

ECOGEOGRAPHICAL AND ECOTOURISTIC RESILIENCE: A SPATIAL ASSESSMENT OF REGIONAL MOISTURE DYNAMICS AND LANDSCAPE TRANSFORMATIONS

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Summary. This study applies a CFE model and Geospatial Analogue Transfer (GAT) technology to assess ecogeographical and ecotourism conditions in Azerbaijan. Based on the heat–moisture principle, the CFE model partitions annual precipitation among surface runoff, effective infiltration, and actual evapotranspiration. The infiltration–evapotranspiration ratio is used to characterise landscape moisture conditions, potential biological productivity, and ecosystem resilience. GAT transfers indicators from reference areas to poorly studied areas with comparable environmental conditions. Hydrometeorological, soil, land-cover, and terrain data from more than 70 measurement and monitoring sites were integrated in a geographic information system to estimate the CFE coefficients and examine relationships among environmental components. The approach was also used to assess landscape changes and distinguish areas requiring further investigation of possible anthropogenic impacts. Validation across approximately 70 catchments yielded coefficients of determination (R^2) of 0.74–0.93 and Nash–Sutcliffe efficiency (NSE) values of 0.62–0.77. Application to the Nakhchivanchay catchment for 1999–2024 revealed contrasting spatial responses to climatic and anthropogenic influences, including substantial differences in vegetation cover, soil degradation, infiltration, evapotranspiration, and “green water” resources. The combined CFE and GAT approach provides a quantitative basis for assessing landscape resilience and recreational carrying capacity, identifying potential ecological corridors, and informing the conservation and sustainable management of natural landscapes and ecological heritage.

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Introduction

The acceleration of global climate change and growing anthropogenic pressures have increased the need for methods that can assess ecosystem resilience. Resilience depends not only on a landscape’s morphological and biological characteristics but also on the quantitative properties of its hydrothermal resources, particularly the moisture cycle (Piao et al., 2020). Conventional macroclimatic indices based on temperature and precipitation describe an area’s overall conditions but provide limited insight into changes at the micro-landscape scale, such as reduced soil infiltration or changes in vegetation’s use of “green water”.

The CFE model examines how precipitation is distributed among surface runoff, infiltration and evaporation, providing a basis for assessing the functional and dynamic state of landscapes (Makhmudov et al., 2023; Teymurov et al., 2026). In particular, the f/e (infiltration–evaporation) ratio characterises the balance within the soil–vegetation–water system and helps quantify landscape moisture and potential biological productivity. In this study, the model is combined with geographic information systems (GIS) and geospatial analysis to examine hydropedological (soil–water) and hydrometeorological (air–water) processes within a single framework. Its sensitivity to changes in moisture conditions and landscape structure also provides a basis for assessing and predicting the effects of anthropogenic disturbance on ecosystem resilience.

From an ecogeographical perspective, the balance between infiltration and evaporation influences soil moisture, vegetation composition and ecosystem resilience. The CFE model can therefore help identify areas that appear healthy but have a disrupted internal water balance, including areas at risk of hidden degradation (“grey zones”) (Javed et al., 2020).

From an ecotourism and ecological heritage perspective, maintaining the hydrological health of natural monuments and landscapes helps preserve their aesthetic and recreational value. Reliable water availability in mountain ecosystems is also important for maintaining the natural conditions on which ecotourism depends (Zhang et al., 2023). Landscape planning informed by the CFE model can bring traditional silvopastoral practices together with contemporary scientific approaches to support the conservation of natural monuments for future generations.

Materials and methods

The empirical basis of this study comprises data from more than 70 measurement and monitoring sites across Azerbaijan. Hydrometeorological data, including precipitation, temperature, aridity indices and runoff, were collected from observation stations. Missing climate data were obtained from the NASA POWER and Copernicus Climate Data Store platforms. Maps depicting soil and atmospheric moisture conditions in the National Atlas of Azerbaijan were also used to collect and compare data (State, 2014).

Geospatial data, including hypsometric and morphometric parameters, were derived from a digital elevation model (DEM). Land use and land cover (LULC) and landscape characteristics were determined from satellite data. Multispectral analysis used vegetation indices (NDVI and SAVI), the bare soil index (BSI), the normalised difference built-up index (NDBI), the normalised difference water index (NDWI), the normalised difference moisture index (NDMI) and the normalised difference drought index (NDDI). In the ecogeographical analysis of LULC classes, soil and vegetation conditions, and biomass dynamics, NDVI was used for arid regions and SAVI for humid areas.

Because temperature and precipitation alone do not adequately characterise ecosystem moisture regimes and their capacity to adapt to change, the assessment considered dozens of hydrogeological and hydrometeorological parameters (Yaeger et al., 2019; Makhmudov et al., 2023). Alongside conventional variables such as temperature, precipitation and aridity indices, parameters associated with the Budyko framework and the SCS-CN, Lvovich, Crow and Horton approaches were considered to characterise soil–water relationships.

The SCS-CN method is based on the relationship between precipitation and soil infiltration capacity. By accounting for hydrological losses, actual and maximum soil water retention, and hydrological soil groups (HSGs), it enables the moisture regime to be assessed using soil properties as well as atmospheric conditions (Ponce & Hawkins, 1996). HSGs reflect infiltration potential and are classified according to soil particle-size composition. The USDA classification distinguishes four groups (A–D) based on the proportions of sand (S), silt (Si), loam (L) and clay (C), with infiltration capacity decreasing towards group D (USDA, 2009).

Following Crow et al. (2017), the effective infiltration coefficient ((f)) was taken as the sum of the groundwater runoff component and actual soil moisture content. The groundwater runoff component indicates water movement and percolation through the soil, whereas soil moisture content indicates water retention. Their combined assessment was used to characterise infiltration and annual moisture availability under the region's soil and climate conditions.

The annual water balance was expressed as $(P=Q+U+E)$, where precipitation ((P)) is partitioned into surface runoff ((Q)), effective infiltration ((U)) and actual evaporation ((E)). The corresponding CFE coefficients were defined so that $(c+f+e=1)$, where (c), (f) and (e) represent the respective fractions. Surface runoff was estimated from observations; where measurements were unavailable, it was reconstructed using interpolation and an inverse approach (Makhmudov & Teymurov, 2023). Effective infiltration was estimated using groundwater runoff measurements and National Atlas data, together with an HSG-based Horton model, the Budyko hypothesis ("Baseflow Curve") and hydrograph separation (Sartika et al., 2020; Bondy et al., 2021). Actual evaporation was calculated by subtracting surface runoff and infiltration from annual precipitation. These estimates were then compared with results obtained using the Budyko framework, the Turc method and the Zhang method, which respectively account for the aridity index, annual precipitation and temperature, and landscape types.

Results and discussion

Assessment of the Hydrothermal Regime and Ecological Status of Landscapes

The components of geosystems (ecosystems) function through hierarchical relationships, so a change in one component can affect the system as a whole. Climate is a major driver of these changes, particularly those affecting landscapes. Accordingly, variation in the heat–moisture balance across landscape types is an important criterion for assessing ecological conditions (Hamdany et al., 2023).

Surface runoff is the portion of precipitation that reaches the drainage network without infiltrating the soil and therefore does not directly contribute to soil moisture. In the proposed approach, the infiltration–evaporation ratio ((f/e)) is used as an indicator of the moisture regime: infiltration represents water entering the soil, while

evaporation represents water returned to the atmosphere. Temperature and precipitation alone do not fully describe this relationship. The assessment therefore considers both the annual amount of precipitation and its distribution among the three water-balance components. The (f/e) ratio is used to assess landscape moisture conditions, ecological resilience and potential biological productivity (Zhang et al., 2025).

Vegetation can alter the balance between infiltration and evaporation. In arid areas, some trees may promote infiltration, whereas others may reduce groundwater availability through high transpiration. Afforestation and other greening measures therefore require different approaches in arid and humid areas. The (f/e) ratio should be considered when selecting plant varieties, particularly because excessively dense vegetation in arid and semi-arid regions can increase transpiration and substantially reduce soil moisture (Zhan et al., 2022). For desertification control and landscape planning, priority is therefore recommended for native species with low water requirements.

In humid areas, anthropogenic deforestation can accelerate degradation. Forest restoration should therefore take biodiversity into account and maintain appropriate spacing between trees. Traditional silvopastoral systems, which integrate trees, forage crops and livestock on the same land, are also considered an effective means of supporting biodiversity in both arid and humid areas (Peri et al., 2024).

The distribution of precipitation among the CFE components was examined at more than 70 sites representing different natural and geographical conditions in Azerbaijan. Observed and reconstructed climate and runoff data were integrated with other environmental variables in an ArcGIS database. The data were classified and analysed using Field Calculator, Calculate Geometry, Spatial Statistics, Modeling Spatial Relationship, Combine, Environments and Weighted Overlay.

First, surface runoff coefficients ((c)) were determined from measured river discharge for different combinations of runoff-generating factors. On an annual basis, effective infiltration was taken as the sum of actual soil moisture and the groundwater contribution to river flow (Makhmudov et al., 2025). The CFE coefficients reflect the combined effects of hydrometeorological conditions, elevation, terrain morphology, slope, aspect, land use and land cover (LULC), lithology and rock permeability.

The methodological analysis examined correlations between the CFE coefficients and the natural components associated with their variation. Dynamic components, including climate, landscape, soil and vegetation cover, were treated as indicators of change. Relatively stable hypsometric and morphometric parameters provided a basis for comparing and classifying geosystems. The (c) coefficients were first grouped into intervals, and their correspondence with the quantitative values of other components was assessed. Initial selections were made using *Select by Attribute*. The *Combine* tool was then used to integrate multiple raster layers and record their unique combinations in a single raster and attribute table. These combinations provided the basis for comparing areas with available data (donor areas) with target areas and for examining the individual and combined associations of environmental factors through sensitivity analysis.

Assessing ecogeographical and ecotourism conditions requires consideration of an area's natural potential, environmental problems and the organisation of tourism activities (Imrani et al., 2025). In this study, the assessment follows the sequence of natural potential, ecological sensitivity, tourism pressure, suitable tourism activities and sustainable management. The constituent parameters of natural potential are assessed first. Table 1 presents the CFE coefficients for selected landscape zones characterised by mean aridity indices of 0.75–1.50, mean slopes of 10–20% and different hydrological soil groups (HSGs).

The CFE approach combines multiple factors with observed data. In a validation analysis using ArcGIS and data from approximately 70 catchments of different sizes, observed values and values estimated from the CFE coefficients showed approximately 74–95% agreement. The coefficient of determination (R^2) ranged from 0.74 to 0.93, while Nash–Sutcliffe efficiency (NSE) ranged from 0.62 to 0.77. These results indicate that the model may be applicable to analogous catchments.

Landscapes are an important component of ecotourism, and changes in land use and land cover (LULC) can indicate changes in environmental conditions. Distinguishing natural from anthropogenic changes helps assess ecological pressure and natural recovery potential. The origin of some land-cover classes, such as settlements, industrial areas and reservoirs, is readily identifiable, whereas changes in forests, meadows, semi-deserts and pastures can have both natural and human causes. One approach to interpreting satellite observations is to estimate the climate-related component with a model and then examine the remaining abrupt or geometrically distinct changes as possible effects of human activity (Imrani et al., 2025).

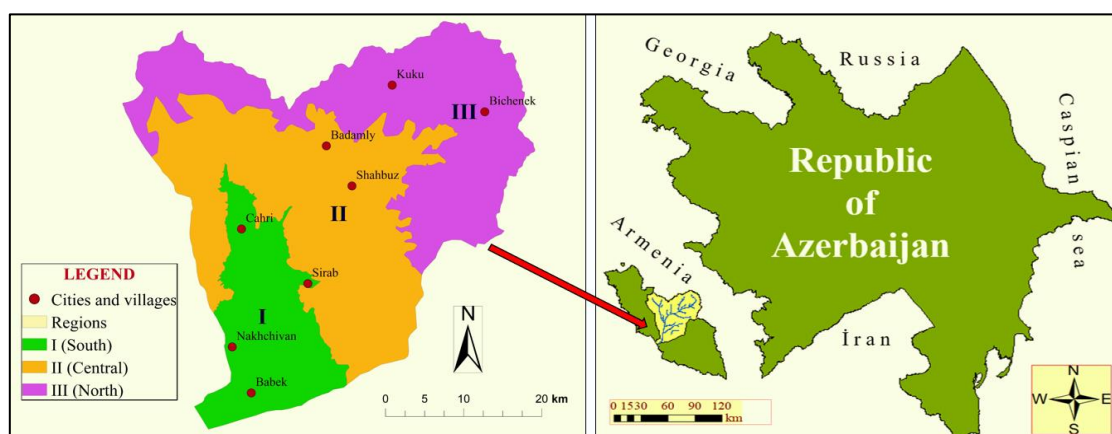
The proposed approach may also help identify “grey zones”: landscapes that appear similar but reflect a combination of natural and anthropogenic influences. A departure of the (f/e) ratio from the characteristic range for an area may signal a change in its internal water balance and warrant further investigation of possible human impacts.

Table 1

Distribution of average annual precipitation according to CFE coefficients

Landscapes (LULC)	HSG	CFE coefficients		
		Surface runoff, c	Effective infiltration (f)	Evapotranspiration (e)
Forests	A	0.085	0.295	0.62
	B	0.10	0.26	0.64
	C	0.115	0.215	0.67
	D	0.125	0.185	0.69
Meadows	A	0.17	0.27	0.56
	B	0.20	0.22	0.58
	C	0.215	0.205	0.58
	D	0.24	0.16	0.60
Cropland	A	0.145	0.255	0.60
	B	0.15	0.22	0.63
	C	0.165	0.175	0.66
	D	0.175	0.125	0.70
Rural settlements	A	0.26	0.26	0.48
	B	0.23	0.21	0.56
	C	0.20	0.17	0.63
	D	0.18	0.14	0.68
Industrial areas	A	0.84	0.080	0.080
	B	0.85	0.065	0.085
	C	0.855	0.050	0.095
	D	0.86	0.040	0.10
Subnival and nival areas	A	0.56	0.11	0.33
	B	0.59	0.09	0.32
	C	0.62	0.07	0.31
	D	0.65	0.05	0.30
Semi-deserts and dry steppes	A	0.075	0.075	0.85
	B	0.0825	0.0325	0.885
	C	0.085	0.015	0.90
	D	0.09	0.008	0.902
Closed water bodies	A	0.00	0.38	0.62
	B	0.00	0.32	0.68
	C	0.00	0.24	0.76
	D	0.00	0.18	0.82

The results were analysed using the Nakhchivanchay catchment in Azerbaijan as a case study. Differences in geographical characteristics and in the intensity of climatic and anthropogenic influences provided the basis for dividing the catchment into three regions: southern, central and northern (Fig. 1).

**Fig. 1.** The Nakhchivanchay catchment and its division into three distinct regions

The CFE coefficients were used to assess moisture conditions in the catchment, estimate its “green water” potential, and examine natural and anthropogenic influences over 1999–2024. The relevance of these changes to ecotourism was assessed through trends in climate, runoff, soil and vegetation cover (Table 2).

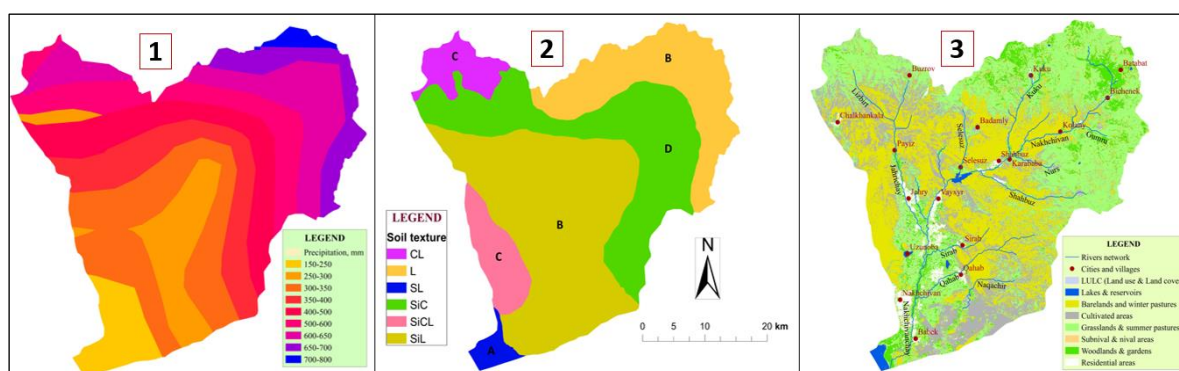
Ecotourism depends on the sustainable use and conservation of landscapes’ natural potential. Figure 2 shows selected environmental components of the three regions in 2024, while Table 3 presents changes in the areas of the predominant landscape types between 1999 and 2024.

Plant diversity contributes to the attractiveness of landscapes for ecotourism and recreation. Changes in vegetation cover in the Nakhchivanchay catchment were therefore examined over the period 1999–2024 (Fig. 3).

Table 2

Quantitative changes in moisture and soil–vegetation resources in the Nakhchivanchay catchment, 1999–2024

Indicator	Southern region		Central region		Northern region	
	Change	%	Change	%	Change	%
Air temperature, °C	+1.4	10.2	+1.01	8.77	+0.43	5.81
Precipitation, mm	-38.7	11.3	-42.9	9.92	-48.2	6.95
Aridity index	+0.41	15.1	+0.26	12.7	+0.061	7.15
Surface runoff, mm	-1.83	6.21	-7.24	23.9	-13.3	11.5
Infiltration, mm	+12.4	21.9	-12.1	27.3	-10.8	7.21
Actual evapotranspiration, mm	-15.7	8.23	+34.3	11.8	+24.1	8.87
Change in vegetation cover, km ²	+61.9	20.1	-98.7	13.9	-25.5	4.21
Soil degradation, km ²	-47.4	15.2	+87.3	12.3	+41.5	7.87
“Green water” resources, million m ³	+8.71	35.7	-36.2	13.1	-21.1	8.97



1 – Precipitation; 2 – Hydrological soil groups (HSGs); 3 – Landscapes and land use/land cover (LULC)

Fig. 2. Maps of selected environmental components in the three regions of the Nakhchivanchay catchment (2024)

Table 3

Changes in landscape area across the three regions of the Nakhchivanchay catchment, 1999–2024 (km²)

Landscapes	Southern region		Central region		Northern region	
	1999	2024	1999	2024	1999	2024
Meadows	61.5	104.2	103.1	61.8	386.9	367.2
Cropland	95.8	71.6	214.7	158.1	57.4	74.9
Forests	28.4	47.6	5.08	5.95	92.6	86.8
Subnival and nival areas	17.8	11.2	24.2	20.3	28.4	26.7
Closed water bodies	2.21	3.08	3.18	6.29	0.545	0.502
Semi-deserts and dry steppes	78.9	32.9	357.8	454.1	35.2	42.7
Residential areas	23.3	37.3	2.73	4.24	4.55	6.85

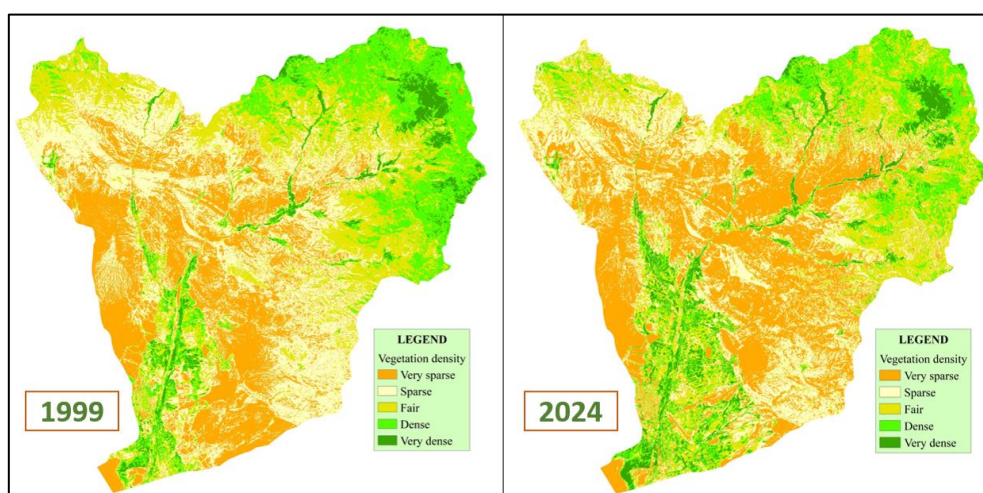


Fig. 3. Spatial and temporal changes in vegetation cover in the Nakhchivanchay catchment between 1999 and 2024

Following the analysis of changes in vegetation cover across the Nakhchivanchay catchment, changes in infiltration ((f)) and evapotranspiration ((e)) under natural and anthropogenic influences were assessed, together with their effects on “green water” resources.

Table 4

Changes in the (f) and (e) coefficients and “green water” resources in the Nakhchivanchay catchment, 1999–2024

Regions	Area, km ²	Precipitation, mm		Change in coefficients		Change in “green water” volume, mln. m ³		
		1999	2024	f	e	f	e	Total
Southern	307.9	342.4	303.7	+0.041	-0.052	+3.85	+4.86	+8.71
Central	710.8	432.3	389.4	-0.043	+0.088	-11.9	-24.3	-36.2
Northern	605.6	693.7	635.5	-0.017	-0.038	-6.54	-14.6	-21.1

Changes in moisture conditions and soil and vegetation cover under climatic and anthropogenic influences are summarised below for the three regions of the Nakhchivanchay catchment over 1999–2024.

1. Southern region. Despite an arid climate and annual precipitation of 303.7 mm in 2024, the analysis attributes 60.3% of the observed change to positive anthropogenic influences, compared with 39.7% to adverse climatic influences. Following greening and afforestation measures, vegetation cover increased by 61.9 km², including an increase in forest area from 28.4 to 47.6 km². Although residential areas expanded from 23.3 to 37.3 km², the area affected by soil degradation decreased by 47.4 km². These changes were accompanied by higher infiltration, lower actual evapotranspiration and an estimated increase of 8.71 million m³ in “green water” resources. According to the study’s counterfactual estimate, forest and meadow area would have declined by an average of 14% without targeted human intervention. Small-scale ecotourism routes could be developed to make use of the region’s natural potential.

2. Central region. Arid conditions and anthropogenic pressures have contributed to ecological degradation in the central region. Both climatic and human factors had adverse effects, with climatic factors accounting for 65.1% of the estimated influence. Vegetation cover declined in areas affected by nomadic livestock grazing and, to a lesser extent, mining, while the share of semi-desert landscapes increased to 21.2%. Plant communities became sparser across 98.7 km², and the area affected by soil degradation increased by 87.3 km². Biomass gains were observed only in localised areas along rivers and around reservoirs. The estimated loss of “green water” resources was 36.2 million m³. Cropland declined from 214.7 to 158.1 km², indicating a reduction in the area available for agriculture. Under these conditions, ecotourism development appears feasible only at selected local sites; degradation associated with land use is a major constraint.

3. Northern region. Landscape degradation was also observed in the northern region despite annual precipitation of 635.5 mm and an aridity index of 0.95. As in the central region, both climatic and anthropogenic factors had adverse effects, although the estimated share of climatic factors was higher, at 76.5%. The areas of

forest, meadow and lake ecosystems declined slightly. Despite an estimated infiltration potential of 149.8 mm, steep slopes and terrain characteristics limited moisture retention in the soil. Over 1999–2024, the region’s “green water” resources decreased by an estimated 21.1 million m³. Although the region’s climatic conditions may support recovery, unregulated settlement and infrastructure development place additional pressure on ecological resilience. Its climate, forests, meadows and lakes remain attractions for ecotourism.

Selection of comparable geospatial areas and their practical significance

Environmental processes are shaped by interacting factors; analysing a poorly understood area therefore requires these factors to be considered together rather than separately (Polazzo et al., 2024). Comparable geospatial areas share relevant physical and geographical characteristics. Remote sensing, geographic information systems (GIS) and other analytical methods can be used to identify such similarities.

The proposed Geospatial Analogue Transfer (GAT) approach transfers environmental indicators from well-studied reference areas to target areas with comparable conditions but limited observations. The transferred information may include physical and biological characteristics relevant to ecogeographical and ecotourism assessments. Reference areas should preferably have long observation records and documented environmental characteristics.

GAT may help reduce the need for intensive monitoring in every target area and support ecosystem management, site selection and the assessment of water, soil and biomass resources. It may be particularly useful for remote or difficult-to-access areas, provided that the similarity between reference and target areas is assessed and the transferred estimates are validated where observations are available.

The role of comparable geospatial areas in ecogeographical and ecotourism assessment

GAT may support ecotourism planning and ecological heritage conservation by identifying areas with terrain and vegetation characteristics comparable to those of established ecotourism routes. Transferring information between such areas can help prioritise potential destinations, plan further surveys and consider environmental sensitivity before infrastructure is developed. In areas with limited data or difficult access, GAT may provide an initial assessment of habitats, natural features requiring protection and the potential pressure associated with tourism. This can inform route selection and preventive conservation measures. Decisions concerning biodiversity and the carrying capacity of sensitive ecosystems should, however, be checked against local observations before implementation.

Multispectral analysis of satellite imagery and geospatial processing in ArcGIS identified nine ecosites with similar natural characteristics (Fig. 4). Their locations and selected geospatial attributes are presented in Table 4.

Four of the selected ecosites are in Azerbaijan, while the other five are in resort and recreational areas of neighbouring countries. They were selected for comparative ecogeographical, ecotourism and ecological heritage (“green heritage”) assessments (GreenHeritage, 2023; Imrani et al., 2024).

The selection considered mountain and riverside scenery, forest landscapes, climate and moisture conditions, slope aspect, geological structure, slope gradient and other comparable characteristics (Fig. 5).

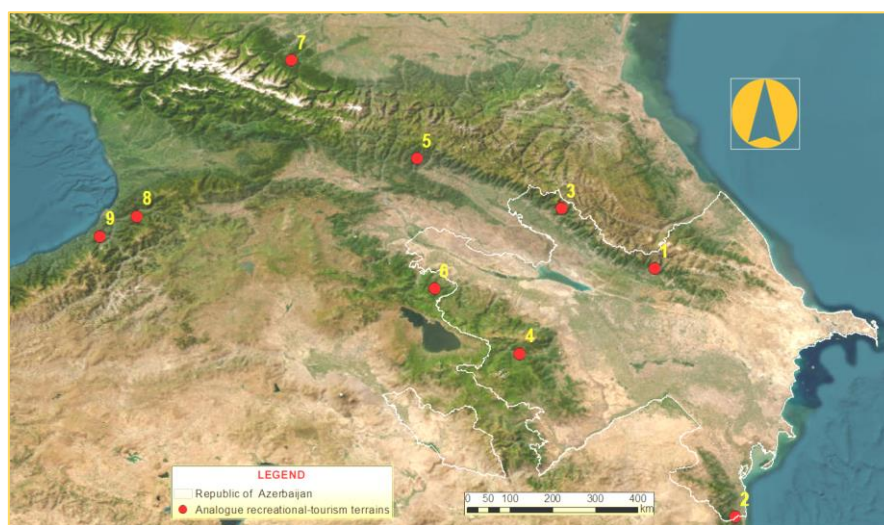
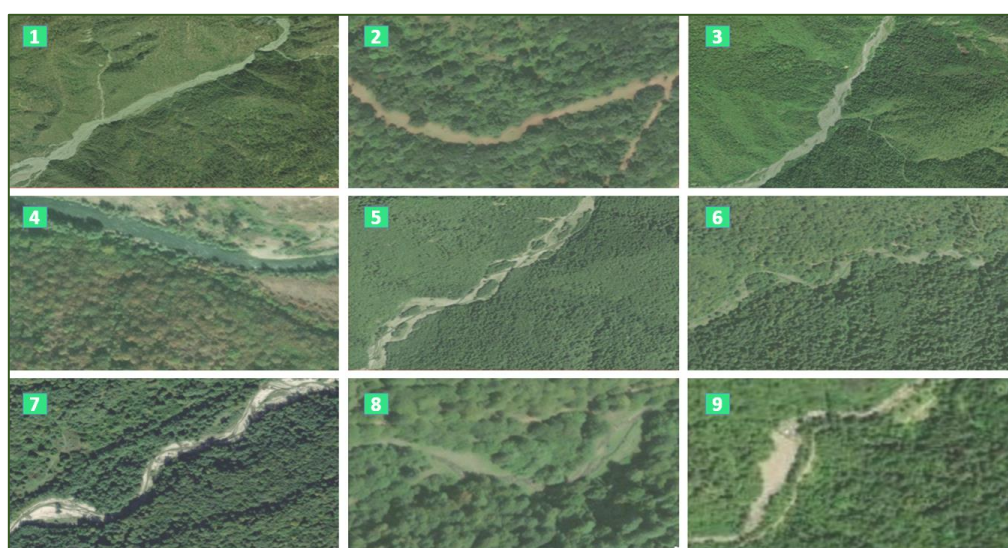


Fig. 4. Locations of the analogous ecosites

Table 4

Geographical coordinates and selected geospatial attributes of the ecosites

Ecosites	Country	Region	X coordinate	Y coordinate	Area, m ²
E1	Azerbaijan	Qabala	47.844	41.032	539
E2	Azerbaijan	Astara	48.757	38.435	496
E3	Azerbaijan	Zagatala	46.785	41.661	547
E4	Azerbaijan	Kalbajar	46.314	40.143	463
E5	Georgia	Akhmeta	45.149	42.186	522
E6	Armenia	Tavush	45.351	40.825	507
E7	Russia	Alania	43.723	43.211	553
E8	Georgia	Batumi	41.973	41.580	482
E9	Turkiye	Artvin	41.554	41.369	518

**Fig. 5.** Analogous ecosites selected from different regions

Considering a wider range of environmental factors can improve the selection of comparable ecosites. Monitoring conducted during 2023–2025 indicated substantial similarity among the selected sites in climate, landscape and vegetation cover, soil and geological characteristics, slope gradient, aridity index and slope aspect. Table 5 presents selected morphometric, climate, moisture, soil and vegetation characteristics of the ecosites.

Table 5

Comparison of key ecogeographical characteristics of the ecosites

Ecosite	Elevation (m)	Slope (%)	Two pre-dominant HSGs	Temperature (°C)	Precipitation (mm)	Moisture co-efficient	Forest cover (%)
E1	681	19.2	BC	11.2	962	1.31	84.2
E2	-21	11.7	CD	14.3	1236	1.57	86.4
E3	496	22.5	BC	11.9	958	1.43	88.7
E4	1575	31.2	DC	8.2	728	0.96	77.6
E5	563	16.4	BC	11.7	795	1.07	85.8
E6	976	25.3	CB	10.2	635	1.22	91.2
E7	1165	28.5	DC	7.4	842	1.18	85.5
E8	-5	17.8	DC	14.0	2340	2.48	86.3
E9	342	18.3	CD	12.3	945	1.42	79.6

GAT can support comparisons of the historical ecogeographical development of ecosystems and geosites that appear similar but have followed different trajectories, provided that suitable records are available. Such comparisons may help distinguish climatic from anthropogenic contributions to landscape change and inform assessments of ecosystem resilience and recreational carrying capacity.

With appropriate wildlife movement and land-use data, geospatial analysis could also help identify potential ecological corridors between fragmented habitats and assess pressures from human activity. These applications may support geomonitoring, geoheritage assessment and planning to restore favourable moisture conditions, but proposed corridors and management measures require validation with local evidence.

Conclusion

The CFE approach uses the balance among surface runoff, effective infiltration and actual evapotranspiration to assess landscape moisture conditions. The infiltration–evapotranspiration ratio ((f/e)) provides an indicator for examining changes in soil moisture and ecosystem conditions. Analysis of the Nakhchivanchay catchment showed that climatic and anthropogenic influences varied across its three regions during 1999–2024.

In the southern region, greening and afforestation coincided with an estimated increase of 8.71 million m³ in “green water” resources despite declining precipitation. In the central region, where the estimated contribution of climatic factors was 65.1%, vegetation loss and soil degradation accompanied a decrease of 36.2 million m³. In the northern region, the estimated climatic contribution was 76.5%, and “green water” resources declined by 21.1 million m³ despite comparatively higher precipitation.

Geospatial Analogue Transfer (GAT) offers a way to use information from well-studied areas when assessing comparable areas with limited observations. Combined with the CFE approach, it can support the identification of areas requiring conservation or more detailed ecotourism assessment. Its application to other regions depends on the comparability of their environmental conditions and validation against local data.

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ЭКОГЕОГРАФИЧЕСКАЯ И ЭКОТУРИСТИЧЕСКАЯ УСТОЙЧИВОСТЬ: ПРОСТРАНСТВЕННАЯ ОЦЕНКА ДИНАМИКИ УВЛАЖНЕНИЯ ТЕРРИТОРИЙ И ТРАНСФОРМАЦИИ ЛАНДШАФТОВ

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Резюме. В исследовании использованы модель CFE и технология геопространственного аналогового переноса (Geospatial Analogue Transfer, GAT) для оценки эколого-географических условий и условий развития экотуризма в Азербайджане. Основанная на принципе соотношения тепла и влаги модель CFE позволяет оценивать распределение годовой суммы атмосферных осадков между поверхностным стоком, эффективной инфильтрацией и фактической эвапотранспирацией. Соотношение инфильтрации и эвапотранспирации используется для характеристики режима увлажнения ландшафтов, их потенциальной биологической продуктивности и устойчивости экосистем. Технология GAT предусматривает перенос показателей с хорошо изученных эталонных территорий на недостаточно изученные территории со сходными природными условиями.

Для определения коэффициентов CFE и анализа взаимосвязей между компонентами природной среды в геоинформационной системе были интегрированы гидрометеорологические данные, сведения о почвах, землепользовании и земельном покрове, а также характеристики рельефа, полученные более чем на 70 пунктах измерений и мониторинга. Предложенный подход также применялся для оценки трансформации ландшафтов и выявления территорий, требующих дополнительного изучения возможного антропогенного воздействия. Проверка модели на данных приблизительно 70 водосборных бассейнов показала значения коэффициента детерминации (R^2) в диапазоне 0,74–0,93 и коэффициента эффективности Нэша — Сатклиффа (NSE) в пределах 0,62–0,77.

Применение разработанного подхода к бассейну реки Нахчыванчай за период 1999–2024 гг. выявило пространственную неоднородность изменений природных условий под влиянием климатических и антропогенных факторов, включая существенные различия в состоянии растительного покрова, деградации почв, инфильтрации, эвапотранспирации и запасах «зеленой воды». Комплексное применение модели CFE и технологии GAT формирует количественную основу для оценки устойчивости ландшафтов и рекреационной ёмкости территорий, выявления потенциальных экологических коридоров, а также научного обоснования мер по сохранению и устойчивому управлению природными ландшафтами и экологическим наследием.

Ключевые слова: устойчивость экосистем, модель CFE, геопространственный аналоговый перенос, трансформация ландшафтов, экотуризм, Азербайджан

EKOĞRAFI VƏ EKOTURİZM DAYANIQLILIĞI: REGIONAL RÜTUBƏT DİNAMİKASININ VƏ LANDŞAFT TRANSFORMASIYALARININ MƏKAN ÜZRƏ QIYMƏTLƏNDİRİLMƏSİ

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Xülasə. Tədqiqatda Azərbaycanda ekoloqrafi şəraitin və ekoturizmin inkişaf imkanlarının qiymətləndirilməsi məqsədilə CFE modeli və Geoməkan Analox Transferi (Geospatial Analogue Transfer, GAT) texnologiyasından istifadə edilmişdir. İstilik və rütubət arasındakı qarşılıqlı əlaqə prinsipinə əsaslanan CFE modeli illik atmosfer yağıntılarının səthi axım, effektiv infiltrasiya və faktiki

evapotranspirasiya arasında paylanmasını qiymətləndirməyə imkan verir. İnfiltrasiya və evapotranspirasiya arasındakı nisbətdən landşaftların rütubət rejiminin, potensial bioloji məhsuldarlığının və ekosistemlərin dayanıqlılığının səciyyələndirilməsi üçün istifadə olunur. GAT texnologiyası yaxşı öyrənilmiş etalon ərazilərin göstəricilərinin oxşar təbii şəraitə malik, lakin kifayət qədər tədqiq edilməmiş ərazilərə köçürülməsini nəzərdə tutur.

CFE əmsallarının müəyyənəşdirilməsi və təbii mühit komponentləri arasındakı qarşılıqlı əlaqələrin təhlili məqsədilə 70-dən çox ölçmə və monitorinq məntəqəsindən əldə edilmiş hidrometeoroloji məlumatlar, torpaqlar, torpaqdan istifadə və yer örtüyü, eləcə də relyef xüsusiyyətlərinə dair göstəricilər coğrafi informasiya sistemində inteqrasiya edilmişdir. Təklif olunan yanaşma landşaft transformasiyalarının qiymətləndirilməsi və mümkün antropogen təsirlərin əlavə tədqiqini tələb edən ərazilərin müəyyənəşdirilməsi üçün də tətbiq edilmişdir. Təxminən 70 su hövzəsinin məlumatları əsasında aparılmış modelin yoxlanılması nəticəsində determinasiya əmsalının (R^2) 0,74–0,93, Neş–Satkliiff səmərəlilik əmsalının (NSE) isə 0,62–0,77 intervalında dəyişdiyi müəyyən edilmişdir.

Hazırlanmış yanaşmanın 1999–2024-cü illər üzrə Naxçıvançay hövzəsinə tətbiqi iqlim və antropogen amillərin təsiri altında təbii şəraitdə baş verən dəyişikliklərin məkan üzrə qeyri-bərabər xarakter daşdığını üzə çıxarmışdır. Bu dəyişikliklər bitki örtüyünün vəziyyətində, torpaq degradasiyasında, infiltrasiya və evapotranspirasiya proseslərində, həmçinin «yaşıl su» ehtiyatlarında əhəmiyyətli fərqlərlə müşayiət olunmuşdur. CFE modeli ilə GAT texnologiyasının kompleks tətbiqi landşaftların dayanıqlılığının və ərazilərin rekreasiya tutumunun qiymətləndirilməsi, potensial ekoloji dəhlizlərin müəyyənəşdirilməsi, eləcə də təbii landşaftların və ekoloji irsin mühafizəsi və davamlı idarə olunması tədbirlərinin elmi əsaslandırılması üçün kəmiyyət əsaslı metodoloji baza formalaşdırır.

Açar sözlər: ekosistem dayanıqlılığı, CFE modeli, Geoməkan Analoz Transferi, landşaft transformasiyası, ekoturizm, Azərbaycan