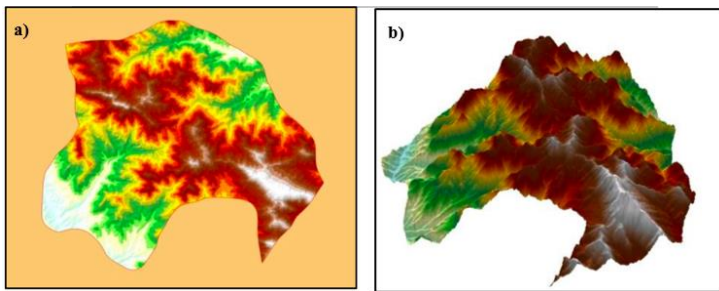


Fig. 3. Elevation indicators (a) and 3D model (b) of the Shusha region

A comparative analysis of NDVI indices for the study area between 2010 and 2020 reveals notable changes across different vegetation density levels. Based on the provided maps, the temporal variation of NDVI values in the Shusha region was systematically examined (see Table 1).

Table 1. NDVI indices of the Shusha region for the period 2010–2020.

NDVI coefficient	Vegetation type	2010 (km ²)	2010 (%)	2020 (km ²)	2020 (%)
< 0	Devoid of vegetation slopes and cliffs	0.004	0.001%	0.01	0.004%
0–0.15	Sparse shrub-meadow plant groups	49.4	18.1%	39.1	14.3%
0.15–0.2	Post-forest xerophytic steppe plants	52.8	28.8%	78.9	19.3%
0.2–0.25	Disturbed forest and forest-steppe plants	108.6	30.2%	105.5	48.2%
> 0.25	Repeated forest thickets and oak-alder, beech-alder woodland	62.6	22.9%	49.9	18.2%

One of the primary parameters employed in the delineation of forest cover is the tonal and textural characteristics observed in satellite imagery. Forested areas typically exhibit dark green to black hues and display a distinctive concentric structural pattern. In contrast, grasslands are characterized by a dark green coloration accompanied by a comparatively smoother texture. Based on these spectral and textural differences, a classification of the satellite images was subsequently conducted (see Figure 4).

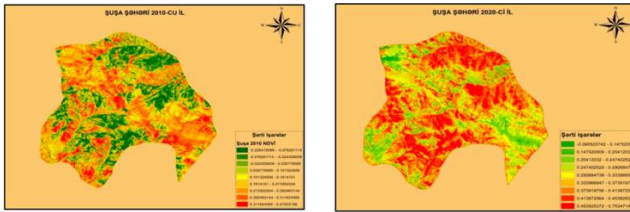


Fig. 4. NDVI indices of the Shusha region for the years 2010 and 2020.

As shown in Table 1, a comparative analysis of NDVI indices between 2010 and 2020 indicates measurable shifts in vegetation cover across the Shusha region. During this period, areas classified as slopes and cliffs devoid of vegetation ($NDVI < 0$) increased marginally by 0.006 km^2 . Conversely, post-forest xerophytic steppe vegetation ($NDVI$ range: $0.15\text{--}0.2$) exhibited a significant expansion of approximately 26.1 km^2 . In contrast, a reduction was observed in several other vegetation categories: sparse shrub-meadow plant formations ($NDVI$ range: $0\text{--}0.15$) decreased by 10.3 km^2 ; disturbed forest and forest-steppe vegetation ($NDVI$ range: $0.2\text{--}0.25$) declined by 3.1 km^2 ; and areas dominated by secondary forest-shrub communities as well as oak–alder and beech–alder woodlands ($NDVI > 0.25$) decreased by 12.7 km^2 .

The Shusha region is characterized by highly complex physical and geographical conditions, and the current political and territorial situation presents significant challenges to the timely and efficient implementation of on-site scientific research. As a result, the assessment of water resources and the regional water balance has been conducted using advanced hydrological modeling techniques that minimize reliance on in-situ observations. The water balance of the region was calculated using the Synthesis Water Balance Method (SWBM), while water resource estimations were performed via the Complex Water Balance Method (CWBM).

These modern methodologies eliminate the need for continuous field-based measurements and enable scientific investigations to be carried out remotely, without spatial or temporal constraints. The application of such methods introduces key advantages, including flexibility, interactivity, and predictive capability. The CWBM, in particular, is an innovative methodological framework that integrates these features to enhance the robustness of hydrological assessments.

The CWBM operates entirely through remote sensing technologies, relying on the analysis of satellite imagery without requiring physical access to the study area. This method accounts for both the generation of surface and subsurface runoff and the influence of a wide range of environmental variables on water resources. The majority of input data is derived from multispectral (including hyperspectral) satellite imagery and is processed using Geographic Information System (GIS) technologies [26,27].

The CWBM categorizes the complex variables influencing water resources into three principal groups:

Surface cover indicators: This group includes landscape types, soil resources, soil texture (granulometric composition), and hydrological soil classifications.

Morphometric parameters: These encompass various geomorphological characteristics such as basin elevation, slope gradient and steepness, basin area, horizontal and vertical dissection of the terrain, and river network density.

Climatic and humidity-related factors: This includes meteorological and hydrological parameters such as atmospheric precipitation, actual and potential evapotranspiration, soil water retention capacity, initial abstraction, and soil moisture content.

The exclusive reliance on satellite imagery in this study eliminates spatial and temporal constraints in acquiring the necessary data. This approach allows scientific investigations to be conducted without direct physical access to the area, thereby reducing dependency on conventional observational datasets. Geographic Information System (GIS) technologies play a critical role in addressing data limitations, especially in cases where little or no ground-based information is available. The following GIS-based methods were employed to identify and estimate such data gaps: spatial interpolation techniques; factor weighting and probabilistic modeling; inverse modeling approaches;

Unlike traditional hydrological assessment methods, GIS-based analytical capabilities enable the reconstruction of missing environmental parameters-including climatic variables and water consumption data-with a high degree of reliability. In particular, the inverse modeling approach allows for the estimation of unknown indicators by integrating accurate and remotely sensed inputs into a comprehensive geospatial database. The inverse modeling technique is predicated on the principle that, when a majority of the contributing flow parameters are known, the remaining unknown variables can be inferred retrospectively. This method essentially reverses the analytical process-starting from known outcomes and tracing back to determine the contributing factors. By selecting appropriate reference points in both space and time, this approach facilitates the complex analysis of interdependent factors, either in isolation or as part of an integrated framework.

The core principle of modern water balance methodologies-such as the Complex Water Balance Method (CWBM)-lies in the determination of flow coefficients that incorporate the cumulative influence of diverse environmental factors. The calculation of water balance and water resource distribution is then derived based on the spatial variation of these coefficients. In constructing flow coefficients, the CWBM method takes into account a wide range of critical variables, including: landscape type and soil composition; vegetation density; soil texture and moisture content; filtration capacity; precipitation volume and atmospheric humidity; elevation, slope, and geomorphological structure; horizontal and vertical dissection of surface materials.

In this study, the CWBM method was used to assess temporal changes in the water balance and water resources of the Shusha region over a 23-year period (1998–2021). This methodological framework enables the identification of long-term trends in water resource availability and provides insights into the influence of climatic, anthropogenic, and other contributing factors. Such analyses are vital for developing strategies for the more efficient and sustainable use of water resources.

Primary data sources included multi-temporal satellite imagery, digital elevation models (DEMs), and hydro-meteorological measurements. Landscape and soil information was extracted from fragments of Landsat-5 TM, Landsat-7 ETM+, and Landsat-

8 OLI/TIRS imagery, while morphometric indicators were derived from high-resolution DEM data. Figure 5 presents maps of selected flow-forming factors in the Shusha region, compiled from satellite imagery.

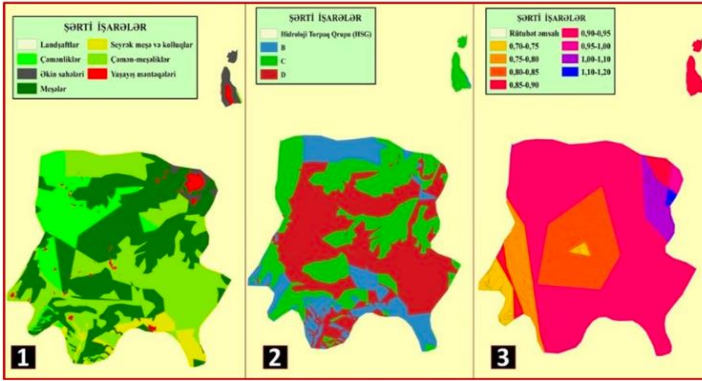


Fig. 5. Maps compiled based on satellite image fragments of the Shusha region: 1 – Landscape and soil cover; 2 – Hydrological soil groups; 3 – Humidity coefficient

All spatial data processing and geospatial analyses were conducted using ArcGIS software. For the statistical analysis and interpretation of the results, the SPSS Statistics software package was employed. To enhance the reliability of the correlation analyses, multiple linear regression models were also applied during the computation process.

According to the Digital Elevation Model (DEM) of the Shusha region, the average elevation was determined to be 1682.7 meters, while the mean slope gradient was calculated as 20.29%. The density of the river network, differentiated by valley lengths, is presented in Table 2.

Table 2. River network density in the Shusha region region based on valley length.

Minimum length of river valley, m	20	50	100	200
Total length of river valleys, km	539.7	202.4	68.51	23.33
River network density, km/km ²	1.741	0.653	0.221	0.075

The river network and the river basin delineation were derived using the “Hydrology” toolset within the GIS environment, based on satellite imagery of the study area. This processing enabled the identification of major watercourses and the delineation of flow accumulation patterns and watershed boundaries. Figure 6 illustrates the hydrological features of the Shusha region, including: the major rivers traversing the territory, and the course of river flow formation and basin separation as generated through GIS-based hydrological modeling.

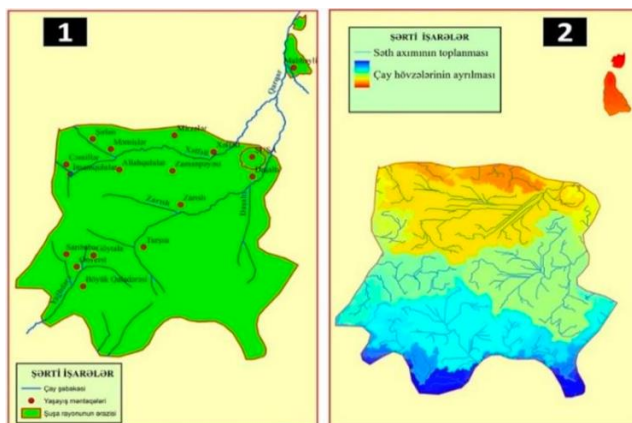


Fig. 6. Major rivers of the Shusha region (1); River flow formation and basin delineation derived through GIS hydrological processing (2).

The modern water resources of the Shusha administrative district are currently estimated at approximately 75.76 million cubic meters (m^3). Although the total volume of water resources in the district is relatively limited, Shusha stands out within the Karabakh economic region for having the highest runoff provision, with an average annual runoff of 244.4 mm, significantly exceeding the regional average of 140.8 mm for the Karabakh area as a whole.

An assessment of water resource dynamics was conducted for two reference years—1998 and 2021—to evaluate long-term trends. The analysis revealed a 37.2% decrease in the district's water resources over the 23-year period. This decline was attributed to both climatic and non-climatic (primarily anthropogenic) factors. Specifically, climatic influences accounted for a 6.8% reduction, while anthropogenic and other non-climatic factors contributed to a more substantial 30.4% decrease.

Table 3. Changes in water balance elements in the Shusha region (1998-2021).

Water balance elements	1998	2021
Precipitation, mm	678.7	591.7
Potential evaporation, mm	617.4	645.2
Humidification coefficient, R	1.045	0.9171
Air temperature, °C	9.93	10.7
Surface runoff, mm	215.3	128.3
Actual soil moisture, mm	311.2	282.5
Subsurface runoff, mm	178.2	118.4
Full flow layer, mm	393.5	246.7
Flow coefficient	0.5798	0.4175
Actual evaporation, mm	285.2	345.0

Key drivers of this decline include landscape transformation and land-use change, most notably: large-scale deforestation and subsequent desertification of forest areas;

land degradation and conversion of natural areas into agricultural or built-up land; expansion of cultivation and settlement zones; inefficient management and use of water resources due to increased anthropogenic pressure.

These factors have significantly altered the hydrological regime of the region. Table 3 presents the quantitative changes observed in the main components of the water balance in the Shusha district over the 1998–2021 period.

In the hydrological balance of the Shusha region, prior to 2021, 21.7% of the average annual precipitation of 591.7 mm contributed to surface runoff (128.3 mm), 20.0% was allocated to groundwater recharge (116.1 mm), and the remaining 58.3% was lost to evapotranspiration (345.0 mm). In contrast, during the period prior to 1998, 31.7% of the precipitation contributed to surface runoff, 26.3% to groundwater recharge, and 42.0% to evapotranspiration.

This comparison indicates a marked shift in the water balance structure over time. Notably, the average annual precipitation in the period prior to 1998 was 678.7 mm, which is 12.8% higher than the value recorded in 2021 (591.7 mm). Moreover, during the earlier period, 58.0% of total precipitation contributed to the formation of river water resources (i.e., surface runoff and groundwater recharge combined). However, by 2021, this share had declined to 41.7%, reflecting both a reduction in precipitation and a weakening of the region's runoff-generating capacity.

4. Conclusion

The comprehensive assessment of vegetation dynamics, water resources, and hydrological balance in the Shusha region—conducted through modern geospatial technologies and remote sensing methods—has yielded several important findings:

Analysis of multi-temporal satellite imagery using NDVI indices for the years 2010 and 2020 revealed significant shifts in vegetation cover across the Shusha region. While areas with post-forest xerophytic steppe vegetation (NDVI 0.15–0.2) expanded by 26.1 km², a decline was observed in high-density vegetation classes, including secondary forests and mixed woodland areas, which decreased by 12.7 km². These changes suggest a trend toward vegetation degradation and a transition to lower-density plant communities, likely influenced by both natural and anthropogenic factors.

The use of GIS and remote sensing tools—such as ArcGIS, ENVI, and statistical processing in SPSS—allowed for detailed spatial and temporal analysis without the need for physical fieldwork. Methodologies like the Complex Water Balance Method (CWBM) and inverse modeling approaches proved effective in reconstructing hydrological parameters and analyzing landscape transformations. These technologies also enabled the integration of diverse data sources, including DEMs, satellite imagery, and hydro-meteorological records.

The study identified a significant 37.2% decrease in water resources in the Shusha region between 1998 and 2021. Of this, 6.8% was attributed to climatic factors (e.g., reduced precipitation), while 30.4% was linked to anthropogenic pressures such as deforestation, land degradation, and inefficient water use. The average annual precipitation also decreased by 12.8% during this period, further reducing the runoff-generating

potential of the landscape. Prior to 1998, 58.0% of atmospheric precipitation contributed to surface and subsurface runoff, whereas by 2021 this had declined to 41.7%, indicating a marked reduction in water yield. Concurrently, the proportion of precipitation lost to evaporation increased from 42.0% to 58.3%, highlighting a shift toward drier hydrological conditions, likely intensified by land cover changes and increased evapotranspiration.

Despite its relatively limited total water resources (75.76 million m³), the Shusha region exhibits the highest runoff levels (244.4 mm) within the Karabakh economic region. The observed decline in water availability underscores the urgent need for sustainable water management strategies, reforestation programs, and the mitigation of land degradation to prevent further hydrological stress.

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Disclosure of Interests. The authors declare that they have no known financial or non-financial competing interests that could have influenced the research or the interpretation of the results presented in this study. All analyses were conducted independently and solely for scientific and academic purposes.

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