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

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Keywords: *ecosystem resilience, CFE model, Geospatial Analogue Transfer, landscape transformation, ecotourism, Azerbaijan*

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 hydropedological 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 (Mahmudov & 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).

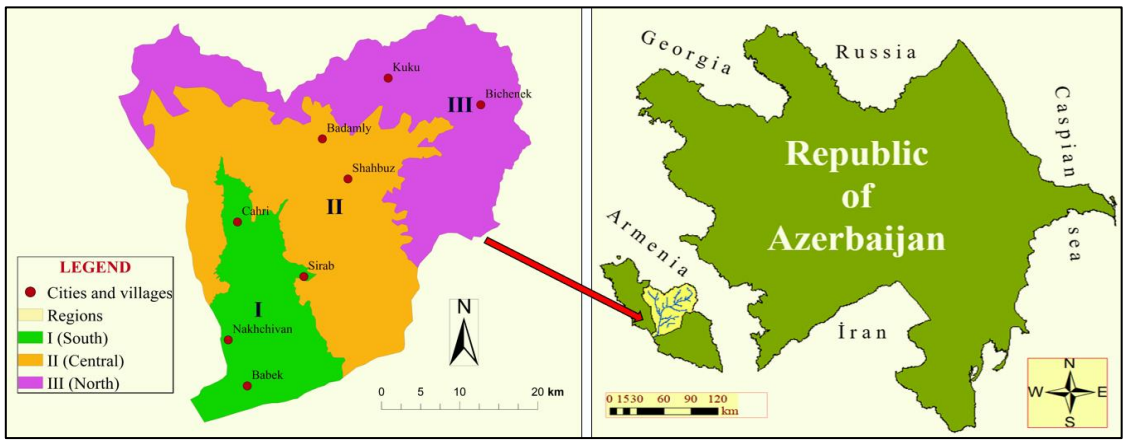


Fig. 1. The Nakhchivanchay catchment and its division into three distinct regions

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).

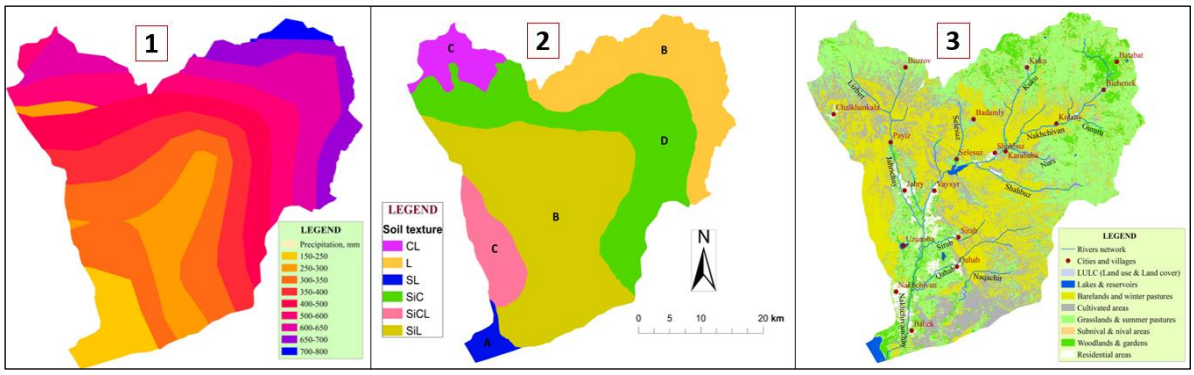
Ecotourism depends on the sustainable use and conservation of landscapes' natural potential. Figure 2 shows selected environmental components of the three regions in 2024, while Table 3 presents changes in the areas of the predominant landscape types between 1999 and 2024.

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, km²	+61.9	20.1	-98.7	13.9	-25.5	4.21
Soil degradation, km²	-47.4	15.2	+87.3	12.3	+41.5	7.87
"Green water" resources, million m³	+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

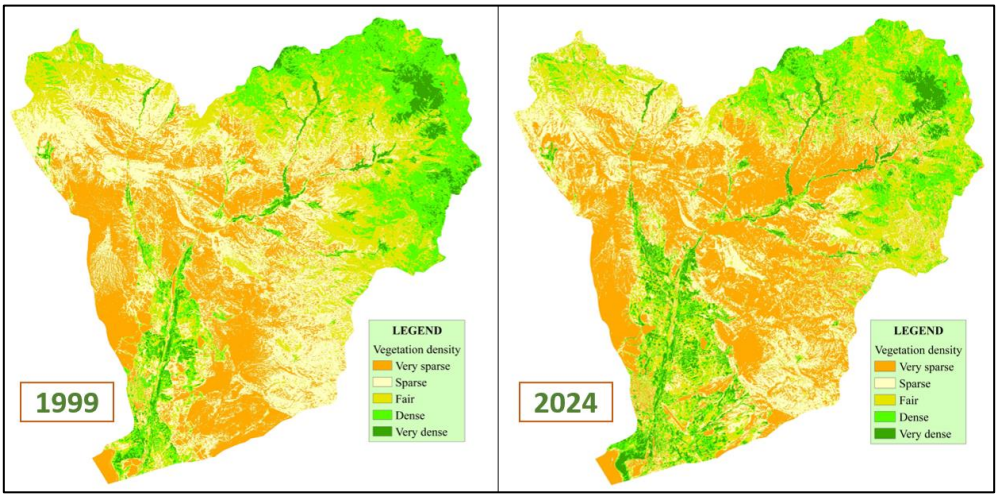


Fig. 3. Spatial and temporal changes in vegetation cover in the Nakhchivanchay catchment between 1999 and 2024

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, km²	Precipitation, mm		Change in coefficients		Change in "green water" volume, mln. m³		
		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).

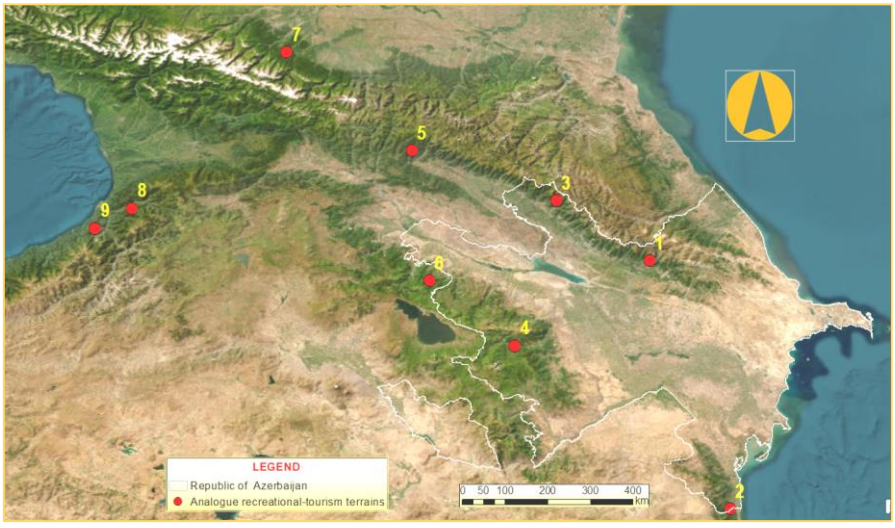


Fig. 4. Locations of the analogous ecosites

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

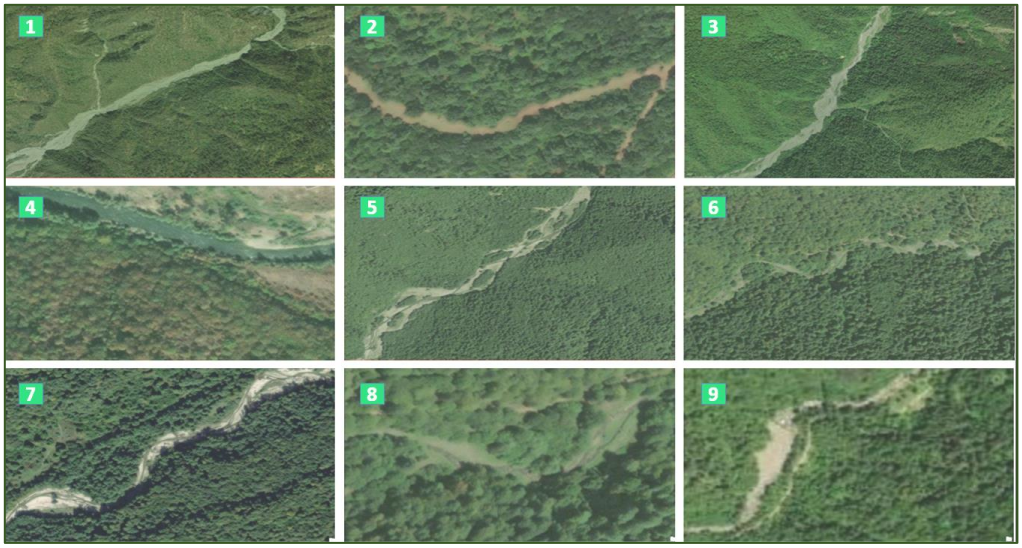


Fig. 5. Analogous ecosites selected from different regions

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 predominant HSGs	Temperature (°C)	Precipitation (mm)	Moisture coefficient	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 «зелёной 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*

EKOCOĞRAFI VƏ EKOTURIZM DAYANIQLILIĞI: REGIONAL RÜTUBƏT DINAMIKASININ VƏ LANDŞAFT TRANSFORMASIYALARININ MƏKAN ÜZRƏ QIYMƏTLƏNDIRILMƏSI

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Xülasə. Tədqiqatda Azərbaycanda ekocoğrafi şəraitin və ekoturizmin inkişaf imkanlarının qiymətləndirilməsi məqsədilə CFE modeli və Geoməkan Analoq 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 müəyyənləşdirilməsi 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 müəyyənləşdirilməsi üçün də tətbiq edilmişdir. Təxminən 70 su hövzəsinin məlumatları əsasında aparılmış modelin yoxlanılması nəticəsində determinasiya əmsalının (R^2) 0,74–0,93, Neş–Satkliff 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 daşıdığını üzə çıxarmışdır. Bu dəyişikliklər bitki örtüyünün vəziyyətində, torpaq deqradasiyasında, 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 müəyyənləşdirilməsi, 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 Analoq Transferi, landşaft transformasiyası, ekoturizm, Azərbaycan*

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SPATIAL DISTRIBUTION AND DIFFERENTIATION OF NATURAL LANDSCAPES IN THE MOUNTAINOUS AREAS OF THE GREATER CAUCASUS WITHIN AZERBAIJAN

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Keywords: *Greater Caucasus, natural landscapes, altitudinal zonation, landscape differentiation, slope aspect, GIS, Azerbaijan*

Summary. This study examines the distribution and differentiation of natural landscapes in the mountainous areas of the Greater Caucasus within Azerbaijan. The analysis integrates landscape, cartographic, comparative-geographical, field and GIS-based approaches with climatic data, satellite imagery and digital elevation models. The results show that altitudinal zonation is the principal regularity of landscape distribution, modified by slope aspect, relief, geological-lithological conditions, moisture regime and west–east climatic gradients. The landscape sequence extends from low-mountain and mountain-steppe complexes through mountain forests, subalpine and alpine meadows to subnival and nival landscapes. Meteorological data confirm pronounced vertical climatic differentiation: mean February temperature reaches −7.9°C at Gyriz, whereas the highest summer value is 26.4°C at Shabran. Landscape-belt boundaries vary between northern and southern slopes and between the humid western and increasingly arid eastern sectors. The study demonstrates that integrating field observations with GIS, satellite imagery and digital elevation models improves the identification of landscape boundaries, particularly in inaccessible high-mountain areas.

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Introduction

The Greater Caucasus is one of the major mountain systems of Eurasia and is characterized by considerable geological, geomorphological and climatic diversity. Within its Azerbaijani sector, substantial variations in elevation, temperature, precipitation, soil and vegetation over relatively short distances produce complex vertical and horizontal landscape differentiation.

Altitudinal zonation is the principal regularity governing mountain landscape distribution. Increasing elevation modifies temperature, moisture, snow cover, soil-forming processes and vegetation, resulting in the successive replacement of natural landscape belts. However, their boundaries are not uniform and vary according to slope aspect, relief, geological substrate and regional climatic conditions (Suleymanov, 2008). The theoretical foundations of mountain landscape studies were established through the concepts of altitudinal zonation and landscape integrity developed by Humboldt, Berg and Solntsev (Humboldt, 1849; Solntsev, 1973). Contemporary landscape research increasingly integrates these principles with GIS, satellite imagery and digital elevation models.

Studies in Azerbaijan have examined the geomorphology, physical geography, landscape structure, soil and vegetation of the Greater Caucasus. Museyibov (1998) analysed the physical-geographical differentiation of Azerbaijan, while subsequent landscape studies contributed to understanding altitudinal belts and their spatial structure. Nevertheless, the degree of investigation remains uneven, particularly in inaccessible high-mountain, subnival and nival areas where field observations and meteorological data are limited.

Remote sensing, GIS and digital elevation models provide opportunities to refine landscape boundaries and examine elevation, slope and aspect in areas where field investigation is difficult. However, satellite

observations cannot fully replace ground-based landscape surveys, making the integration of field and geospatial methods particularly important.

Accordingly, this study aims to identify the principal regularities governing the distribution of natural landscapes in the mountainous areas of the Greater Caucasus within Azerbaijan. Particular attention is given to altitudinal zonation, horizontal differentiation, slope aspect, climatic gradients and the distribution of major landscape belts, as well as to the application of contemporary geospatial methods for improving their assessment.

Materials and methods

The study combines field, comparative-geographical, cartographic, analytical and GIS-based methods to investigate the distribution and differentiation of natural landscapes in the mountainous areas of the Greater Caucasus. Field observations were used to examine relief, soil, vegetation and hydrological conditions across different altitudinal belts, while comparative analysis was applied to identify differences between northern and southern slopes and between western and eastern sectors.

Cartographic materials, satellite imagery and digital elevation models (DEMs) were used to analyse landscape distribution and determine elevation, slope inclination and aspect. GIS enabled the integration of geological, geomorphological, climatic, soil and vegetation data and supported the refinement of landscape boundaries, particularly in high-mountain and less accessible areas. The combined use of geospatial and environmental data provides a more comprehensive basis for landscape assessment (Mammadova et al., 2022; Mammadova et al., 2025).

Monthly mean temperature data from Guba, Altiaghac, Shabran, Khaltan, Gyriz and Gusar stations were analysed to assess climatic differentiation within the study area. The integration of field observations, climatic data and geospatial methods was used to evaluate the effects of altitudinal zonation, horizontal differentiation and slope aspect on landscape distribution.

Results and discussion

The distribution of natural landscapes in the mountainous areas of the Greater Caucasus is controlled by the combined influence of elevation, relief, climate, geological-lithological conditions, slope aspect, soil, vegetation and hydrology. These factors interact spatially, producing pronounced vertical and horizontal differentiation. Relief is particularly important because mountain ranges, valleys, intermontane depressions and slope inclination modify temperature, precipitation, runoff, soil development and vegetation patterns (Museyibov, 1998).

Altitudinal zonation is the principal regularity of landscape distribution. With increasing elevation, declining temperature and changes in moisture conditions lead to the successive replacement of low-mountain and mountain-steppe landscapes by mountain forests, subalpine and alpine meadows, and finally subnival and nival complexes (Museyibov, 1998; Suleymanov, 2008). However, landscape-belt boundaries are not uniform throughout the region and vary according to local relief, slope aspect and climatic conditions.

Slope aspect produces substantial differences in landscape structure. South-facing slopes generally receive greater solar radiation and are therefore warmer and relatively drier, whereas north-facing slopes tend to maintain lower temperatures and higher moisture levels. These contrasts influence soil development, vegetation composition and the elevation of forest and meadow boundaries. Consequently, the same landscape belt may occur at different elevations on opposing slopes.

A pronounced west–east differentiation is also observed. The western sector is generally more humid and supports more extensive forest landscapes, whereas increasing continentality and aridity toward the east favour mountain-steppe and xerophytic complexes. Geological structure further modifies these patterns: lithology and rock resistance influence relief development, soil formation, erosion and landslide processes, while river valleys generate localized intrazonal landscape complexes (Gurbanov, 2015; Museyibov, 1998).

The Azerbaijani sector of the Greater Caucasus therefore contains a complex sequence of **l**ow-mountain, mountain-forest, subalpine, alpine, subnival and nival landscapes. High-mountain areas around peaks such as Bazardüzü, Shahdagh and Tufandag are characterized by severe climatic conditions, prolonged snow cover, rocky surfaces and high-mountain meadow complexes, while forest landscapes are concentrated mainly within the middle-mountain belt (Museyibov, 1998). Vegetation distribution also provides an important indicator of landscape differentiation, particularly in forest and high-mountain environments (Yusifov, 2005).

Climate is one of the principal factors governing landscape formation. Temperature and precipitation determine soil-forming processes, vegetation cover, and the hydrological regime. In the Greater Caucasus, climate varies depending on elevation, slope aspect, and the position of mountain ranges relative to prevailing air masses. Temperature decreases with increasing elevation. As temperature decreases, the growing season becomes shorter and the composition of vegetation cover changes. While thermophilic and drought-resistant

plants predominate in low-mountain areas, cold-tolerant alpine and subnival plant communities are distributed in high-mountain areas. The amount and seasonal distribution of atmospheric precipitation also influence the distribution of landscapes. Forest landscapes develop extensively in humid areas, whereas mountain-steppe and xerophytic plant communities predominate in arid areas (Table 1, Figure 1).

Analysis of the monthly mean temperatures at Guba, Altiaghac, Shabran, Khaltan, Gyriz and Gusar stations reveals pronounced seasonal and altitudinal climatic differentiation (Table 1; Figure 1). The lowest mean temperature occurs at Gyriz in February (−7.9°C), followed by Khaltan (−5.4°C), whereas Shabran records a considerably higher February value of −0.2°C. During summer, the highest July temperature is observed at Shabran (26.4°C), while Gyriz remains substantially cooler at 16.0°C. Shabran also exhibits the greatest annual temperature range, 26.6°C, from −0.2°C in February to 26.4°C in July. These differences primarily reflect variations in absolute elevation, relief and local climatic conditions and confirm the importance of vertical climatic differentiation in the formation and distribution of mountain landscapes.

Table 1

Monthly Mean Temperature Values (°C) for Districts and Stations Located in the Mountainous Areas of the Greater Caucasus

Region	Jan	Feb	Mart	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Guba	3,1	−1,9	8,2	11,3	16,2	19,8	24,6	24,2	16,8	12,7	9,9	3,4
Altiaghac	1,6	−4,3	6,1	10,5	14,7	16,2	20,9	21,4	14,0	11,4	10,0	1,2
Shabran	4,0	−0,2	7,7	12,0	17,4	21,4	26,4	26,1	19,0	14,6	10,9	5,5
Khaltan	0,2	−5,4	4,9	10,3	14,6	16,3	21,3	22,3	14,0	10,9	7,1	0,0
Gyriz	−1,4	−7,9	2,1	6,2	10,7	10,9	16,0	16,5	9,4	8,3	6,8	−2,2
Gusar	2,5	−2,7	7,4	10,6	15,7	18,3	23,2	22,9	15,6	11,6	8,9	2,2

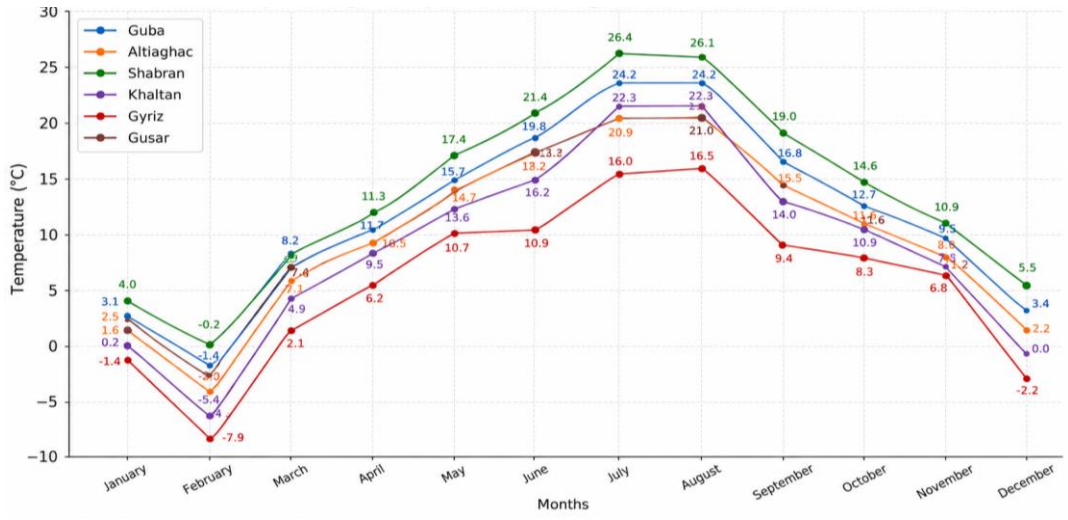


Fig. 1. Monthly average temperature of regions in the Greater Caucasus

Slope aspect plays an important role in the distribution of mountain landscapes. South-facing slopes receive greater solar radiation and are generally characterized by higher temperatures, more intensive evaporation, and lower soil moisture, whereas north-facing slopes are cooler and more humid, with longer-lasting snow cover. These differences influence vegetation distribution and the elevation of the forest boundary, which may extend higher on humid and shaded slopes than on sunny and dry slopes.

Soil and vegetation cover also vary considerably with altitude. Relatively dry soils occur in low-mountain areas, mountain-forest soils predominate in the middle-mountain belt, and mountain-meadow soils are widespread in the subalpine and alpine belts. Vegetation responds sensitively to changes in climatic and soil conditions and therefore serves as an important indicator of landscape differentiation. The forest, subalpine, and alpine landscapes of the Greater Caucasus are characterized by rich flora and numerous endemic species (Yusifov, 2005).

Overall, altitudinal zonation is the principal regularity governing the distribution of natural landscapes in the mountainous areas of the Greater Caucasus. As elevation increases, changes in climatic conditions lead to the successive replacement of soil and vegetation cover and the formation of distinct landscape belts along the altitudinal gradient (Figure 2).

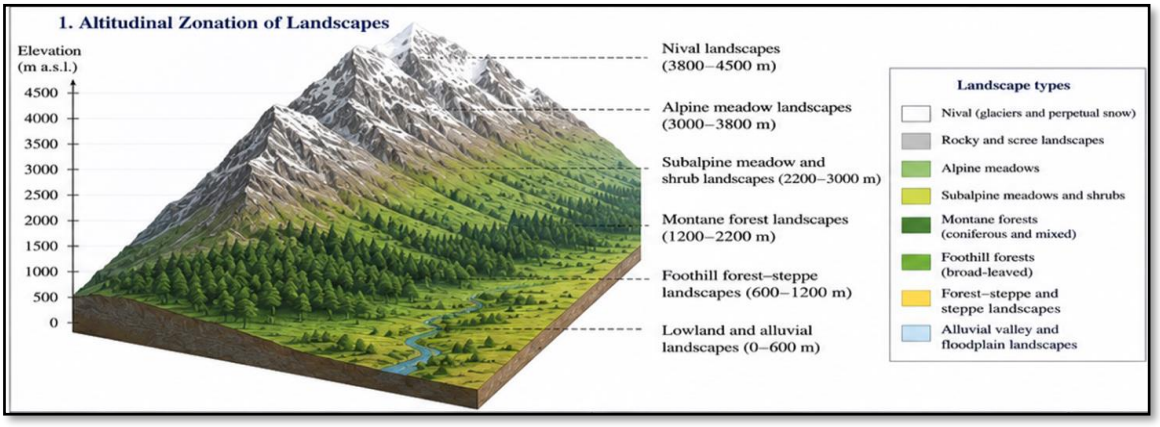


Fig. 2. Natural landscapes of the mountainous areas of the Greater Caucasus region.

As shown in Figure 2, the natural landscapes of the Greater Caucasus exhibit a distinct altitudinal sequence, extending from dry low-mountain and mountain-steppe complexes through mountain forests and subalpine and alpine meadows to subnival, nival, and rocky landscapes. The boundaries of these belts vary according to relief, slope aspect, geological conditions, and regional climatic differences.

In addition to altitudinal zonation, pronounced horizontal and sectoral differentiation occurs across the region. The western part is generally more humid and supports more extensive forest and meadow landscapes, whereas increasing continentality and aridity toward the east restrict forest distribution and favor dry mountain-steppe and xerophytic complexes. Slope aspect further modifies this pattern: south-facing slopes are generally warmer and drier because of greater solar radiation, while north-facing slopes are cooler and more humid. Local geomorphological and hydrological conditions, including river valleys, rocky areas, and landslide zones, also contribute to the formation of intrazonal and azonal landscape complexes.

The low-mountain belt encompasses foothill and relatively low-elevation areas characterized by comparatively warm and dry conditions. Mountain-steppe, shrub, and drought-resistant vegetation complexes predominate. In humid areas, forests may begin at lower elevations, whereas in arid sectors mountain-steppe landscapes may extend higher. Relief dissection and local climatic conditions further increase landscape variability within this belt.

The middle-mountain belt represents the principal zone of forest landscapes. Favorable temperature and moisture conditions support oak, hornbeam, beech, maple, and other woody species. Forest composition and belt boundaries vary with elevation, slope aspect, and moisture conditions; forests are generally more extensive on humid slopes, whereas on drier slopes they become more open and may be replaced by mountain-steppe complexes (Museyibov, 1998).

The subalpine belt forms a transition between mountain forests and alpine meadows and is characterized by tall-grass meadows, shrub communities, and diverse herbaceous vegetation. Compared with lower elevations, climatic conditions are cooler and more humid and the growing season is shorter. Its lower and upper boundaries vary according to relief and slope aspect.

The alpine belt is characterized by low-growing meadow vegetation, low temperatures, a short growing season, strong winds, and high solar radiation. Woody vegetation is absent, while numerous endemic and relict plant species adapted to high-mountain conditions increase the biogeographical significance of these landscapes.

The subnival belt occurs between alpine meadows and areas of persistent snow and ice. Severe climatic conditions and a very short growing season result in sparse vegetation concentrated mainly in rock fissures, stony surfaces, and relatively stable soil patches. Its boundaries depend on elevation, slope aspect, and the duration of snow cover.

The nival belt occupies the highest parts of the Greater Caucasus and is dominated by long-lasting snow cover, glacial areas, rocky surfaces, and stony terrain. Soil and vegetation are poorly developed, while physical weathering and freeze–thaw processes are dominant. The distribution of these uppermost high-mountain landscapes is controlled primarily by elevation, high-peak distribution, and climatic conditions (Museyibov, 1998; Suleymanov, 2005, 2008).

Regional differences modify this general altitudinal sequence. The western Greater Caucasus is more humid, with more extensive and continuous forest landscapes and widespread subalpine and alpine meadows.

The central sector is characterized by strongly dissected high-mountain relief, deep river valleys, and extensive alpine, subnival, and nival complexes. Toward the eastern sector, increasing aridity and continentality favor dry mountain-steppe and xerophytic landscapes, while forests become increasingly restricted to humid areas and favorable slopes.

On the northeastern slope, landscape differentiation is additionally influenced by the Caspian Sea, regional atmospheric processes, local orography, and differences among individual river basins. Previous research on the northern slope of the Greater Caucasus similarly demonstrates substantial differentiation of mountain landscapes according to elevation and regional moisture conditions (Bratkov & Ataev, 2013).

The southern slope, in contrast, is strongly affected by the orographic influence of humid air masses and higher solar radiation, producing differences in thermal and moisture conditions and consequently in the elevation of landscape-belt boundaries.

Conclusion

The distribution of natural landscapes in the mountainous areas of the Greater Caucasus is governed primarily by altitudinal zonation, modified by regional climatic conditions, relief, geological-lithological structure, and slope aspect. With increasing elevation, low-mountain and mountain-steppe landscapes are successively replaced by mountain forests, subalpine and alpine meadows, and subnival and nival complexes. However, the boundaries of these landscape belts vary spatially according to local physical-geographical conditions.

Landscape distribution also demonstrates pronounced horizontal and sectoral differentiation. Increasing continentality and decreasing moisture from west to east favor the transition from more humid forest landscapes to dry mountain-steppe and xerophytic complexes. Differences in solar radiation, temperature, and moisture between northern and southern slopes further modify the elevation and spatial extent of individual landscape belts.

The interaction of geological structure, relief, climate, hydrological conditions, soil, and vegetation also contributes to local landscape differentiation, including the formation of intrazonal and azonal complexes in river valleys, rocky areas, and other distinctive landforms. The combined use of field observations, satellite imagery, digital elevation models, and GIS improves the identification and assessment of landscape boundaries, particularly in less accessible high-mountain areas. The development of a unified digital landscape database for the mountainous Greater Caucasus would provide an important basis for further landscape research.

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ПРОСТРАНСТВЕННОЕ РАСПРЕДЕЛЕНИЕ И ДИФФЕРЕНЦИАЦИЯ ПРИРОДНЫХ ЛАНДШАФТОВ ГОРНЫХ ТЕРРИТОРИЙ БОЛЬШОГО КАВКАЗА В ПРЕДЕЛАХ АЗЕРБАЙДЖАНА

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Резюме. В исследовании рассматриваются особенности распространения и дифференциации природных ландшафтов горных территорий Большого Кавказа в пределах Азербайджана. Анализ основан на комплексном применении ландшафтоведческого, картографического, сравнительно-географического, полевого и геоинформационного методов с использованием климатических данных, спутниковых снимков и цифровых моделей рельефа. Результаты исследования показывают, что основной закономерностью пространственного распределения ландшафтов является высотная поясность, проявление которой определяется экспозицией склонов, особенностями рельефа, геолого-литологическими условиями, режимом увлажнения и климатическими градиентами в направлении с запада на восток. Высотно-поясная последовательность ландшафтов охватывает низкогорные и горно-степные комплексы, горные леса, субальпийские и альпийские луга, а также субнивальные и нивальные ландшафты. Метеорологические данные подтверждают выраженную вертикальную климатическую дифференциацию. Так, средняя температура февраля в Грызе достигает −7,9°C, тогда как максимальное значение температуры в летний период отмечается в Шабране и составляет 26,4°C. Границы ландшафтных поясов различаются на северных и южных склонах, а также между увлажнёнными западными и постепенно приобретающими более аридный характер восточными секторами исследуемой территории. Установлено, что интеграция полевых наблюдений с геоинформационными технологиями, спутниковыми снимками и цифровыми моделями рельефа способствует более точному определению границ ландшафтов, особенно в труднодоступных высокогорных районах.

Ключевые слова: *Большой Кавказ, природные ландшафты, высотная поясность, ландшафтная дифференциация, экспозиция склонов, ГИС, Азербайджан*

BÖYÜK QAFQAZIN AZƏRBAYCAN ƏRAZİSİNDƏKİ DAĞLIQ SAHƏLƏRİNDƏ TƏBİİ LANDŞAFTLARIN YAYILMASI VƏ DİFERENSİASİYASI

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Xülasə. Tədqiqatda Böyük Qafqazın Azərbaycan ərazisindəki dağlıq sahələrində təbii landşaftların yayılması və diferensiasiyası araşdırılır. Təhlildə landşaft, kartoqrafik, müqayisəli-coğrafi, çöl və CİS əsaslı yanaşmalar iqlim məlumatları, peyk təsvirləri və rəqəmsal yüksəklik modelləri ilə birləşdirilir. Nəticələr göstərir ki, hündürlük qurşaqlığı landşaftların yayılmasının əsas qanunauyğunluğudur və yamacların baxarlığı, relyef, geoloji-litoloji şərait, rütubət rejimi və qərbdən şərqə doğru iqlim dəyişikliklərinin təsiri ilə fərqli xüsusiyyətlər qazanır. Landşaft ardıcıllığı alçaqdağlıq və dağ-çöl komplekslərindən başlayaraq dağ meşələri, subalp və alp çəmənlikləri vasitəsilə subnival və nival landşaftlara qədər uzanır. Meteoroloji məlumatlar şaquli istiqamətdə nəzərəçarpan iqlim diferensiasiyasını təsdiqləyir: Qrızda fevral ayının orta temperaturu −7,9 °C-yə çatır, ən yüksək yay göstəricisi isə Şabranda 26,4 °C təşkil edir. Landşaft qurşaqlarının sərhədləri şimal və cənub yamacları, həmçinin rütubətli qərb və şərqə doğru aridliyi artan sektorlar arasında fərqlənir. Tədqiqat göstərir ki, çöl müşahidələrinin CİS, peyk təsvirləri və rəqəmsal yüksəklik modelləri ilə inteqrasiyası xüsusilə əlçatmaz yüksəkdağlıq sahələrdə landşaft sərhədlərinin müəyyənləşdirilməsini təkmilləşdirir.

Açar sözlər: *Böyük Qafqaz, təbii landşaftlar, hündürlük qurşaqlığı, landşaft diferensiasiyası, yamacların baxarlığı, CİS, Azərbaycan*

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FEATURES OF THE FORMATION AND DYNAMICS OF LANDSCAPE-ECOLOGICAL CONDITIONS IN THE COASTAL GEOSYSTEMS OF THE CASPIAN SEA (A CASE STUDY OF THE SAMUR-DAVACHI LOWLAND)

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Keywords: *Samur-Davachi lowland, Caspian Sea coast, transgression, regression, aqual landscapes*

Summary. This study investigates the spatio-temporal dynamics, structural transformation, and ecological stability of coastal landscapes across the Samur-Davachi lowland under the dual influence of Caspian Sea level fluctuations and anthropogenic activities. Integrating multi-decadal sea-level records, field landscape mapping, and hydrogeological data, we evaluate landscape response across transgressive (1978–1995) and subsequent regressive (post-1995, below -29.0 m) phases. Results indicate that during peak transgression, marine waters inundated 80-100 km² of coastal semi-desert, forcing shorelines inland by 200-300 m in the north, up to 1500 m in the south, and 4-5 km in the Agzybir lagoon sector, re-establishing the historical 1926 baseline. Rising groundwater tables induced three distinct waterlogging tiers: severely (0.0–0.5 m depth), moderately (0.5–1.5 m depth), and weakly (1.5–3.5 m depth) waterlogged geosystems, driving widespread transition into subaqueous aqual and wetland complexes. On the Shollar plain, century-long anthropogenic pressure reduced forest cover by 2.0-2.5 times, leaving 60-65% as secondary stands and accelerating forest steppification. Crucially, increased soil hydromorphy accelerated vegetation colonization on coastal dunes, dampening aeolian mobility and stabilizing psammomorphic systems. These findings highlight the non-linear coupling of natural and anthropogenic drivers and emphasize the necessity of adaptive land-use strategies along dynamic Caspian coastal zones.

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Introduction

The Caspian Sea the largest enclosed inland body of water on Earth and its surrounding coastal environments function as an integrated natural complex (Kostianoy & Kosarev, 2005). Characterized as a highly complex, multifunctional, and self-regulating geosystem, this unique environment exists in a dynamic equilibrium that can either accommodate sustainable human activity or suffer catastrophic degradation from uncoordinated and intensive anthropogenic pressure (Lattuada et al., 2019). The structural origin, ongoing functionality, and evolutionary trajectories of these coastal landscapes are fundamentally governed by the natural periodic and cyclical oscillations of the Caspian Sea level.

In recent decades, the compounding impacts of falling Caspian Sea levels and escalating regional land use have given rise to intricate, stressed landscape-ecological conditions (Ismayilov et al., 2023; Lahijani et al. 2023]. A prime example of this environmental vulnerability is observed in the Samur-Davachi lowland (located along the northwestern coast of the Caspian Sea in northern Azerbaijan). This accumulative lowland plain, serves as a vital ecological corridor containing forest ecosystems (Ismayilov & Jabrayilov, 2019).

Understanding the mechanisms driving the formation and temporal dynamics of landscape-ecological conditions within the Samur-Davachi lowland is crucial for both environmental monitoring and sustainable land-use planning. Therefore, this study aims to evaluate the spatio-temporal evolution of coastal geosystems in the Samur-Davachi lowland, analyzing the complex interplay between Caspian Sea level variations, hydrological regime changes, soil-vegetation successions, and anthropogenic influences.

Methods

To evaluate the spatio-temporal dynamics and ecological transformations of coastal landscapes across the Samur-Davachi lowland, this study integrated empirical field landscape mapping with historical and multi-source spatial datasets. Field surveys conducted along transsect lines recorded local hydro-geomorphological parameters, plant community successions, soil profile characteristics (specifically depth to groundwater, soil moisture, and salinization markers), and coastal dune morphometrics. These field observations were synthesized with multi-decadal Caspian Sea level records (1926–present), long-term hydrogeological monitoring data, land-use/land-cover archival records, and multi-scale topographic and thematic maps. Spatial differentiation of landscape units was carried out using a factor-dynamic geosystem framework, categorizing coastal environments into distinct hazard tiers based on waterlogging severity (0.0–0.5 m, 0.5–1.5 m, and 1.5–3.5 m groundwater depths), substrate genesis, and structural resilience under transgressive and regressive marine phases.

Analysis and discussion

A multi-temporal analysis of the modern and long-term functional dynamics, directionality, and intensity of coastal landscape development reveals three primary driving factors:

1. *Hydro-climatic fluctuations:* Variations in the base level of the Caspian Sea, combined with broader regional changes in river discharge and basin runoff regimes across Azerbaijan (Makhmudov et al., 2025), dictate the fundamental spatial-temporal oscillations between hydromorphic (wetland) and xeromorphic (drier terrestrial) landscape states across the coastal strip.

2. *Neotectonic dynamics:* Tectonic movement and morphostructural variations across coastal lowlands generate localized differences in slope, subsidence, and uplift, thereby controlling the specific direction and rate of landscape evolution.

3. *Anthropogenic pressures:* Human land use introduces a complex layer of modification that interacts with natural cycles, particularly in heavily settled and farmed areas such as the Samur-Davachi lowland.

The interaction between natural environmental cycles and human activities creates complex operational dynamics within these coastal geosystems. This superimposition manifests primarily through two distinct mechanisms:

- *Synergistic amplification* (anthropogenic acceleration of natural trends): Human activities can accelerate natural degradative or evolutionary landscape processes. For instance, during phases of Caspian Sea level rise, natural waterlogging and coastal water table elevation across the Samur-Davachi lowland are further aggravated by intensive agricultural surface irrigation around rural settlements such as Valamir, Tikanlioba, and Barakhum. The cumulative effect of rising groundwater and over-irrigation induces secondary soil salinization and marsh formation.
- *Anthropogenic neutralization and buffer interventions:* Conversely, targeted structural engineering can partially suppress or counteract natural landscape trends. Within the Samur-Davachi lowland, human engineering works actively alter natural hydromorphic trajectories. The construction and operation of widespread collector-drainage networks serve as a buffer, mitigating excessive waterlogging, lowering saline water tables, and maintaining agricultural viability against coastal flooding and groundwater rising.

Changes in landscape-ecological conditions in relation to Caspian Sea level fluctuations.

One of the primary natural drivers influencing the dynamics of coastal lowland landscapes is the fluctuation of the Caspian Sea level (Duan et al., 2025). It contributes to alterations in the morphological structure of landscapes, increases the complexity of intra-landscape differentiation, and accelerates the intensity of other natural processes.

Long-term meteorological records along the Caspian littoral reveal complex multi-decadal cycles in moisture availability and thermal regimes. M.J. Ismayilov (1986) classified precipitation dynamics along the Caspian coast (1848–1980) into three major hydro-climatic phases: a relatively arid phase (1848–1902), a prolonged humid phase (1903–1952), and a subsequent dry phase beginning in 1953. In parallel, analysis of thermal dynamics by G.A. Hajiyev (1975) distinguished two primary multi-decadal temperature epochs: a cooler period (1848–1910) during which mean temperatures remained 0.3°C below the long-term baseline, followed by a warmer period (1911–1972) with temperatures averaging 0.4°C above the prior epoch.

These climatic oscillations closely correspond to significant non-linear shifts in the hydrological base level of the Caspian Sea:

- ***1882–1977 regressive phase:*** A continuous decline in sea level resulting in a cumulative drop of 3.82 m [5].
- ***1978–1995 transgressive phase:*** A rapid sea-level rise of 2.8 m documented through continuous instrumental observations.

- ***1995–present regressive phase:*** A substantial level drop exceeding 3.0 m, which has significantly exposed littoral zones and restructured coastal wetland habitats (Fig. 1).
- ***Recent morphological observations (Jan–Jul 2026):*** Morphological assessment of coastal ecosystems during the first half of 2026 indicates a slight localized rise in sea level of 5–8 cm. Long-term instrumental monitoring remains necessary to determine whether this rebound signals a multi-year shift or a brief seasonal fluctuation.



Fig. 1. Exposed rocky formations resulting from sea-level regression (left) and diagenetic structures (right)

Crucially, the direct cause and effect relationship between regional precipitation/temperature anomalies and Caspian Sea level variations remains intricate and non-linear. Although the broader regional climate has remained relatively dry since the mid-20th century, the sea level has undergone two major, opposing multi-decadal oscillations during this same period. These base-level variations serve as the primary driver for ecological succession, triggering intense spatial differentiation, soil salinization/desiccation, and structural reorganization across both pristine natural habitats and human-modified agricultural landscapes.

Field investigations and office-based (analytical) studies revealed that the influence of sea-level drawdown on groundwater depth diminishes with increasing distance from the coastline. Specifically, during the study period, the zone of intensive groundwater table decline along the Samur-Davachi lowland coastal belt extended to a width of 0.5–1.0 km. Studies demonstrate that following 1929, over a 50-year period, the Caspian Sea retreated by nearly 4 km. As a result, vast areas of the Davachi lagoon and the shallow coastal shelf zone adjacent to the Samur-Davachi lowland transitioned to continental development conditions.

An analysis of climatic data reveals that during the period when the Caspian Sea level fell by 2.5 m, annual potential evapotranspiration in the coastal section of the Khachmaz district increased by 5–8% compared to the long-term baseline (1900–1930). The shrinking surface area of the Caspian Sea due to base-level regression intensified climatic continentality, which in turn accelerated desertification processes across the western Caspian coast and drove the replacement of degraded hygrophytic and mesophytic plant communities with xerophytic ones. Notably, the drop in Caspian Sea levels also directly impacts the biological productivity of coastal landscapes.

In connection with the retreat of the sea prior to 1977, the mineralization (salinity) of groundwater in the coastal depressions of the Samur-Davachi lowland gradually decreased. This reduction facilitated a vegetative succession from obligate halophytes (*Salicornia* and *Suaeda* species), through transitional plant groupings, to a meadow-solonchak plant complex dominated by *Salsola soda*, *Puccinellia* (alkali grass), *Petrosimonia*, and ephemeral species.

Starting in 1977, a rise in the level of the Caspian Sea took place, leading to an elevation of groundwater tables and an overall transformation of the ecological environment within natural-territorial complexes (NTCs). By 1998, the sea level had risen by more than 2.0 meters, after which a relative stabilization was observed. Consequently, over the past two decades, the operational trajectory and evolutionary direction of contemporary landscapes have fundamentally shifted.

The latter induces waterlogging/submersion. To define this phenomenon accurately: first, the target object of waterlogging must be clearly specified (e.g., the soil-substrate horizon, plant root systems, building foundations, etc.); second, the drivers causing the groundwater level rise are not included in the strict definition of waterlogging itself. From this, it follows that the waterlogging of an object occurs when that object, originally situated above the groundwater table (or above the capillary fringe) becomes fully or partially submerged in a groundwater-saturated medium as a result of a table rise (Kupriyanova & Trapeznikova, 1997).

Based on field landscape investigations, supplemented by published literature and archival records (including data on groundwater depths, natural landscape structure, land use patterns, and long-term Caspian Sea level dynamics), as well as topographic and thematic maps, coastal geosystems of the Samur-Davachi lowland were classified into distinct types according to the degree of transformation induced by the Caspian Sea:

1. Fundamentally transformed (submerged) geosystems;

2. Geosystems subject to varying degrees of waterlogging.

The first geosystem type encompasses narrow coastal strips of the Samur-Davachi lowland. Here, semi-desert landscapes predominantly occupy the immediate shoreline of the Caspian Sea, while across the territory of the Khachmaz and Siyazan districts, their boundaries gradually extend toward the central part of the lowland from northwest to southeast. The width of this landscape zone varies in response to local physical-geographic conditions.

From the southern tributaries of the Samur River southeastward to the settlement of Niyazoba, the semi-desert landscape in the coastal zone of the Caspian Sea occupies only a narrow strip, approximately 400–1200 m in width. In contrast, in the Siyazan area, its width reaches 3–4 km. Prior to the rise in Caspian Sea levels, younger and more dynamic landscapes were actively forming here.

Contemporary deposits along the coastal zone of the sea are primarily represented by sand and gravel, framing the coastline as a narrow strip (Anoikin et al., 2023). Gravel and pebbles are predominantly distributed along the coast of the Yalama and Mukhtadir areas. To the south, in the Khachmaz and Shabran districts, these are gradually replaced by sand along the littoral zone. Moving southward from the Samur River delta, the width of the highly dynamic and unstable beach complexes increases significantly. For instance, along the Yalama and Mukhtadir coasts, the width of the coastal semi-desert landscape varies between 100 and 1,200 meters, whereas in the Khachmaz and Shabran sectors, the shallow shelf waters extend to 3–4 kilometers in width. This condition has driven the formation of sandy ridges that constitute elementary landscape units.

In connection with the rise in the Caspian Sea level up to 1998, the semi-desert landscape shifted inland by 200-300 m in the northern part of the coast to 1000-1500 m in the southern part. The primary portion of this semi-desert landscape transitioned to a subaqueous development regime, transforming into aquatic landscapes. Even in the area of the Agzybir lagoon, the shoreline moved 4-5 km inland, reconstituting the historical shoreline position of 1926. According to our calculations, 80-100 km² of semi-desert landscape was inundated by marine waters.

Based on landscape characteristics, coastal aeolian (wind-formed) landforms can be divided into stabilized (anchored) and unstabilized (active/mobile) groups. Unstabilized or mobile sand-and-shell materials include coastal dune ridges extending along the shore from northwest to southeast. The relative height of these dunes ranges from 2-3 meters to 10-12 meters, reaching 15-17 meters above the Caspian Sea level in certain places.

Within the functional-dynamic structure of the coastal plain landscapes of the Samur-Davachi lowland, a purely natural component could not be isolated. The anthropogenic factor has become fully integrated within it, driving highly diverse trends in landscape evolution (Gu et al., 2022). On the aeolian-marine plain, overgrazing exacerbates landscape instability. On the Shollar plain, forests with a canopy density of 0.4-0.5 currently account for 75% of the forested area. The reduction in forest canopy density here is primarily linked to unmanaged logging, livestock grazing, and the spread of timber diseases. Over the past 100 years, the forest cover of the Shollar plain has decreased by a factor of 2 to 2.5; secondary forests now constitute 60-65% of the existing oak-hornbeam and ash-hornbeam forest complexes (Figure 2).

Conclusion

Natural and anthropogenic factors can be unidirectional, such as the mutual intensification of hydromorphy, thereby accelerating the overall process, which is currently taking place across many irrigation systems on the Caspian coast of the Samur-Davachi lowland. Conversely, when observed natural processes operate in multidirectional orientations, they tend to cushion, if not mitigate, the adverse consequences of human activities. Such is the natural process of dune ridge stabilization under conditions of increasing hydromorphy within the landscape waterlogging zone.

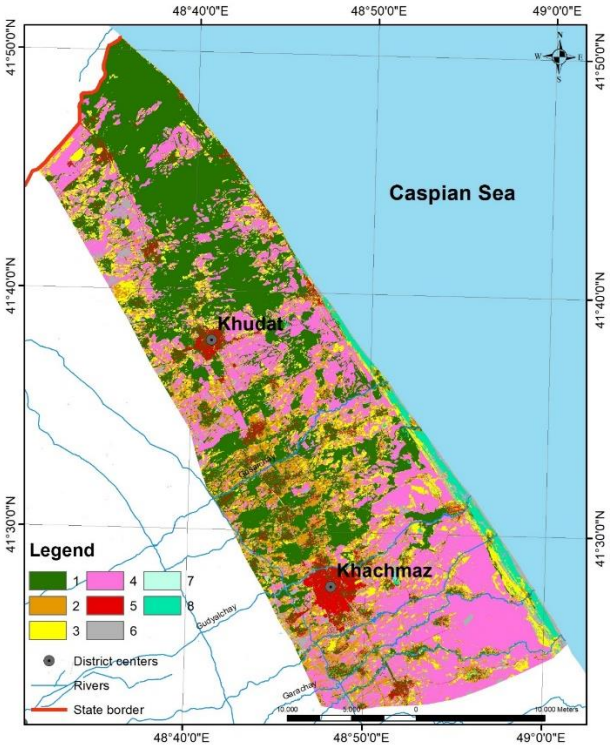


Fig. 2. Dynamics of transformation of forest cover on the Shollar plain from 1910 to 2025

Legend: 1. Existing oak-hornbeam forest ecosystems; 2. Deforested shrubby dry steppes affected by anthropogenic impacts; 3. Post-forest pasture-hayfield complex; 4. Post-forest agrolandscapes; 5. Rural and urban residential (seliteb) landscapes; 6. Coastal sandy and pebbly beach landscape; 7. Lakes (artificial reservoirs); 8. Coastal reedy and meadowy hydromorphic landscapes formed by the retreat of the sea.

Thus, an analysis of studies related to Caspian Sea level fluctuations demonstrates that a fully synchronous correlation between long-term dynamics of air temperature, atmospheric precipitation, and sea level oscillations is weakly observed. Over the past 50 years, during which dry and warm climatic periods were recorded, the sea level exhibited both a significant transgressive phase (1978–1995) and a subsequent regressive phase (from 1995 to the present). This situation necessitates more rigorous, comprehensive research into sea level fluctuations. Under these circumstances, prioritizing scientific investigations focused on the problems of human land-use adaptation to sea level oscillations becomes paramount.

As a result of Caspian Sea level fluctuations, the natural and economic structures of the coastal zone undergo substantial changes, though these are not always negative for human society. However, further unmitigated oscillations in the level of the Caspian Sea will drastically intensify negative impacts on economic activities across the Samur-Davachi Lowland.

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ОСОБЕННОСТИ ФОРМИРОВАНИЯ И ДИНАМИКИ ЛАНДШАФТНО-ЭКОЛОГИЧЕСКИХ УСЛОВИЙ ПРИБРЕЖНЫХ ГЕОСИСТЕМ КАСПИЙСКОГО МОРЯ (НА ПРИМЕРЕ САМУР-ДИВИЧИНСКОЙ НИЗМЕННОСТИ)

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Резюме. В исследовании рассматриваются пространственно-временная динамика, структурная трансформация и экологическая устойчивость прибрежных ландшафтов Самур-Дивичинской низменности в условиях совместного воздействия колебаний уровня Каспийского моря и антропогенной деятельности. На основе комплексного анализа многолетних данных об уровне моря, результатов полевого ландшафтного картографирования и гидрогеологических показателей оценена реакция ландшафтов на изменения природных условий в периоды трансгрессии (1978–1995 гг.) и последующей регрессии (после 1995 г., при снижении уровня моря ниже отметки −29,0 м). Установлено, что в период максимальной трансгрессии морские воды затопили 80–100 км² прибрежных полупустынных ландшафтов, вызвав смещение береговой линии вглубь суши на 200–300 м на севере, до 1500 м на юге и на 4–5 км в районе лагуны Агзыбир. В результате береговая линия вернулась к своему историческому положению, зафиксированному в 1926 г. Повышение уровня грунтовых вод обусловило формирование трёх категорий геосистем по степени переувлажнения: сильно переувлажнённых (глубина залегания грунтовых вод 0,0–0,5 м), умеренно переувлажнённых (0,5–1,5 м) и слабо переувлажнённых (1,5–3,5 м). Эти процессы способствовали масштабной трансформации прибрежных ландшафтов в субаквальные и водно-болотные комплексы. На Шолларской равнине в результате столетнего антропогенного воздействия площадь лесного покрова сократилась в 2,0–2,5 раза, при этом 60–65% сохранившихся лесных насаждений представлены вторичными древостоями, что сопровождалось активизацией процессов остепнения лесов. Вместе с тем усиление гидроморфизма почв способствовало ускоренному заселению прибрежных песчаных дюн растительностью, снижению интенсивности эоловых процессов и стабилизации псаммоморфных геосистем. Полученные результаты свидетельствуют о нелинейном характере взаимодействия природных и антропогенных факторов и подчёркивают необходимость разработки адаптивных стратегий землепользования в динамично изменяющихся прибрежных зонах Каспийского моря.

Ключевые слова: *Самур-Девечинская низменность, побережье Каспийского моря, трансгрессия, регрессия, аквальные ландшафты*

XƏZƏR DƏNİZİNİN SAHİL GEOSİSTEMLƏRİNDƏ LANDŞAFT-EKOLOJİ ŞƏRAİTİN FORMALAŞMASI VƏ DİNAMİKASININ XÜSUSİYYƏTLƏRİ (SAMUR-DƏVƏÇİ OVALIĞI TİMSALINDA)

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Xülasə. Tədqiqatda Xəzər dənizinin səviyyə tərəddüdləri və antropogen fəaliyyətin birgə təsiri şəraitində Samur-Dəvəçi ovalığının sahil landşaftlarının məkan-zaman dinamikası, struktur transformasiyası və ekoloji dayanıqlılığı araşdırılmışdır. Dəniz səviyyəsinin çoxillik müşahidə məlumatları, çöl landşaft xəritələşdirilməsinin nəticələri və hidrogeoloji göstəricilər kompleks şəkildə təhlil edilərək transqressiya (1978–1995-ci illər) və sonrakı reqressiya (1995-ci ildən sonra dəniz səviyyəsinin −29,0 m-dən aşağı enməsi)

mərhələlərində landşaftların dəyişikliklərə reaksiyası qiymətləndirilmişdir. Nəticələr göstərir ki, transqressiyanın maksimum mərhələsində dəniz suları sahilboyu yarımsəhra landşaftlarının 80–100 km² sahəsini basmış, sahil xəttinin şimalda 200–300 m, cənubda 1500 m-ə qədər, Ağzıbir laqunu ərazisində isə 4–5 km quruya doğru irəliləməsinə səbəb olmuşdur. Bununla da sahil xətti 1926-cı ildə qeydə alınmış tarixi vəziyyətinə qayıtmışdır. Qrunt sularının səviyyəsinin yüksəlməsi nəticəsində izafi rütubətlənmənin üç dərəcəsi fərqləndirilmişdir: güclü (qrunt sularının dərinliyi 0,0–0,5 m), orta (0,5–1,5 m) və zəif (1,5–3,5 m) izafi rütubətlənməyə məruz qalan geosistemlər. Bu proses sahil landşaftlarının geniş ərazilərdə sualtı akval və bataqlıq komplekslərinə transformasiyasını sürətləndirmişdir. Şollar düzənliyində bir əsr ərzində davam edən antropogen təzyiq nəticəsində meşə örtüyünün sahəsi 2,0–2,5 dəfə azalmış, mövcud meşəliklərin 60–65%-ni törəmə meşəliklər təşkil etmiş və meşələrin çölləşməsi prosesi intensivləşmişdir. Bununla yanaşı, torpaqların hidromorfluq dərəcəsinin artması sahilboyu qum təpələrində bitki örtüyünün formalaşmasını sürətləndirmiş, eol proseslərinin fəallığını zəiflətmiş və psammomorf geosistemlərin sabitləşməsinə şərait yaratmışdır. Tədqiqatın nəticələri təbii və antropogen amillər arasındakı qeyri-xətti qarşılıqlı əlaqələri üzə çıxarır və Xəzər dənizinin dinamik sahil zonalarında torpaqdan istifadənin dəyişən təbii şəraitə uyğunlaşdırılmış strategiyalar əsasında təşkilinin zəruriliyini əsaslandırır.

Açar sözlər: *Samur-Dəvəçi ovalığı, Xəzər dənizi sahili, transqressiya, reqressiya, akval landşaftlar*

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BIG GEOSPATIAL DATA ANALYTICS FOR SUSTAINABLE NATURAL RESOURCE MANAGEMENT

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Summary. Big geospatial datasets offer opportunities for natural-resource monitoring, but spatial dependence, unstable indicator weights, model transferability, and uncertainty complicate their integration. This study evaluates a reproducible workflow combining pressure indexing, degradation-risk modelling, spatiotemporal validation, predictor interpretation, intervention analysis, and computational scaling. A synthetic benchmark of 2,400 grid cells observed over 24 months (57,600 records) was analysed using seven normalized indicators. Indicator weights were assessed through 100 spatial block-bootstrap samples, while logistic regression and gradient boosting were evaluated under four validation schemes. Permutation analysis and Monte Carlo simulations assessed predictor contributions and intervention uncertainty. The first principal component explained 60.7% of variance, the mean pressure index was 0.502, and Moran's I was 0.954. Logistic regression achieved AUC values of 0.804 under random validation and 0.785 under buffered spatial validation, performing comparably to gradient boosting. Hydro-ecological variables provided the strongest transferable predictive information. The integrated intervention reduced the priority-area index by 12.3% and the critical share by 29.0 percentage points. Computational scaling remained near-linear up to 2.30 million records. The workflow supports uncertainty-aware natural-resource assessment, although operational use requires local observations and independent field validation.

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1. Introduction

Natural-resource monitoring increasingly integrates satellite observations, climate reanalysis, digital soil products, sensor networks, and administrative data. Their volume, heterogeneity, and spatial dependence make them central to geospatial big-data research, particularly for monitoring water, soil, forests, and agricultural systems (Ma et al., 2015; Koh et al., 2022). Remote sensing provides repeated observations, GIS links them to terrain and management units, and cloud platforms facilitate large-scale processing (Gorelick et al., 2017; Sharma et al., 2024).

However, computational capacity alone does not ensure reliable environmental prediction. Spatial dependence can make random train-test splits overly optimistic, while collinearity, unstable composite-index weights, model transferability, and scenario uncertainty can affect interpretation and decision support (Dormann et al., 2013; Roberts et al., 2017; Valavi et al., 2019; Ploton et al., 2020; Koldasbayeva et al., 2024; Stock, 2025).

This study addresses the lack of a compact workflow that jointly evaluates index-weight stability, spatial and temporal transfer, correlated predictor groups, intervention uncertainty, and computational scaling. A controlled synthetic benchmark is used because its data-generating process can be evaluated systematically (Morris et al., 2019). The analysis examines the stability of the pressure index under spatial resampling, the effect of validation design on predictive performance, the transferability of predictor groups, and the robustness of intervention results to variation in weights and treatment effects.

2. Materials and methods

2.1. Analytical design and benchmark construction

Figure 1 summarizes the workflow. In an empirical application, observations could be drawn from Sentinel-2, ERA5-Land and SoilGrids and then joined with terrain, infrastructure and field measurements (Drusch et al., 2012; Munoz-Sabater et al., 2021; Poggio et al., 2021). The present benchmark is synthetic because no verified dataset for a named study area was available.

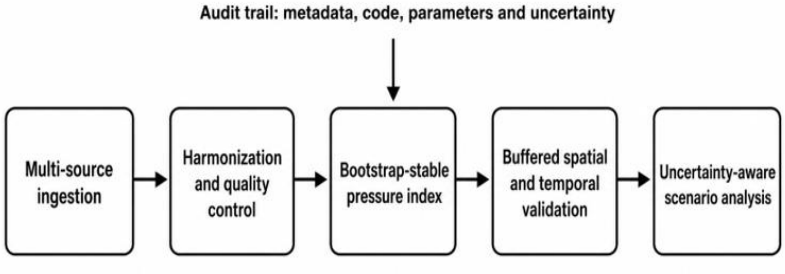


Fig. 1. Uncertainty-aware and reproducible analytical workflow

The benchmark contains 40 rows, 60 columns and 24 monthly observations, giving 57,600 cell-month records over a synthetic area of 6,000 square kilometres. The random seed was fixed at 42. Five spatially structured latent fields represent aridity, human pressure, terrain, water proximity and an unobserved effect. Gaussian-smoothed noise was rescaled to the 0-1 interval and transformed into the variables shown in Table 1.

Dry- and wet-season components were calculated first.

$$D_m = \frac{1+\sin(2\pi(m \bmod 12)/12-\pi/2)}{2}$$
$$W_m = 1 - D_m$$

Rainfall anomaly, road density, slope and distance to water were then generated.

$$R = \text{clip}[\varepsilon(0,0.65) - 0.90A - 0.55D_m + 0.25W_m, -2.5, 1.5]$$
$$\text{Road density} = \text{clip}[0.05 + 0.90(0.75H + 0.25H_2), 0, 1]$$
$$\text{Slope} = \text{clip}(0.05 + 0.85S, 0, 1)$$
$$\text{Distance to water} = 1 - P$$

In the expressions, A, H, S and P denote aridity, human pressure, slope and water proximity; H_2 is a second smoothed human-pressure field, and ε(0, σ) denotes zero-mean Gaussian error with standard deviation σ.

Table 1

Synthetic benchmark variables and generation rules

Variable	Range	Pressure direction	Rule before clipping
Vegetation index	0.08-0.85	Lower = pressure	$0.80 - 0.42A - 0.17H - 0.13S$ $+0.11W + 0.10R + \varepsilon(0,0.035)$
Water index	-0.35-0.45	Lower = pressure	$0.34 - 0.46A - 0.10H$ $+0.10W + 0.09R + \varepsilon(0,0.045)$
Soil moisture	0.04-0.58	Lower = pressure	$0.56 - 0.38A - 0.07H$ $+0.09W + 0.075R + \varepsilon(0,0.028)$
Temperature anomaly	-5.9 to 9.9 °C	Higher = pressure	$-3.0 + 9.5A + 2.1H + 2.7(1 - W)$ $-0.8R + \varepsilon(0,0.70)$
Drought occurrence	0 or 1	Occurrence = pressure	$s_D = -1.55 + 2.5A + 1.25(1 - W) - 1.05R$ Bernoulli$\{\text{logit}^{-1}(s_D)\}$
Land-use intensity	0.08-0.96	Higher = pressure	$0.06 + 0.86H + 0.025\sin(\text{month phase})$ $+\varepsilon(0,0.02)$
Erosion susceptibility	0.07-0.87	Higher = pressure	$0.03 + 0.43S + 0.28(\text{land use}) + 0.20A$ $+0.11(1 - \text{vegetation}) + \varepsilon(0,0.025)$

Source: Synthetic benchmark used in this study. A = aridity; H = human pressure; S = slope; W = wet-season component; R = rainfall anomaly.

2.2. Bootstrap-stable pressure index

All layers were matched by grid cell and month. For empirical data, the same stage would retain cloud masks, quality flags, measurement units, resampling rules and spatial reference information. The normalized difference vegetation index and normalized difference water index were calculated with Equations (1) and (2), where NIR denotes near-infrared reflectance (Tucker, 1979; McFeeters, 1996).

$$\mathrm{NDVI} = \frac{\mathrm{NIR}-\mathrm{Red}}{\mathrm{NIR}+\mathrm{Red}} \tag{1}$$

$$\mathrm{NDWI} = \frac{\mathrm{Green}-\mathrm{NIR}}{\mathrm{Green}+\mathrm{NIR}} \tag{2}$$

Each variable was converted to a pressure score q_{ij} between 0 and 1. Equation (3) was used for direct-pressure indicators and Equation (4) for indicators where higher original values represented better conditions. Here x_{ij} is observation i for indicator j, while a_j and b_j are fixed lower and upper limits.

$$q_{ij} = \frac{x_{ij}-a_j}{b_j-a_j} \tag{3}$$

$$q_{ij} = \frac{b_j-x_{ij}}{b_j-a_j} \tag{4}$$

Pressure scores were standardized before principal component analysis. Absolute first-component loadings were rescaled to sum to one. Weight stability was evaluated with 100 spatial block-bootstrap samples based on 10 by 10 cell blocks, retaining all months for selected blocks. Equation (5) defines the bootstrap weights, their median and the bootstrap-stable index. Critical probability was the share of bootstrap indices at or above 0.65. Equal weights and thresholds from 0.60 to 0.70 provided sensitivity checks.

$$w_j^{(b)} = \frac{\left|l_{j1}^{(b)}\right|}{\sum_k \left|l_{k1}^{(b)}\right|}, \quad \widetilde{w}_j = \mathrm{median}_b\left[w_j^{(b)}\right], \quad \text{BS-SRPI}_i = \sum_j \widetilde{w}_j\, q_{ij} \tag{5}$$

2.3. Prediction, validation and decision analysis

A binary degradation event was generated for prediction. Equation (6) combines the seven normalized pressures, temperature-soil-moisture and land-use-erosion interactions, negative rainfall anomaly and an unobserved spatial field U. The outcome y_i follows a Bernoulli distribution with probability p_i; prevalence in the generated data was 47.3%.

$$\begin{aligned}\eta_i &= -4.55 + 1.35q_V + 1.05q_W + 1.35q_{SM} + 0.95q_T + 0.65D + 1.15q_{LU} + 1.10q_E \\ &+1.15q_Tq_{SM} + 0.80I(q_{LU} > 0.58, q_E > 0.55) + 0.35\max(-R, 0) + 0.35U \\ p_i &= [1+\exp(-\eta_i)]^{-1}, \qquad y_i \sim \text{Bernoulli}(p_i)\end{aligned} \tag{6}$$

Two classifiers were compared. Logistic regression used L2 regularization, C = 1.0 and balanced class weights. Histogram-based gradient boosting used 120 iterations, learning rate 0.06, 31 terminal leaves, minimum leaf size 30 and L2 regularization 0.5. Predictors were the seven indicators, rainfall anomaly, slope, road density, distance to water and normalized coordinates.

Validation used a stratified 75:25 split, five buffered vertical spatial folds, five horizontal folds for logistic regression, a temporal holdout with months 1-18 for training and 19-24 for testing, and a combined holdout for later months in an unseen eastern block. A two-cell buffer separated spatial test blocks from training data. Performance was measured by area under the receiver operating characteristic curve, balanced accuracy, F1, Brier score and calibration coefficients (Gneiting & Raftery, 2007). Buffer-width sensitivity was checked at 0, 1, 2, 4 and 6 cells. A paired 2,000-resample bootstrap compared model AUCs on the spatiotemporal holdout; details are reported in Supplementary File S2.

$$\text{Balanced accuracy} = \frac{1}{2}\left(\frac{TP}{TP+FN} + \frac{TN}{TN+FP}\right) \tag{7}$$

$$\text{Brier score} = \frac{1}{n}\sum_i (p_i - y_i)^2 \tag{8}$$

Global Moran's I was calculated from the 24-month mean index with first-order rook adjacency and 999 permutations. Grouped permutation importance was evaluated on the spatiotemporal holdout with 30 repetitions for hydro-ecological, land-and-erosion and spatial-context groups. Twenty individual permutations were retained as a secondary check.

Three intervention bundles targeted the highest-pressure 15% of cells. Two hundred Monte Carlo runs varied treatment effects by 20% and sampled a bootstrap weight vector. Results are medians with 95% intervals and are interpreted as sensitivity estimates, not causal forecasts. Computational scaling was tested from 57,600 to 2,304,000 records using seven float32 layers; each size was repeated three times. Python 3.13 and five logical processors were used. Full code is supplied in Supplementary File S1.

$$I = \frac{n}{W}\left(\frac{\sum_i \sum_j w_{ij} z_i z_j}{\sum_i z_i^2}\right) \quad (9)$$

3. Results

The first principal component explained 60.7% of variance. Median stable weights were 0.190 for vegetation, 0.185 for water, 0.188 for soil moisture and 0.184 for temperature. Land use had the least stable weight at 0.031, with a 95% interval of 0.003-0.069. The mean pressure index was 0.502. Equal- and stable-weight indices were strongly related (r = 0.982), but class agreement was lower at 86.3%. Only 2.4% of records had an uncertain critical classification.

Low, moderate, high and critical shares were 18.6%, 30.2%, 32.7% and 18.4%. Figure 2 shows the spatial gradient. Moran's I was 0.954 (p = 0.001), indicating strong clustering in the synthetic grid. When the critical threshold changed from 0.60 to 0.70, the critical share fell from 28.0% to 11.2%.

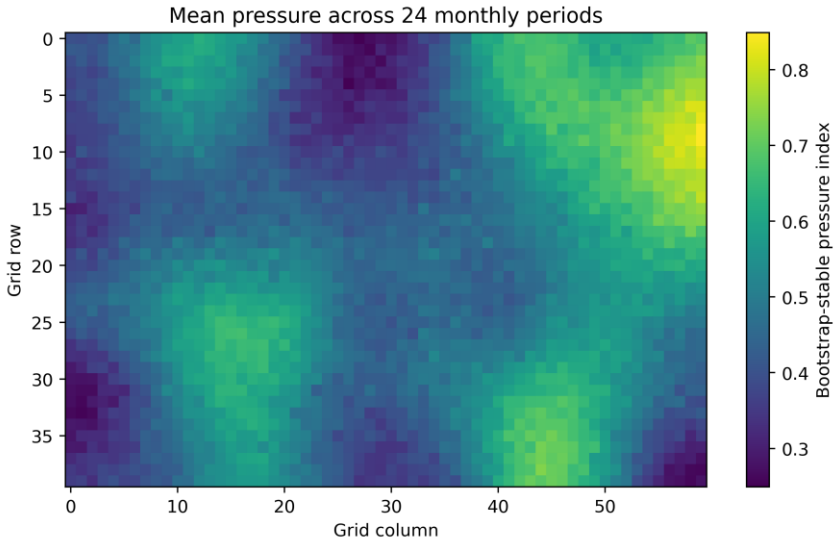


Fig. 2. Mean bootstrap-stable pressure index across the synthetic grid
Note: The grid is synthetic and not georeferenced. A scale bar, north arrow and coordinate reference system are not applicable.

Model discrimination was nearly identical across algorithms (Table 2). Logistic regression reached an AUC of 0.804 with random validation and 0.785 with buffered spatial validation; gradient boosting reached 0.802 and 0.784. Temporal AUC values were 0.802 and 0.799, while spatiotemporal values were 0.809 and 0.808. For logistic regression, mean spatial AUC stayed within 0.78531-0.78540 across buffer widths from 0 to 6 cells. The paired spatiotemporal AUC difference was 0.0017 (95% CI -0.0014 to 0.0048), supporting practical equivalence of the two models.

Table 2

Discrimination across validation designs

Model	Random AUC	Buffered spatial AUC	Temporal AUC	Spatiotemporal AUC
Logistic regression	0.804	0.785 +/- 0.016	0.802	0.809
Gradient boosting	0.802	0.784 +/- 0.017	0.799	0.808

Source: Calculations based on the synthetic benchmark. AUC = area under the receiver operating characteristic curve. Buffered spatial values are reported as mean +/- standard deviation.

Buffered spatial classification and calibration are reported in Table 3. Both models had a mean calibration slope of 0.987 and a Brier score of 0.180. Logistic regression was retained for interpretation because its predictive performance was essentially the same as gradient boosting. Its spatiotemporal calibration intercept was -0.346.

Table 3

Classification and calibration under buffered spatial validation

Model	Balanced accuracy	F1 score	Brier score	Calibration slope
Logistic regression	0.690 +/- 0.022	0.680 +/- 0.129	0.180 +/- 0.008	0.987 +/- 0.031
Gradient boosting	0.690 +/- 0.023	0.676 +/- 0.131	0.180 +/- 0.008	0.987 +/- 0.023

Source: Calculations based on the synthetic benchmark. Values are mean +/- standard deviation across five buffered folds.

Grouped permutation results are shown in Figure 3. Permuting the hydro-ecological group reduced AUC by 0.300, with a 95% interval of 0.279-0.322. The decrease for land and erosion was 0.006, while spatial context was unstable. Individual checks ranked soil moisture, vegetation and drought highest. These values describe predictive contribution rather than causality.

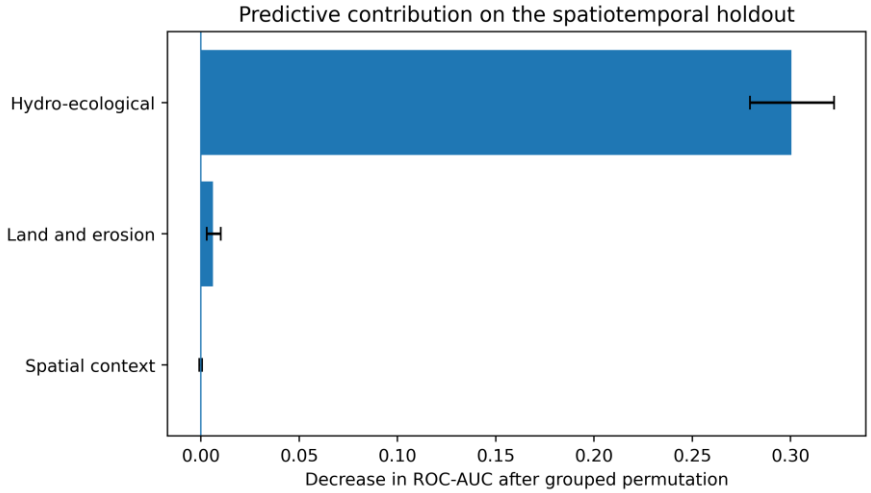


Fig. 3. Grouped permutation importance on the spatiotemporal holdout
Source: Calculations based on the synthetic benchmark. Error bars show 95% empirical intervals from 30 permutations.

Table 4 summarizes the intervention scenarios. The integrated option reduced the priority-area index by a median of 12.3% (95% interval 10.2-15.0%) and the critical share by 29.0 percentage points (23.4-35.5). Hydro-ecological and land-and-erosion actions reduced the index by 7.6% and 3.8%, respectively. The direction of change remained stable across uncertainty runs.

Table 4

Monte Carlo intervention effects in priority cells

Intervention bundle	Median index change (95% interval)	Median critical-share change (95% interval)
Hydro-ecological	-7.6% (-9.6 to -5.4)	-17.0 pp (-22.5 to -11.9)
Land and erosion	-3.8% (-6.0 to -1.5)	-8.0 pp (-13.4 to -3.4)
Integrated	-12.3% (-15.0 to -10.2)	-29.0 pp (-35.5 to -23.4)

Source: Calculations based on the synthetic benchmark. Negative values show lower pressure; pp = percentage points.

At 2,304,000 records, the in-memory calculation had a scaling exponent of 1.12 and estimated working memory of 138.2 MB (Figure 4). This result describes the normalization and index kernel only; file transfer, masking and archive latency were outside the timing test.

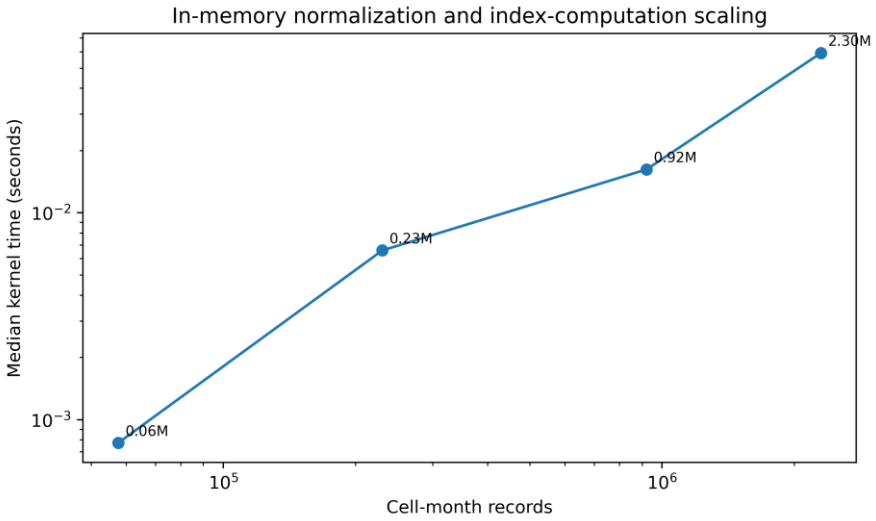


Fig. 4. Scaling of the in-memory normalization and index kernel
Source: Calculations based on the synthetic benchmark. Each point represents the median of three runs.

4. Discussion

The results show that uncertainty in a composite index enters through the indicator weights as well as through the final score. The block bootstrap revealed that land-use weight varied more than the main hydro-ecological weights. Broad spatial ordering may therefore remain similar while records near a management threshold change class. For decision support, a probability of critical status is more informative than a single fixed boundary (Koldasbayeva et al., 2024).

Validation design produced a second key finding. Random AUC was about 0.02 higher than buffered spatial AUC, which is consistent with evidence that random cross-validation can be optimistic when structured dependence is ignored (Roberts et al., 2017; Ploton et al., 2020). In this benchmark, changing the buffer from 0 to 6 cells had little effect on mean AUC, but the result still shows that validation geometry should match the prediction setting (Stock, 2025; Wang et al., 2025).

Temporal and spatiotemporal tests add a calibration perspective. Discrimination remained close to the spatial result, but calibration shifted, indicating that locations may still be ranked usefully while predicted probabilities require local recalibration. This supports evaluating generalization, autocorrelation and uncertainty together rather than as isolated technical checks (Koldasbayeva et al., 2024).

Logistic regression and gradient boosting produced almost identical transfer performance. Because the paired bootstrap interval for the spatiotemporal AUC difference included zero, the more complex model showed no meaningful discrimination advantage. Logistic regression was therefore retained because it is easier to audit while offering comparable accuracy and calibration.

The workflow also differs from studies focused mainly on data access or image processing. Google Earth Engine makes planetary-scale remote-sensing analysis technically feasible (Gorelick et al., 2017), but computational access alone does not solve validation and uncertainty problems. The present benchmark therefore concentrates on the analytical stage between data access and management use: index stability, model transfer and uncertainty-aware scenarios.

Table 5 positions the workflow relative to selected studies. Its novelty lies in combining uncertainty-aware indexing, spatial-temporal validation, grouped interpretation, intervention analysis and a reproducible scaling check within one framework.

This integration has practical value. Pressure maps can identify areas needing closer monitoring, bootstrap probabilities can show where prioritization is uncertain, spatial validation can estimate transfer beyond sampled locations, and grouped importance can guide continued monitoring. The integrated package produced the largest reduction, but its uncertainty interval is more informative than a single point estimate because local evidence may change expected treatment effects.

Empirical transfer should follow a clear sequence. Synthetic layers should be replaced by harmonized Sentinel-2, ERA5-Land, SoilGrids and local administrative data with quality and spatial-reference metadata. Field sampling should cover both high- and low-pressure zones, index weights and decision thresholds should be recalculated locally, and model outputs should be compared with independent field observations before the workflow supports investment or regulation (Sharma et al., 2024).

Table 5

Position of the present workflow relative to selected studies

Study	Main focus	Validation / uncertainty emphasis	Relation to this workflow
Roberts et al. (2017); Stock (2025)	Cross-validation design for structured spatial data	Spatial dependence and block-size choice	Supports blocked validation and sensitivity checks
Ploton et al. (2020); Wang et al. (2025)	Geospatial prediction evaluation	Spatial transfer and clustered samples	Supports caution when interpreting a single CV design
Koldasbayeva et al. (2024)	Environmental geospatial modelling	Autocorrelation, generalization and uncertainty	Motivates joint treatment of validation and uncertainty
Sharma et al. (2024)	Remote sensing and GIS for resource management	Importance of in-situ information	Supports field validation before operational use
Present benchmark	Integrated decision workflow	Weights, spatial-temporal transfer, grouped importance and scenarios	Combines these checks in one reproducible experiment

Source: Comparative synthesis based on the cited studies.

The limitations remain important. The degradation event is synthetic and generated from known predictors, so the benchmark demonstrates analytical behaviour rather than external ecological validity. The scenarios omit costs, delays, institutional constraints and ecological feedback, and the scaling test covers only the in-memory kernel. The next step is to test the same workflow in a named study area with observed outcomes and an independent field-validation set.

5. Conclusion

The analysis shows that big geospatial data can be organized into a reproducible workflow for pressure indexing, transfer testing, predictor interpretation and uncertainty-aware scenario comparison. Spatial resampling exposed weight instability that a single principal-component solution would hide. Random validation was slightly optimistic relative to buffered spatial validation, while logistic regression and gradient boosting produced nearly identical transfer performance. Hydro-ecological information dominated the grouped predictive signal, and the integrated intervention remained beneficial after uncertainty was propagated through both weights and treatment effects.

The main contribution is methodological: accuracy, spatial dependence, calibration, uncertainty and management sensitivity are evaluated together rather than in separate steps. The benchmark is suitable for auditing the workflow, not for direct regulatory use. The next stage is an empirical application in a defined study area using harmonized satellite-climate-soil data and independent field observations. Local thresholds and probability calibration should be estimated and tested before operational use.

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АНАЛИЗ БОЛЬШИХ ГЕОПРОСТРАНСТВЕННЫХ ДАННЫХ ДЛЯ УСТОЙЧИВОГО УПРАВЛЕНИЯ ПРИРОДНЫМИ РЕСУРСАМИ

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Резюме. Большие массивы геопространственных данных открывают новые возможности для мониторинга природных ресурсов, однако их интеграцию осложняют пространственная зависимость, нестабильность весов показателей, переносимость моделей и неопределённость. В исследовании оценивается воспроизводимая методика, объединяющая построение индекса нагрузки, моделирование риска деградации, пространственно-временную валидацию, интерпретацию предикторов, анализ мер воздействия и оценку вычислительной масштабируемости. Синтетический набор данных, включающий наблюдения за 2400 ячейками сетки в течение 24 месяцев (57 600 записей), проанализирован с использованием семи нормированных показателей. Веса показателей оценивались по 100 выборкам пространственного блочного бутстрэпа, а логистическая регрессия и градиентный бустинг — по четырём схемам валидации. Перестановочный анализ и моделирование методом Монте-Карло использовались для оценки вклада предикторов и неопределённости мер воздействия. Первая главная компонента объясняла 60,7% дисперсии, средний индекс нагрузки составлял 0,502, а индекс Морана I — 0,954. Значения AUC логистической регрессии достигли 0,804 при случайной валидации и 0,785 при пространственной валидации с буферными зонами; её результаты были сопоставимы с результатами градиентного бустинга. Гидроэкологические переменные обеспечивали наибольшую переносимую прогностическую информативность. Комплекс мер снизил индекс приоритетных территорий на 12,3%, а долю

территорий в критическом состоянии — на 29,0 процентного пункта. Рост вычислительных затрат оставался близким к линейному при объёме данных до 2,30 млн записей. Методика позволяет оценивать природные ресурсы с учётом неопределённости, однако её практическое применение требует местных наблюдений и независимой полевой валидации.

Ключевые слова: *облачные вычисления, поддержка принятия решений, наблюдение Земли, машинное обучение, пространственная перекрёстная валидация*

TƏBİİ RESURSLARIN DAYANIQLI İDARƏ EDİLMƏSİ ÜÇÜN BÖYÜK GEOMƏKAN MƏLUMATLARININ TƏHLİLİ

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Xülasə. Böyük həcmli geoməkan məlumatları təbii ehtiyatların monitorinqi üçün yeni imkanlar yaradır, lakin məkan asılılığı, göstəricilərin çəki əmsallarının qeyri-sabitliyi, modellərin digər ərazilərə tətbiq edilə bilməsi və qeyri-müəyyənlik onların inteqrasiyasını çətinləşdirir. Tədqiqatda təzyiq indeksinin hesablanmasını, deqradasiya riskinin modelləşdirilməsini, məkan-zaman validasiyasını, proqnozlaşdırıcı dəyişənlərin şərhini, müdaxilə tədbirlərinin təhlilini və hesablama miqyaslanmasının qiymətləndirilməsini birləşdirən təkrarlana bilən metodika qiymətləndirilir. 24 ay ərzində müşahidə olunan 2400 şəbəkə xanasını əhatə edən sintetik məlumat dəsti (57 600 qeyd) yeddi normallaşdırılmış göstərici əsasında təhlil edilmişdir. Göstəricilərin çəki əmsalları 100 məkan bloklu butstrep seçməsi, loqistik reqressiya və qradiyent gücləndirmə modelləri isə dörd validasiya sxemi üzrə qiymətləndirilmişdir. Proqnozlaşdırıcı dəyişənlərin töhfəsini və müdaxilə tədbirlərinin qeyri-müəyyənliyini müəyyənləşdirmək üçün permutasiya təhlili və Monte-Karlo simulyasiyaları tətbiq edilmişdir. Birinci əsas komponent dispersiyanın 60,7%-ni izah etmiş, orta təzyiq indeksi 0,502, Moranın I indeksi isə 0,954 olmuşdur. Loqistik reqressiyanın AUC göstəricisi təsadüfi validasiyada 0,804, bufer zonaları tətbiq edilən məkan validasiyasında isə 0,785 təşkil etmiş və nəticələr qradiyent gücləndirmə modeli ilə müqayisəolunan olmuşdur. Hidroekoloji dəyişənlər digər ərazilərə tətbiq zamanı ən yüksək proqnostik informativliyi təmin etmişdir. Kompleks müdaxilə tədbirləri prioritet ərazilərin indeksini 12,3%, kritik vəziyyətdə olan ərazilərin payını isə 29,0 faiz bəndi azaltmışdır. Məlumatların həcmi 2,30 milyon qeydə çatdıqda hesablama xərclərinin artımı xəttiyə yaxın qalmışdır. Metodika təbii ehtiyatların qeyri-müəyyənlik nəzərə alınmaqla qiymətləndirilməsini dəstəkləyir, lakin praktik tətbiq üçün yerli müşahidə məlumatları və müstəqil çöl validasiyası tələb olunur.

Açar sözlər: *bulud hesablamaları, qərarların qəbulunun dəstəklənməsi, Yer səthinin müşahidəsi, maşın öyrənməsi, məkan üzrə çarpaz validasiya*

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DYNAMICS AND CLASSIFICATION OF FLOODS IN THE RIVERS OF THE GREATER CAUCASUS

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Keywords: *mudflow, sediment transport, intense rainfall, river basin, natural hazards, Greater Caucasus, mudflow classification*

Summary. Mudflows represent one of the major natural hazards affecting river basins of the Greater Caucasus, where their dynamics are controlled by the interaction of hydrometeorological conditions, basin characteristics, sediment availability, and anthropogenic pressures. This study investigates the dynamics of mudflow events in the Azerbaijani part of the Greater Caucasus and develops a classification framework for evaluating their potential hazard. The analysis was based on hydrometeorological records and long-term monitoring materials, with particular attention to rainfall intensity and direction, spatial coverage of river basins, and mudflow characteristics. The results indicate that the spatial progression of intense rainfall plays an important role in the development of catastrophic mudflows. Rainfall progressing from the upper mountainous parts of a basin toward the downstream reaches creates particularly favorable conditions for the formation of high-magnitude mudflows, whereas rainfall of comparable intensity progressing in the opposite direction does not necessarily produce catastrophic events. Based on the combined characteristics of rainfall and basin coverage, mudflows were classified into seven groups. The seventh group, in which intense rainfall affects the entire river basin from the high-mountain zone to the lowland reaches, represents the highest hazard level and corresponds to catastrophic mudflow events. The proposed classification provides a basis for differentiating mudflow hazards and may support the selection of appropriate engineering and risk-reduction measures in vulnerable river basins of the Greater Caucasus.

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Introduction

Recent monitoring observations indicate that mudflow activity remains significant in the Greater Caucasus and has also been recorded in rivers where such events were not previously observed. The rivers of the Greater Caucasus provide a particularly relevant setting for mudflow research because the major types of mudflows recognized in existing classifications occur within this region. Unlike conventional floods, mudflows can mobilize and transport large volumes of weathered material accumulated within a catchment over extended periods. Therefore, investigating their hydrological characteristics and flow dynamics is essential for understanding their magnitude and potential hazard.

Previous studies have addressed various aspects of mudflow and flood processes, including mudflow modelling, rainfall-induced slope instability, mudflow dynamics, flood mapping, and the influence of forest cover on runoff and hazard formation (Chen & Wang, 2014; Inaba, 2003; Mills & Paul, 2003; Oğuz et al., 2016; Petrascheck & Kienholz, 2003). These issues have also been investigated in Azerbaijan (Guliyeva et al.,

2019; Mamedov, 2024; Nabiyev et al., 2019). In particular, the transport of coarse bed material and the development of methods for quantifying sediment movement are important for evaluating mudflow dynamics and identifying their hydrological regularities (Mamedov, 2025).

The Azerbaijani part of the Greater Caucasus is characterized by physical-geographical conditions favorable for hazardous natural processes, including catastrophic mudflows. The mudflow disturbance coefficient of river basins ranges from 0.03 to 0.59, indicating substantial spatial variability in mudflow activity across the region (*Catalogue of Mudflow-Prone Rivers of Azerbaijan*, 2008). The interaction of steep mountainous terrain, hydrological processes, sediment availability, and intense precipitation makes the region particularly important for investigating the mechanisms controlling mudflow formation and development.

Despite previous research on the geomorphological, climatic, and geographical aspects of mudflows, their hydrological dynamics and associated regularities remain insufficiently investigated in the Greater Caucasus. This limitation is partly related to the scarcity of long-term stationary observations, limited instrumental measurements, methodological difficulties in quantitative assessment, and challenging field conditions. In particular, the dynamic characteristics of catastrophic mudflows and the influence of rainfall distribution across river basins require further investigation. Therefore, this study aimed to investigate mudflow dynamics in the Greater Caucasus, with particular emphasis on the erosion, transport, and deposition of mudflow sediments, and to develop a systematic classification framework for assessing mudflow behavior and associated hazards.

Materials and methods

The study was based on hydrometeorological data provided by the National Hydrometeorological Service of the Ministry of Ecology and Natural Resources of the Republic of Azerbaijan, together with monitoring materials collected by the Institute of Geography in recent years. A comparative approach was applied to evaluate differences in mudflow dynamics under varying hydrometeorological conditions.

Particular attention was given to the onset, intensity, spatial extent, and direction of intense rainfall across river basins, as these factors were used to assess differences in mudflow formation and development. Rainfall conditions were compared with observed mudflow characteristics to identify patterns associated with the formation of high-magnitude and catastrophic events.

Results and discussion

The Azerbaijani part of the Greater Caucasus is characterized by complex and highly differentiated relief (Imrani et al., 2022). Pronounced altitudinal zonation contributes to considerable spatial variability in climatic conditions, landscapes, soils, and vegetation (Museyibov, 1998). These physical-geographical conditions also influence weathering processes, sediment availability, and the accumulation of transported material within mudflow depositional cones.

The deposition and redistribution of mudflow sediments depend strongly on flow dynamics. High-velocity mudflows generate considerable kinetic energy and hydrodynamic pressure, which affect the transport and deposition of coarse and fine material. To examine these processes, the depositional cones of the Balakanchay, Talachay, Mukhakhchay, and Kurmukchay rivers were selected as representative study sites. These rivers provide relatively favorable natural conditions for examining lateral sediment redistribution because mudflows enter comparatively straight channel sections within their depositional cones.

Field observations suggest that the lateral redistribution of mudflow material may also be associated with the Coriolis effect. In relatively straight channel sections, flow deflection could contribute to transverse asymmetry and influence the distribution of transported sediments between the riverbanks. However, this potential effect should be considered together with local channel morphology, flow velocity, sediment characteristics, and other hydrodynamic factors.

Mudflow dynamics were also strongly influenced by the onset, intensity, spatial extent, and direction of intense rainfall across the river basin. Catastrophic mudflows characterized by high flow velocities and destructive potential were associated with intense rainfall reaching approximately 3 mm min^{-1} and extending from high-mountain mudflow source areas toward the depositional cone. The spatial progression of rainfall affected the mobilization, transport, and accumulation of sediment within the channel and could contribute to the formation of temporary sediment blockages and increased hydrodynamic pressure (Figure 1).



Fig. 1. Flash flood in the Balakanchay River, September 27, 2025

The direction of rainfall progression is therefore an important factor in interpreting mudflow development. When intense rainfall progressively affects the basin from the upper mountainous source areas toward the downstream reaches, runoff and sediment supplied from different parts of the catchment may contribute successively to the main channel. Under favorable conditions, this process can increase the magnitude and destructive potential of the resulting mudflow. In contrast, rainfall progressing in the opposite direction may produce a different sediment-transport response because of the transient characteristics of flow within the river channel. These differences provide an important basis for evaluating mudflow dynamics and for the subsequent classification of mudflow events according to their hydrometeorological characteristics.

The lateral displacement of high-magnitude mudflows within depositional cones may also be influenced by centrifugal and Coriolis effects. In particular, the hydraulic impact generated by a high-velocity sediment-laden flow can be estimated as:

$$P = \frac{1000\ FV^2}{g} \tag{1}$$

where P is the hydraulic impact force, F is the area of the sediment-barrier wall (m^2), V is the mean flow velocity (m/s), and g is the acceleration due to gravity (m/s^2).

Under intense rainfall conditions of approximately 3 mm min^{-1} or greater, mudflows originating in the high-mountain zone may substantially increase in volume as they move toward the depositional cone. The resulting high-magnitude flows may exhibit lateral displacement within the channel, potentially reflecting the combined influence of flow momentum, channel geometry, centrifugal effects, and Coriolis forcing. The Coriolis effect on mountain rivers remains subject to uncertainty because these rivers generally have smaller dimensions, confined valleys, and lower discharges than large lowland rivers. Its influence may therefore be negligible during low- and moderate-flow conditions but could become more detectable during exceptionally large mudflow events. Accordingly, the observed lateral asymmetry of catastrophic mudflows in the Greater Caucasus is treated here as a potential hydrodynamic effect rather than definitive evidence of Coriolis forcing alone.

The catastrophic mudflows recorded in the Mukhakhchay and Talachay rivers in 1964 provide evidence of pronounced lateral asymmetry in sediment deposition. In Mukhakhchay, large-diameter boulders were predominantly deposited along the right side of the channel, whereas finer sand and loamy sediments accumulated mainly on the left side (Mamedov, 2014). This spatial differentiation may indicate the influence of transverse hydrodynamic forces, including a potential Coriolis effect, particularly during high-magnitude mudflow events.

Mudflow volumes also varied considerably among years and river basins. According to historical records, the mudflow volume in the Balakanchay River was approximately 372,000 m^3 in September 1932 and reached 1,780,000 m^3 in July 2003. Similarly, the mudflow volume in the Talachay River was approximately 282,000 m^3 in 1964 and reached 4,473,000 m^3 in July 2003 (Mamedov, 2011). These substantial differences may reflect the combined influence of physical-geographical conditions, hydrometeorological variability, and anthropogenic pressure within the river basins.

Field observations indicate that intense rainfall in the upper parts of the basins initiates surface runoff and mobilizes weathered material, while mudflow activity becomes more pronounced farther downstream as runoff and sediment contributions converge within the main channel. After tributaries enter the main river, temporary sediment blockages may form in narrow and curved channel sections. The failure of these blockages can generate high hydrodynamic pressure, contributing to the transformation of high-magnitude flows into catastrophic mudflows.

The 1964 events demonstrate the destructive consequences of this process. The Talachay mudflow caused extensive damage to Zagatala and settlements located farther downstream, while the Mukhakhchay mudflow affected agricultural areas around Mukhakh, Chobankol, Zayam, and Tasmali. In contrast, Gozbarakh, located on the left side of Mukhakhchay, experienced comparatively limited damage. The branch directed toward Mukhakh was characterized predominantly by coarse mudflow deposits, whereas the branch toward Chobankol and Zayam contained a greater proportion of suspended and fine material. In the latter area, sand and clay deposits exceeding 1 m in thickness were recorded. This pronounced lateral differentiation in sediment size and deposition supports the presence of complex transverse flow dynamics during catastrophic mudflows and may be consistent with a Coriolis contribution, although local channel morphology and other hydrodynamic controls should also be considered.

The spatial variability in the hydrodynamic characteristics of high-magnitude mudflows on the southern slope of the Greater Caucasus may also be associated with regional climatic conditions, particularly variations in the degree of continentality (Table 1).

Table 1

Indicators Determining the Degree of Continentality in the Studied River Basins

Location	Absolute elevation, m	Long-term absolute		Latitude, degrees	Temperature amplitude, °C	Cloudiness, points	Degree of continentality
		Maximum temperature, °C	Minimum temperature, °C				
Balakan	400	+37°	-21°	41°40′	58°	6,6	1,40
Zagatala	487	+38°	-23°	41°38′	61°	6,4	1,47
Gakh	600	+38°	-23°	41°20′	61°	6,2	1,48
Sheki	639	+37°	-23°	41°13′	60°	6,1	1,46
Oghuz	700	+38°	-23°	41°04′	61°	6,0	1,49
Gabala	781	+37°	-26°	40°57′	63°	5,8	1,55
Goychay	94	+41°	-16°	39°15′	57°	5,6	1,46
Aghsu	165	+43°	-17°	40°35′	60°	5,8	1,49
Shamakhi	750	+38°	-19°	40°38′	57°	5,9	1,41

Analysis of Table 1 shows considerable spatial variation in the degree of continentality across the southern slope of the Greater Caucasus. The highest value was recorded in Gabala (1.55) and the lowest in Balakan (1.40). With the exception of Sheki, continentality generally increases from Balakan toward Gabala and subsequently decreases toward Shamakhi. This spatial pattern is associated with differences in elevation, cloudiness, precipitation, and temperature amplitude. In particular, the relatively high elevation of Gabala and lower winter cloudiness favor radiative cooling and a greater temperature amplitude. Large temperature amplitudes may intensify physical weathering and consequently increase the availability of unconsolidated material within river basins.

The formation of catastrophic mudflows on the southern slope of the Greater Caucasus is associated with the combined influence of intense rainfall, sediment availability, and basin conditions. Rainfall progressing from the upper basin toward downstream reaches may promote runoff concentration and the formation of temporary channel blockages, whose failure can generate high hydrodynamic pressure. Climatic variability, increasing aridity, and anthropogenic modification of catchment surfaces may further influence mudflow activity. On the northeastern slope, damaging mudflows were also recorded in 2009, affecting orchards and settlements located along river channels.

Precipitation is particularly important for mudflow formation in the study area. At elevations of 1,700–3,600 m on the southern slope of the Greater Caucasus, mean daily precipitation during June–September ranges from approximately 6 to 13 mm, which is reported to be 1.2–1.5 times higher than in other mountainous regions of Azerbaijan. Historical records indicate extreme precipitation totals of 100 mm at Damarjiq and 140 mm at Gabala in 1932, and 171 and 188 mm at Zagatala in 1944 and 1964, respectively. In 1983, precipitation reached 176 mm at Gabizdara, whereas recorded values during 1992–2007 ranged from 15.1 to 119 mm.

The intensity of extreme rainfall events generally ranges from 1 to 3 mm min^{-1}. Such rainfall may affect both lower and high-mountain parts of river basins, resulting in rapid accumulation of runoff. To quantify this process, the river basins were divided into three spatial components and potential water accumulation was estimated for different rainfall intensities and durations. For a rainfall intensity of 1 mm min^{-1} lasting 30 min, each square kilometre of basin area receives approximately 30,000 m^3 of precipitation water. Accordingly, basins larger than approximately 40 km^2 may receive more than 1 million m^3 during such an event. Estimated

volumes reach approximately 15.51 million m³ for a 517 km² basin, 28.56 million m³ for 952 km², and 45.0 million m³ for 1,500 km². The accumulated volume increases further with longer rainfall durations (Table 2).

Table 2

Volume of Water Accumulated in River Basins and Their Elementary Subareas on the Southern Slope of the Greater Caucasus

No.	River–station	Total basin area and its elementary subareas, F, f_1, f_2 (km²)	Volume of intense rainfall at 1, 2, and 3 mm/min (10^3 m³)								
			volume (10^3 m³)			30-min volume (10^3 m³)			60-min volume (10^3 m³)		
			1 mm/min	2 mm/min	3 mm/min	1 mm/min	2 mm/min	3 mm/min	1 mm/min	2 mm/min	3 mm/min
1	Hamamchay–Ilisu	f_1 20,7	21	41	62	621	1242	1863	1242	2484	3726
		f_2 41,2	41	82	124	1236	2472	3768	2472	4944	7416
		F 62	62	124	186	1860	3720	5580	3720	7440	11160
2.	Bulanigsu–Saribash	f_1 6,8	7	14	20	204	408	612	408	816	1224
		f_2 13,6	14	27	41	408	816	1224	816	1632	2448
		F 20,5	20	41	62	615	1230	1854	1230	2460	3690
3.	Aghchay–Aghchay	f_1 14	14	28	42	420	840	1260	840	1680	2520
		f_2 28	28	56	84	840	1680	2520	1680	3360	5040
		F 42	42	84	126	1260	2520	3780	7520	5040	7560
4.	Eyrichay–Bashdashagil	f_1 30,7	31	61	92	921	1842	2763	1842	3684	5526
		f_2 61,4	61	123	184	1842	3684	5526	3684	7368	11052
		F 92	92	184	276	2760	5520	8280	5520	11040	16560
5.	Damarjig–Near the mouth	f_1 11,7	12	23	35	351	702	1053	702	1404	2106
		f_2 23,4	23	47	70	702	1404	2106	1404	2808	4202
		F 35	35	70	105	1050	2100	3150	2100	4200	6300
6	Oghuzchay–Oghuz	f1 10,2	10	20	31	306	612	918	612	1224	1836
		f2 20,4	20	41	61	612	1224	1836	1224	2448	3672
		F 30,6	31	61	92	918	1836	2754	1836	3672	5508
7.	Tikanlichay–Tikanli	f_1 40	40	80	120	1200	2400	3600	2400	4800	7200
		f_2 80	80	160	240	2400	4800	7200	4800	9600	14400
		F 120	120	240	360	3600	7200	10800	7200	14400	21600
10.	Bumchay–Bum	f_1 32	32	64	96	960	1920	2880	1920	3840	5760
		f_2 64	64	128	192	1920	3840	5760	3840	7680	11520
		F 96	96	192	288	2880	5760	8640	5760	11520	17280
12.	Damiraparanchay–Gabala	f_1 42	42	84	126	1260	2520	3780	2520	5040	7560
		f_2 84	84	168	252	2520	5040	7560	5040	10080	15120
		F 126	126	252	378	3780	7560	11340	7560	15120	22680
15.	Goychay–Goychay	f_1 493,3	493	987	1480	14799	29598	44397	29598	59196	88794
		f_2 986,6	987	1973	2960	29598	59196	88974	59196	118392	177588
		F 1480	1480	2960	4440	44400	88800	133200	88800	177600	266400
16.	Ahohchay–Khanagah	f_1 22,1	22	44	66	663	1326	1989	1326	2662	3978
		f_2 44,2	44	88	133	1326	2652	3978	2652	5304	7956
		F 66,4	66	133	199	1992	3984	5976	3984	7968	11952
17	Vandamchay–Vandam	f_1 23,1	23	46	69	693	1386	2079	1386	2772	4158
		f_2 46,2	46	92	139	1386	2772	4158	2772	5544	8316
		F 69,4	69	139	208	2082	4164	6246	4164	8328	12492
18.	Girdimanchay–Garanohur	f_1 117,3	117	235	352	3519	7038	10557	7038	14076	21114
		f_2 234,6	235	469	235	7038	14076	21114	14076	28152	42228
		F 352	352	704	1056	10560	21120	31680	21120	42240	63360
19.	Sangarchay–Galajig	f_1 14,4	14	29	43	432	864	1296	864	1728	2592
		f_2 28,8	29	58	86	864	1728	2592	1728	3456	5184
		F 43,2	43	86	130	1296	2592	3888	2592	5184	7776
20.	Aghsu–Aghsu	f_1 122,3	122	245	367	3669	7338	11007	7338	14676	22014
		f_2 244,6	245	489	734	7338	14676	22014	14676	29352	44028
		F 367	367	734	1101	11010	22020	33030	22020	44040	66060
21.	Pirsaat–Poladli	f1 331,7	332	663	995	9951	19902	29853	19902	39804	59706
		f2 663,4	663	1327	1990	19902	39804	59706	39804	79608	119412
		F 995	995	1990	2985	29850	59700	89550	59700	119400	179100

These calculations demonstrate the strong dependence of potential runoff volume on rainfall intensity, duration, and basin area. Together with sediment availability and channel conditions, these factors determine the magnitude and destructive potential of mudflows. Mudflows are distinguished from conventional floods by their high sediment concentration, greater density, substantial transport of coarse material, and distinct flow dynamics. Therefore, a classification that differentiates mudflow events according to their hydrometeorological and basin characteristics is necessary for hazard assessment and for selecting appropriate risk-reduction measures.

Classification of mudflows

Based on the combined effects of the controlling factors, mudflows were classified according to the spatial extent of intense rainfall within the river basin and the resulting hydrodynamic and sediment-transport characteristics. To ensure comparability among the classes, a constant rainfall intensity of 3 mm min^{-1} and a duration of 2 h were considered. Rainfall progression was evaluated in two principal directions: from the foothills toward the high-mountain zone and from the high-mountain zone toward the foothills.

Class I. Weak mudflows occurring mainly in the lower river reaches when intense rainfall affects the lowland and foothill zones. Their relatively low magnitude is associated with the limited contributing area and comparatively short flow path.

Class II. Mudflows generated when intense rainfall extends from the lowland to the lower-mountain zone. Compared with Class I, the larger contributing area increases surface runoff, sediment transport, and flow energy.

Class III. Mudflows occurring when rainfall affects the area from the lowland to the middle-mountain zone. The larger contributing area results in greater runoff and sediment transport than in the preceding classes.

Class IV. Mudflows generated when intense rainfall extends from the lowland to the high-mountain zone. These events involve a larger proportion of the basin and are characterized by greater sediment transport and higher flow magnitude.

Class V. Mudflows associated with intense rainfall affecting the high- and middle-mountain zones. Although the contributing area may be smaller than in some preceding classes, these events are characterized by a relatively high integrated sediment load and may produce temporary channel blockages whose failure generates strong hydraulic impacts.

Class VI. Mudflows occurring when intense rainfall extends from the high-mountain to the lower-mountain zone. Compared with Class V, the larger contributing area results in greater sediment mobilization and more powerful flows.

Class VII. Mudflows generated when intense rainfall affects the entire basin, from the high-mountain zone to the lowland reaches. These events are characterized by the maximum integrated sediment load and the highest destructive potential and are therefore classified as catastrophic mudflows.

Conclusion

The results demonstrate that river basins of different sizes can generate substantially different mudflow volumes even under rainfall of the same intensity and duration. The proposed seven-class classification indicates a progressive increase in mudflow magnitude as the spatial extent of intense rainfall and the contributing basin area increase. Class VII, in which intense rainfall affects the entire basin from the high-mountain source areas to the lowland reaches, represents the highest hazard level and corresponds to catastrophic mudflow events.

Catastrophic mudflows on the southern slope of the Greater Caucasus are associated with the combined effects of intense rainfall, sediment availability, basin characteristics, and channel processes. Rainfall progressing from the upper mountainous parts of a basin toward downstream reaches can promote rapid runoff concentration, sediment mobilization, and the formation of temporary channel blockages. Failure of these blockages under increasing hydraulic pressure can substantially increase the magnitude and destructive potential of the resulting mudflow. The classification developed in this study therefore provides a practical framework for differentiating mudflow hazard levels and selecting appropriate risk-reduction and engineering measures for individual river basins.

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ДИНАМИКА И КЛАССИФИКАЦИЯ ПАВОДКОВ НА РЕКАХ БОЛЬШОГО КАВКАЗА

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Резюме. Селевые потоки представляют собой одну из основных природных опасностей, характерных для речных бассейнов Большого Кавказа. Их динамика определяется взаимодействием гидрометеорологических условий, природных особенностей водосборных бассейнов, наличия рыхлообломочного материала и антропогенных воздействий. В исследовании рассматривается динамика селевых явлений в пределах азербайджанской части Большого Кавказа и разрабатывается классификационная система для оценки степени их потенциальной опасности. Анализ основан на гидрометеорологических данных и материалах многолетнего мониторинга. Особое внимание уделено интенсивности и направлению перемещения атмосферных осадков, пространственному охвату речных бассейнов и характеристикам селевых потоков. Результаты исследования показывают, что направление пространственного перемещения зоны интенсивных осадков играет важную роль в формировании катастрофических селей. Перемещение зоны осадков от высокогорных участков бассейна вниз по течению создаёт особенно благоприятные условия для формирования мощных селевых потоков. В то же время перемещение осадков сопоставимой интенсивности в противоположном направлении не обязательно приводит к возникновению катастрофических селевых явлений. На основе совокупного учёта характеристик осадков и степени охвата ими территории речного бассейна селевые потоки классифицированы на семь групп. Седьмая группа, характеризующаяся выпадением интенсивных осадков на всей территории речного бассейна — от высокогорной зоны до равнинных участков, соответствует наивысшему уровню опасности и включает катастрофические селевые явления. Предложенная классификация создаёт научно-методическую основу для дифференциации селевой опасности и может использоваться при выборе соответствующих инженерно-защитных мероприятий и мер по снижению рисков в селеопасных речных бассейнах Большого Кавказа.

Ключевые слова: *сель, перенос наносов, интенсивные дожди, речной бассейн, природные опасности, Большой Кавказ, классификация селей*

BÖYÜK QAFQAZ ÇAYLARINDA SELLƏRİN DİNAMİKASI VƏ TƏSNİFATI

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Xülasə. Sel hadisələri Böyük Qafqazın çay hövzələrinə təsir göstərən əsas təbii təhlükələrdən biridir. Onların dinamikası hidrometeoroloji şəraitin, hövzələrin təbii xüsusiyyətlərinin, sel materialının mövcudluğunun və antropogen təsirlərin qarşılıqlı əlaqəsi ilə müəyyən olunur. Tədqiqatda Böyük Qafqazın Azərbaycan hissəsində baş verən sel hadisələrinin dinamikası araşdırılmış və onların potensial təhlükəlilik dərəcəsinin qiymətləndirilməsi üçün təsnifat sistemi hazırlanmışdır. Təhlil hidrometeoroloji müşahidə məlumatları və uzunmüddətli monitorinq materialları əsasında aparılmış, yağıntıların intensivliyinə və hərəkət istiqamətinə, çay hövzələri üzrə məkan əhatəsinə və sel hadisələrinin xüsusiyyətlərinə xüsusi diqqət yetirilmişdir. Nəticələr göstərir ki, intensiv yağıntıların ərazi üzrə hərəkət istiqaməti fəlakətli sellərin formalaşmasında mühüm rol oynayır. Yağıntıların hövzənin yüksək dağlıq hissələrindən aşağı axın istiqamətində hərəkət etməsi güclü sellərin yaranması üçün xüsusilə əlverişli şərait formalaşdırır. Bunun əksinə olaraq, eyni intensivliyə malik yağıntıların əks istiqamətdə hərəkəti heç də həmişə fəlakətli sel hadisələrinin baş verməsinə səbəb olmur. Yağıntıların xüsusiyyətləri və çay hövzələrini əhatə etmə dərəcəsi birlikdə nəzərə alınmaqla sel hadisələri yeddi qrupa təsnif edilmişdir. Yeddinci qrup intensiv yağıntıların çay hövzəsinin yüksək dağlıq qurşağından düzənlik hissələrinə qədər bütün ərazisini əhatə etdiyi halları birləşdirir və ən yüksək təhlükəlilik dərəcəsinə malik olmaqla fəlakətli sel hadisələrinə uyğun gəlir. Təklif olunan təsnifat sel təhlükəsinin dərəcələr üzrə fərqləndirilməsi üçün elmi-metodoloji əsas yaradır və Böyük Qafqazın sel təhlükəsinə məruz qalan çay hövzələrində müvafiq mühəndis-mühafizə tədbirlərinin və risklərin azaldılması istiqamətində tədbirlərin seçilməsinə kömək edə bilər.

Açar sözlər: *sel, gətirmələrin daşınması, intensiv yağışlar, çay hövzəsi, təbii təhlükələr, Böyük Qafqaz, sellərin təsnifatı*

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FRAMING CLIMATE HAZARDS: A CRITICAL DISCOURSE ANALYSIS OF ENGLISH MASS MEDIA REPORTS

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Keywords: *climate communication, climate hazards, critical discourse analysis, framing, media discourse, news headlines*

Summary. This study examines how English-language mass media frame climate hazards through lexical choice, grammatical agency, quantification, evaluation, and epistemic qualification. The corpus comprises 18 headlines published in 2024 by Reuters, the Associated Press, and The Guardian, with six items from each outlet. A mixed-methods approach combines framing analysis, critical discourse analysis, lexical frequency analysis, and binary coding across seven categories. Explicit climate attribution, severity/urgency, and quantification/evidence each occur in 12 of 18 headlines (66.7%), whereas preparedness/response appears in only three (16.7%), producing an attribution-response gap of 50 percentage points and an urgency-response ratio of 4.0. Reuters shows the strongest epistemic caution, the Associated Press emphasizes human-centred consequences, and The Guardian records the highest urgency-response ratio. Dominant frames remain relatively diverse (normalized Shannon entropy = 0.90), but response-oriented framing is weak. The findings support a cause-impact-response model linking climate attribution with vulnerability, institutional accountability, and feasible adaptation or mitigation measures.

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1. Introduction

Climate hazards are physical events, but their public meaning is shaped through discourse. News organizations influence which aspects become salient, how causal agency and vulnerability are represented, and which responses are presented as feasible. Framing therefore contributes to defining problems, diagnosing causes, evaluating consequences, and suggesting responses (Entman, 1993). Headlines are especially important because they condense complex events into highly salient propositions that shape the interpretation of the accompanying report (Dor, 2003).

This communicative role has become increasingly important as climate-related extremes intensify. The IPCC (2023) concludes that human-caused climate change has already affected weather and climate extremes in every region, while the WMO (2025) identifies 2024 as the warmest year in the 175-year observational record, with global mean near-surface temperature approximately 1.55 ± 0.13°C above the 1850–1900 average. Media analysis must therefore consider not only whether climate change is mentioned, but also how hazards are connected with causation, evidence, uncertainty, vulnerability, responsibility, and action.

Previous research documents a shift away from overt climate scepticism and false balance while identifying persistent differences among media systems, journalistic norms, and ideological cultures (Antilla, 2005; Boykoff & Boykoff, 2007; Carvalho, 2007; Schäfer & Schlichting, 2014; Vu et al., 2019). Even when anthropogenic climate change is accepted, headlines may emphasize scientific attribution, human consequences, urgency, quantification, uncertainty, or institutional response.

Against this background, the study examines a balanced corpus of 18 climate-hazard headlines published in 2024 by Reuters, the Associated Press (AP), and The Guardian. It investigates dominant frames, lexical and grammatical constructions of causation and urgency, outlet-level differences, and the balance between threat-

oriented and response-oriented communication. The study combines headline-level critical discourse analysis with reproducible quantitative measures of frame prevalence, density, balance, and diversity.

2. Materials and methods

2.1. Research design and corpus construction

A small-corpus mixed-methods design was adopted. The empirical material consists of 18 English-language headlines published between February and December 2024: six from Reuters, six from AP, and six from The Guardian. Inclusion required that an item report a climate-related hazard or a scientifically attributed extreme event, be published in 2024, and represent news, analysis, or explanatory reporting rather than an opinion column. The sample covers heatwaves, floods, wildfires, drought, tropical storms, and multi-hazard summaries.

The headline was selected as the unit of analysis because it is comparable across outlets and is constrained by brevity, editorial salience, and newsworthiness. The corpus contains 230 lexical words. Table 1 presents the balanced outlet structure and principal thematic coverage.

Table 1

Composition of the headline corpus

Outlet	n	Principal thematic coverage	Share (%)
Reuters	6	Heat, floods, wildfire, drought, tropical storms	33.3
Associated Press	6	Heat, floods, hurricanes, multi-hazard impacts	33.3
The Guardian	6	Heat, rain/floods, global records, multi-hazard losses	33.3
Total	18	Six principal hazard groupings	100.0

Source: Author's corpus compiled from the 2024 media items listed in the original dataset.

The equal number of headlines per outlet prevents one source from dominating the descriptive results. It also makes outlet-level rates directly comparable because every percentage is based on the same denominator of six headlines.

2.2. Coding framework

Each headline was manually coded for seven non-exclusive categories. A category received a value of 1 when at least one clear textual marker was present and 0 when absent. Because the categories are non-exclusive, one headline could simultaneously express attribution, urgency, evidence, human impact, and response. A separate mutually exclusive dominant-frame code was then assigned to identify the principal interpretive emphasis. The operational framework is summarized in Table 2.

Table 2

Operational frame categories and linguistic indicators

Category	Operational definition	Indicative markers
Explicit climate attribution	Direct link to climate change, climate crisis, or a warming climate	climate change; climate crisis; warming climate; made; blame
Human impact	Deaths, affected populations, displacement, suffering, or lived consequences	kills; killed; deadly; people; missing; sweltering; destruction
Severity/urgency	Language intensifying danger, scale, exceptionality, or immediacy	extreme; devastating; worst; red alert; impossible; dangerous; costly
Quantification/evidence	Numbers, studies, records, reports, or probability claims authorizing the proposition	scientists; study; report; data; record; twice; 45 times
Preparedness/response	Planning, adaptation, preparedness, or a response imperative	not prepared; plans; combat; reminder; adaptation
Uncertainty/qualification	Epistemic limits, probability, or contrastive qualification	unclear; feared; likely; chance; less severe; interrogative form
Economic/infrastructure	Material systems, trade routes, infrastructure, or financial loss	Panama Canal; damages; costly; infrastructure; economic loss

Source: Developed from Entman (1993), Fairclough (2003), Bednarek and Caple (2017), and climate-framing literature.

2.3. Quantitative measures and analytical procedure

The analysis proceeded in three stages. First, the headlines were read and coded according to Table 2. Second, dictionary-assisted searches verified recurrent lexical markers and produced word counts. Third, the coded patterns were interpreted through critical discourse analysis, with attention to transitivity, modality, evaluative intensity, scientific sourcing, and the visibility of response. Six transparent measures were used.

The normalized frequency of a lexical item w per 1,000 headline words is calculated by Equation (1), where f(w) is the observed frequency and N is the total number of words in the corpus.

$$\mathrm{NF(w)} = \frac{\mathrm{f(w)}}{\mathrm{N}} \times 1000 \tag{1}$$

For example, the word climate occurs 14 times in a 230-word corpus: NF(climate) = (14/230) × 1000 = 60.9.

Category prevalence is calculated by Equation (2), where n(j) is the number of headlines containing category j and n = 18.

$$\mathrm{P(j)} = \frac{\mathrm{n(j)}}{\mathrm{n}} \times 100 \tag{2}$$

Thus, explicit climate attribution appears in 12 headlines: P(attribution) = (12/18) × 100 = 66.7%.

Outlet-level category density measures the average number of coded category occurrences per headline. In Equation (3), n(o,j) is the number of occurrences of category j in outlet o and n(o) is the number of headlines from that outlet.

$$\mathrm{D(o)} = \frac{\Sigma\, \mathrm{n(o,j)}}{\mathrm{n(o)}} \tag{3}$$

The attribution-response gap measures the percentage-point distance between headlines naming climate causation and headlines naming preparedness or response.

$$\mathrm{G(AR)} = \mathrm{P(attribution)} - \mathrm{P(response)} \tag{4}$$

The urgency-response ratio compares the number of severity/urgency markers with the number of preparedness/response markers. The max function prevents division by zero in a replication with an outlet that contains no response markers.

$$\mathrm{R(UR, o)} = \frac{\mathrm{n(severity,o)}}{\max[1,\mathrm{n(response,o)}]} \tag{5}$$

Finally, normalized Shannon entropy summarizes the diversity of the six mutually exclusive dominant frames. In Equation (6), p(i) is the share of dominant frame i and k is the number of dominant-frame categories. Values approach 0 when one frame dominates and 1 when all frames are equally distributed.

$$\mathrm{H(N)} = -\frac{\Sigma\, \mathrm{p(i)\ ln\ p(i)}}{\ln \mathrm{k}} \tag{6}$$

Because this is a single-author exploratory study, no inter-coder reliability coefficient is claimed. Transparency is instead supported by explicit definitions, disclosed category counts, worked calculations, and a corpus structure that can be independently checked.

3. Results

3.1. Overall frame prevalence

Three categories dominate the corpus: explicit climate attribution, severity/urgency, and quantification/evidence each occur in 12 of 18 headlines (66.7%). Human impact appears in seven headlines (38.9%), uncertainty/qualification in six (33.3%), preparedness/response in three (16.7%), and economic/infrastructural consequences in two (11.1%). Table 3 provides the complete outlet comparison.

The distribution reveals a systematic asymmetry. The corpus is strong at naming climate causation, danger, and evidential authority, but weak at naming response options, responsible institutions, or adaptive capacity. Readers are four times more likely to encounter an urgency marker than a response marker in the sampled headlines.

Table 3

Frame prevalence by outlet, n (%)

Frame category	Reuters	Associated Press	The Guardian	Total
Explicit climate attribution	4 (66.7)	5 (83.3)	3 (50.0)	12 (66.7)
Human impact	1 (16.7)	4 (66.7)	2 (33.3)	7 (38.9)
Severity/urgency	4 (66.7)	2 (33.3)	6 (100.0)	12 (66.7)
Quantification/evidence	3 (50.0)	4 (66.7)	5 (83.3)	12 (66.7)
Preparedness/response	1 (16.7)	1 (16.7)	1 (16.7)	3 (16.7)
Uncertainty/qualification	4 (66.7)	1 (16.7)	1 (16.7)	6 (33.3)
Economic/infrastructure	1 (16.7)	0 (0.0)	1 (16.7)	2 (11.1)

Note: Categories are non-exclusive; therefore, column totals exceed the number of headlines. Source: Author's coding.

3.2. Outlet-specific patterns and derived indicators

Figure 1 visualizes the outlet differences. Reuters combines attribution with frequent epistemic qualification; AP most consistently connects climate attribution to human-centred consequences; and The Guardian uses severity/urgency language in all six headlines. The figure also shows that preparedness/response remains equally rare across all outlets.

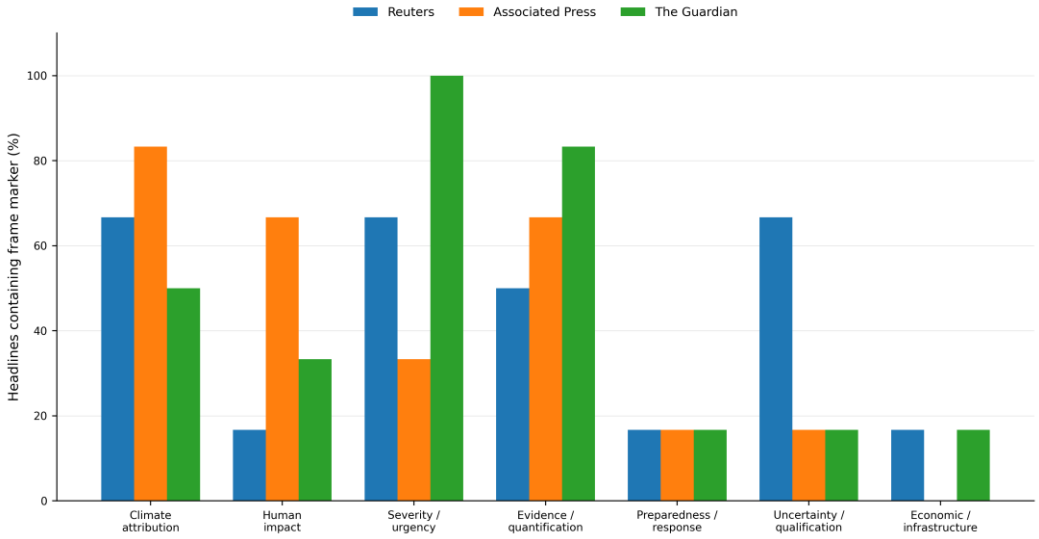


Fig. 1. Percentage of headlines containing each frame marker, by outlet
Source: Author's calculations based on the 18-headline corpus.

The derived indicators in Table 4 make the imbalance more explicit. Category density is calculated from the total number of coded occurrences in each outlet: Reuters has 18 occurrences, AP 17, and The Guardian 19. The Guardian therefore has the densest framing profile (3.17 markers per headline), while AP has the lowest (2.83).

Table 4

Derived quantitative indicators

Outlet	Category occurrences	Density D(o)	Attribution-response gap (pp)	Urgency-response ratio
Reuters	18	18/6 = 3.00	(4−1)/6 × 100 = 50.0	4/1 = 4.00
Associated Press	17	17/6 = 2.83	(5−1)/6 × 100 = 66.7	2/1 = 2.00
The Guardian	19	19/6 = 3.17	(3−1)/6 × 100 = 33.3	6/1 = 6.00
Overall	54	54/18 = 3.00	(12−3)/18 × 100 = 50.0	12/3 = 4.00

Source: Author's calculations from Table 3. pp = percentage points.

The overall attribution-response gap equals 50 percentage points: 66.7% of headlines name climate attribution, but only 16.7% name preparedness or response. AP records the largest attribution-response gap (66.7 points) because attribution is highly visible while response remains rare. The Guardian records the highest urgency-response ratio (6.00), meaning that urgency markers outnumber response markers six to one. Reuters occupies an intermediate position, whereas AP's ratio of 2.00 reflects its stronger orientation toward human consequences and quantification rather than uniformly intensified crisis language.

3.3. Dominant frames, lexicalization, and agency

When one dominant frame is assigned to each headline, scientific attribution leads with six items (33.3%), followed by human consequences with five (27.8%). Uncertainty / qualification, adaptation / preparedness, and crisis / urgency each account for two headlines (11.1%), while economic/systemic loss accounts for one (5.6%). Substitution of these shares in Equation (6) gives H(N) = 0.901, approximately 0.90. Dominant frames are therefore relatively diverse, even though response-oriented framing remains infrequent.

The lexical calculations support this interpretation. Climate occurs 14 times (60.9 per 1,000 words), change eight times (34.8), heat five times (21.7), floods four times (17.4), and crisis three times (13.0). Scientific authorization is signalled by study/studies four times, scientists twice, report twice, and data once. Numbers such as twice, 45 times, death totals, wind-speed increments, and financial losses convert abstract risk into measurable scale.

Causal agency is frequently encoded through active transitive verbs: climate change made, climate change doubles, climate change goosed, climate crisis exposed, and climate crisis to blame. These constructions reduce ambiguity about the relation between anthropogenic warming and hazardous outcomes. However, climate change often functions as an abstract grammatical actor, while fossil-fuel production, land-use decisions, infrastructure inequality, and regulatory choices remain backgrounded. Scientific causation is visible, but political and institutional responsibility is only partly articulated.

4. Discussion

4.1. Convergence and outlet differentiation

Two thirds of the sampled headlines explicitly connect hazards to climate change, contrasting with earlier coverage in which climate science was often omitted or contested (Antilla, 2005; Boykoff & Boykoff, 2007). Nevertheless, clear outlet differences remain. Reuters emphasizes scientific authority and epistemic qualification, AP combines attribution with measurable human consequences, while The Guardian employs the strongest urgency language. These differences support Carvalho's (2007) argument that shared scientific premises can be framed through different professional and ideological cultures.

4.2. The response deficit and climate efficacy

The most important structural imbalance is the limited visibility of response: only three headlines foreground preparedness or action, producing an attribution-response gap of 50 percentage points and an urgency-response ratio of 4.0. Repeated emphasis on danger without visible efficacy may leave audiences with little indication of who can act or how risks can be reduced. Even within the constraints of headline writing, concise response cues can connect urgency with preparedness, adaptation, or institutional responsibility (Nisbet, 2009).

4.3. Quantification, uncertainty, and climate justice

Quantification strengthens climate-hazard reporting by translating probability, casualties, physical changes, and economic losses into measurable terms, although such figures require appropriate context. Reuters' frequent uncertainty markers also demonstrate that qualification does not necessarily weaken scientific knowledge; rather, it can distinguish between event probability, intensity, frequency, and other dimensions of risk (Painter, 2013).

Human-centred framing is strongest in AP, but vulnerability is represented mainly through immediate consequences rather than structural inequality. A broader climate-justice perspective should also consider differences in exposure, access to protection, infrastructure, socioeconomic conditions, and institutional responsibility.

4.4. Editorial implication: a cause-impact-response model

The findings support a compact cause-impact-response model for climate-hazard reporting. The cause component communicates the strongest available attribution evidence; impact identifies affected people and systems; and response indicates preparedness, adaptation, mitigation, or institutional responsibility. In practical terms, climate-hazard reporting should address four questions: What happened? How is climate change related? Who is most affected and why? What response is possible or required?

5. Conclusion

This study examined 18 climate-hazard headlines from Reuters, the Associated Press, and The Guardian published in 2024. Explicit climate attribution, severity/urgency, and quantification/evidence each appear in 66.7% of the sample. Reuters privileges scientific sourcing and epistemic caution, AP combines attribution with quantified human consequences, and The Guardian uses the most intensive urgency vocabulary.

These calculations clarify the central imbalance. The corpus contains an attribution-response gap of 50 percentage points and an urgency-response ratio of 4.0. The Guardian's ratio reaches 6.0, while AP records the largest attribution-response gap at 66.7 points. Although dominant-frame diversity is high (normalized Shannon entropy = 0.90), preparedness and response remain structurally underrepresented.

The study therefore recommends cause-impact-response framing that connects scientifically grounded attribution with vulnerability, institutional accountability, and feasible action. The corpus is small, limited to three English-language outlets and one calendar year, and headline analysis cannot capture article bodies, images, or audience reception. Future studies should expand the sample, compare headlines with leads and visuals, and apply multiple coders or computational methods. Nevertheless, the transparent coding scheme and worked calculations provide a replicable conference-scale model for studying how climate hazards become public discourse.

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СТРАТЕГИИ ОСВЕЩЕНИЯ КЛИМАТИЧЕСКИХ УГРОЗ В АНГЛОЯЗЫЧНЫХ СМИ: КРИТИЧЕСКИЙ ДИСКУРС-АНАЛИЗ МЕДИЙНЫХ ПУБЛИКАЦИЙ

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Резюме. В исследовании рассматривается, каким образом англоязычные средства массовой информации формируют фреймы климатических угроз посредством лексического выбора, грамматического выражения субъектности, количественных показателей, оценочных средств и эпистемической модальности. Корпус исследования включает 18 новостных заголовков, опубликованных в 2024 году агентствами Reuters, Associated Press и изданием The Guardian, по шесть заголовков от каждого источника. Смешанный методологический подход объединяет фрейм-анализ, критический дискурс-анализ, анализ лексических частот и бинарное кодирование по семи категориям. Прямая атрибуция климатических явлений изменению климата, выражение серьёзности и неотложности угроз, а также использование количественных показателей и доказательств представлены в 12 из 18 заголовков (66,7%) по каждой из указанных категорий. В то же время подготовка к климатическим угрозам и меры реагирования упоминаются лишь в трёх заголовках (16,7%). Разрыв между частотой климатической атрибуции и освещением мер реагирования составляет 50 процентных пунктов, а соотношение частот выражения неотложности и упоминания мер реагирования достигает 4,0. Reuters характеризуется наиболее выраженной эпистемической осторожностью, Associated Press акцентирует внимание на последствиях климатических угроз для человека, тогда как The Guardian демонстрирует наибольшее соотношение частот выражения неотложности и освещения мер реагирования. Доминирующие фреймы характеризуются относительно высоким разнообразием (нормализованная энтропия Шеннона = 0,90), однако фреймирование, ориентированное на меры реагирования, выражено слабо. Полученные результаты обосновывают применение модели «причина–воздействие–реагирование», связывающей атрибуцию климатических явлений с уязвимостью, институциональной ответственностью и практически осуществимыми мерами адаптации или смягчения последствий изменения климата.

Ключевые слова: *климатическая коммуникация, климатические опасности, критический дискурс-анализ, фреймирование, медиадискурс, новостные заголовки*

İNGILISDILLI KÜTLƏVI INFORMASIYA VASITƏLƏRINDƏ IQLIM TƏHLÜKƏLƏRININ IŞIQLANDIRILMASI: MEDIA MATERIALLARININ TƏNQIDI DISKURS TƏHLILI

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Xülasə. Tədqiqatda ingilisdilli kütləvi informasiya vasitələrinin iqlimlə bağlı təhlükələri leksik seçim, qrammatik subyektlik, kəmiyyət göstəriciləri, qiymətləndirmə və epistemik ehtiyatlılıq vasitəsilə necə çərçivələndirdiyi araşdırılır. Tədqiqat korpusu Reuters, Associated Press və The Guardian tərəfindən 2024-cü ildə dərc edilmiş, hər media qurumundan altı olmaqla ümumilikdə 18 xəbər başlığını əhatə edir. Qarışıq metodoloji yanaşma çərçivələndirmə təhlilini, tənqidi diskurs təhlilini, leksik tezlik təhlilini və yeddi kateqoriya üzrə binar kodlaşdırmanı birləşdirir. İqlim dəyişikliyi ilə açıq səbəb əlaqəsinin qurulması, təhlükənin ciddiliyi və təcililiyi, eləcə də kəmiyyət göstəriciləri və sübutlara istinad kateqoriyalarının hər biri 18 başlıqdan 12-də (66,7%) müşahidə edilmişdir. Bunun əksinə olaraq, hazırlıq və cavab tədbirləri yalnız üç başlıqda (16,7%) əks olunmuşdur. Nəticədə iqlim dəyişikliyi ilə səbəb əlaqəsinin qurulması və cavab tədbirlərinin işıqlandırılması arasında 50 faiz bəndi fərq, təcililik və cavab tədbirlərinin qeyd olunma tezlikləri arasında isə 4,0 nisbəti müəyyən edilmişdir. Reuters epistemik ehtiyatlılığın ən yüksək səviyyəsi ilə seçilir, Associated Press iqlim təhlükələrinin insanlara təsirini ön plana çıxarır, The Guardian isə təcililik və cavab tədbirlərinin qeyd olunma tezlikləri arasında ən yüksək nisbətə malikdir. Dominant çərçivələndirmə modelləri nisbətən yüksək müxtəliflik nümayiş etdirsə də (normallaşdırılmış Şennon entropiyası = 0,90), cavab tədbirlərinə yönəlmiş çərçivələndirmə zəif ifadə olunmuşdur. Tədqiqatın nəticələri iqlim dəyişikliyi ilə səbəb əlaqəsinin qurulmasını həssaslıq, institusional cavabdehlik, eləcə də həyata keçirilməsi mümkün olan uyğunlaşma və ya təsirlərin azaldılması tədbirləri ilə əlaqələndirən «səbəb–təsir–cavab tədbirləri» modelinin tətbiqini əsaslandırır.

Açar sözlər: *iqlim kommunikasiyası, iqlim təhlükələri, tənqidi diskurs təhlili, çərçivələndirmə, media diskursu, xəbər başlıqları*

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SUSTAINABLE USE AND CONSERVATION OF WATER RESOURCES IN THE GANJA PHYSICAL-GEOGRAPHICAL REGION

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Keywords: *Ganja Physical-Geographical Region, water resources, rivers, lakes, reservoirs, groundwater, sustainable water management*

Summary. The study examines the sustainable use and conservation of water resources in the Ganja Physical-Geographical Region under increasing water demand and climate-related pressures. The region possesses a diverse hydrographic network consisting of mountain rivers, lakes, reservoirs, groundwater, and springs that support drinking-water supply, agriculture, industry, recreation, and ecosystem functioning. Most rivers originate on the northeastern slope of the Lesser Caucasus and belong to the Kura River basin; with the exception of Aghstafachay, they are generally less than 100 km long. The study shows that river flow is extensively used for irrigation and is regulated by reservoirs and hydraulic structures, while mountain lakes, particularly those within Goygol National Park, constitute important freshwater and ecological resources. At the same time, seasonal water scarcity, inefficient irrigation, pollution, and increasing demand create significant pressures on regional water resources. Sustainable management therefore requires the wider application of water-saving irrigation technologies, improved flow and water-quality monitoring, control of wastewater discharge, protection of groundwater and river corridors, and conservation of water bodies within protected areas. These measures are essential for maintaining the long-term ecological and socioeconomic functions of the region's water resources.

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Introduction

Sustainable use and conservation of water resources have become increasingly important under the growing impacts of climate change and rising water demand. This issue is particularly relevant for Azerbaijan, where water resources are relatively limited and their efficient management is essential for maintaining water supply, agricultural production, and ecological stability.

The Ganja Physical-Geographical Region encompasses the northeastern slope of the Lesser Caucasus and its foothill plains and is characterized by a relatively dense hydrographic network. Its water resources consist primarily of mountain rivers originating in the Murovdagh and Shahdagh ranges, together with groundwater, springs, lakes, and reservoirs. Most rivers belong to the Kura River basin and flow as right tributaries of the Kura. These resources play an important role in drinking-water supply, irrigation, industry, and the functioning of regional ecosystems.

Accordingly, the study focuses on the spatial and hydrological characteristics of the region's principal water resources, their current patterns of use, major environmental pressures, and measures required for their sustainable management and conservation.

Analysis and discussion

The rivers of the Ganja Physical-Geographical Region belong to the Kura River basin and are fed mainly by snow, rainfall, and groundwater. Stable groundwater recharge plays an important role in the annual runoff regime, while relief, geological structure, soil and vegetation cover, basin morphology, lake coverage, wetland conditions, and glaciation influence runoff formation (Mammadov, 2012).

The river network is unevenly distributed across the region and varies considerably with elevation. Drainage density generally increases toward mountainous areas and is particularly high in the middle-mountain zone, where most rivers originate. However, this relationship is also controlled by precipitation and other local physical-geographical conditions. Surface water and groundwater together determine the regional water-resource potential, while the relative contribution of individual alimentation sources is reflected in the hydrological regime (*Constructive Geography of the Republic of Azerbaijan*, 1996–1999).

Rivers constitute the principal component of the region's water resources. With several exceptions, including Aghstafachay and Hasansuchay, most originate within the Azerbaijani part of the Lesser Caucasus and are extensively used for irrigation, domestic water supply, and other economic purposes.

Hasansuchay originates in the Murguz Range of the Lesser Caucasus and is a transit river fed mainly by snow and groundwater. Its lower reaches carry significant flow primarily during periods of heavy precipitation because its water is extensively used for irrigation. Summer floods, particularly in June and July, coincide with high agricultural water demand, emphasizing the need for efficient use while maintaining sufficient downstream flow (Museyibov, 1998).

Aghstafachay, another transit river, originates in the Pambak Range and is fed by groundwater, snowmelt, and rainfall. Its flow is regulated by a reservoir and is extensively used for irrigation. The river generally maintains a high-flow regime until the end of June, providing favorable conditions for seasonal water use.

Akhynchachay originates near the Bashkent Pass of the Kecheldagh Range. Its water resources are particularly important during summer, when heavy rainfall can increase discharge in July (Ayyubov & Hajiyev, 1984). A reservoir regulates its flow for irrigation. Its tributary Tovuzchay, originating in the Murguz Range, is also a transit river and is regulated by the Khatinli Reservoir. More than four main canals withdraw water for irrigation, while upstream water use reduces the flow entering Azerbaijan. The river is also exposed to pollution associated with industrial activities within its basin.

Asrikchay, a right tributary of Akhynchachay, is formed by small spring-fed rivers originating in the Shahdagh Range. Rainfall and groundwater constitute its principal sources of alimentation. The river has hydrorecreational importance and is also intensively used for irrigation through five main canals.

Zayamchay originates on the northern slope of the Shahdagh Range at the confluence of Shakarbaychay and Chatindara rivers and drains parts of Shamkir, Tovuz, and Gadabay districts. It is fed by groundwater, rainfall, and snowmelt and is characterized by a spring high-water regime. Its irrigation use is supported by small hydraulic structures that regulate river discharge.

Shamkirchay is one of the region's most important rivers. It originates on the northeastern slope of the Shahdagh Range at the confluence of Sarisu and Aghdashsu rivers. Goygol, situated at an elevation of 2,470 m, contributes to the Shamkirchay system through one of the Sarisu tributaries, and its regulated outflow provides additional water during periods of intensive irrigation. Shamkirchay is also connected with Ganjachay by an irrigation canal and has important irrigation, hydrorecreational, and ecological functions (Mammadov, 2012).

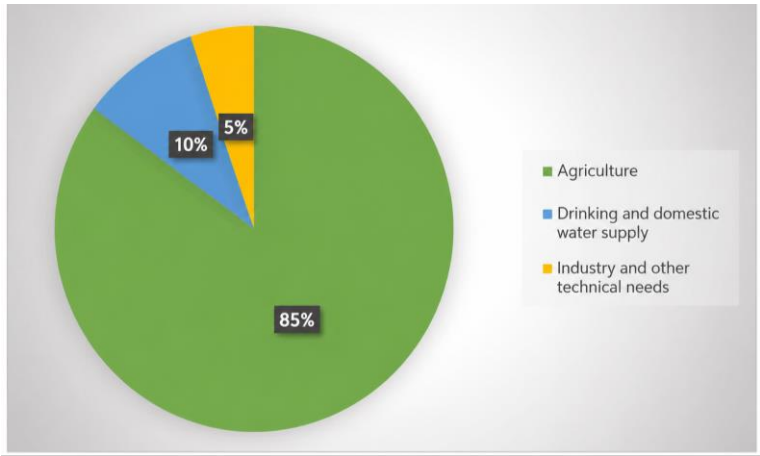


Fig. 1. Distribution of Shamkirchay River water use by sector (%).

Goshgarchay originates on the northern slope of Mount Goshgar in the Murovdagh Range and is formed by the confluence of Khoshbulag and Hamamchay, the latter being supplied by permanent springs. Its upper basin has a dense river network. Although its water is used in agriculture and industry, contamination by mining waste restricts its effective use.

The water resources of other rivers of the Ganja Physical-Geographical Region, including Ganjachay, Goranchay and Incechay, are also used for irrigation. The Rasul and Khan channels have been constructed from Ganjachay, supplying water for irrigation around Ganja. More than seven channels withdraw water from Goranchay for irrigation of surrounding areas. The water of Incechay does not reach the Kura River because it is fully utilized; more than five main canals withdraw water from the river. Analysis of the hydrological characteristics and sustainable use of Aghsuchay and Kurekchay shows that several lakes were formed in the Aghsuchay valley as a result of earthquakes. The largest of these lakes is Goy-Gol. Kurekchay is formed by the confluence of three rivers—Ilkhidara, Omerchay and Banovshachay. Hydrologically, Ilkhidara is regarded as the principal river. Kurekchay flows into the Kura River downstream of the Mingachevir Reservoir. Because rural settlements are located along the river, its water is widely used for irrigation.



Fig. 2. Ganjachay River (Topalhasanli village).

A portion of the water resources of the Ganja Physical-Geographical Region is concentrated in lakes. As noted above, landslide-dammed lakes were formed when the collapse of Mount Kapaz during an earthquake blocked the course of Aghsuchay. The picturesque mountain lakes Goygol, Maralgol, Zeligol, Shamligol and others are located within forest and subalpine meadow zones and constitute freshwater sources. The lakes are distinguished by their transparency, with visibility reaching depths of approximately 13 m. Because Goygol has an outlet, its water is used as a source of freshwater.

In the vicinity of Mount Kapaz in the Ganja Physical-Geographical Region, in addition to Goygol, there are Maralgol, Zeligol, Ordekgol, Shamligol, Aynagol, Garagol, Jeyrangol, Ayigol, Chiligol and Qushgol. All of these lakes are freshwater bodies. They have exceptional economic importance within the ecological-recreational system and water-resource balance of the physical-geographical region. The lakes are used sustainably for various purposes and constitute the area's greatest tourism and recreation potential. These lakes are located within Goygol National Park. Their therapeutic and recreational significance is considerable. Because the lakes are situated in mountain-forest and subalpine meadow zones, the area is characterized by clean, oxygen-rich air and a cool microclimate. Mountain lakes are sources of clean, high-quality freshwater and also play a major role in river alimentation (N. N. Hajiyeva, Economic-Geographical Assessment of the Natural Conditions and Resources of Azerbaijan, Ganja, 2025, p. 178, Star Printing House).

The Ayigol, Chiligol and Qushgol (Ordekgol) lakes were formed when landslides caused by the Ganja earthquake blocked river valleys. Ayigol is a small freshwater lake located at the intersection of dense mountain forests and meadow zones. According to the results of the studies, the lake was named in connection with the presence of mountain fauna, particularly Caucasian brown bears, which found shelter in the surrounding forests and came to the area to drink water. Chiligol, located in Goygol National Park, is one of the small lakes. Its water is shallow and relatively marshy. It is called Chiligol because dense aquatic vegetation, including reeds and other wetland plants, grows both on its surface and underwater.



Fig. 3. Goygol Lake.

Among the small lakes in the Goygol and Maralgol basins, Qushgol (Duck Lake) was formed as a result of an earthquake. It received this name because various species of mountain and aquatic birds, particularly ducks, are abundant around and on the water.

All three lakes are fed mainly by snow, rainfall and springs. Their water is cold and transparent. They are located within Goygol National Park and are of considerable importance as water resources.

It should be noted that rivers originating from the lakes or enriched by their outflow play a major role in supplying settlements in the Ganja–Goygol area with drinking water. Lakes are highly important for regulating groundwater in the Ganja Physical-Geographical Region. They contribute to maintaining a continuous supply of water to springs and groundwater in surrounding areas. The hydrographic network formed by these lakes is vital for agriculture in foothill and lowland areas. During the summer irrigation season, lake water resources are intensively utilized. Water from rivers flowing out of the lakes is used to irrigate cultivated lands in Ganja, Dashkasan and Goygol districts.

The Shamkir Reservoir, which concentrates a portion of the water resources of the Ganja Physical-Geographical Region, receives the inflow of up to seven small rivers and contains up to four small lakes within its basin. Since 1956, the lake has functioned as an artificial water body and has been used to regulate the flow of Shamkirchay. It is an outflowing freshwater body.

The lakes located in the Ganja Physical-Geographical Region regulate air humidity within the mountain-forest ecosystem, moderate the microenvironment and function as natural reservoirs that help prevent soil erosion. Since the lakes mentioned above are included within specially protected natural areas, their economic use is primarily carried out within the framework of protected ecotourism, scientific research and sustainable water supply.

As shown in Table 1, water resources are used most extensively for domestic purposes, agriculture and industrial activities.

Over the past century, significant changes have been observed in various components of natural conditions. Excessive exploitation of natural resources, particularly water resources, as well as inefficient use of these resources, has contributed to the emergence of various problems. The conservation of water resources is therefore extremely important under present conditions and constitutes a foundation of environmental policy (Sh. Goychayli and Telman Ismayilov, Economic and Environmental Foundations of Nature Management, MBM, 2009).

The Ganja Physical-Geographical Region is among the areas with a relatively high population density. Adequate water supply and good water quality are highly important for human health and agricultural development. Excessive use of water resources can lead to water losses in some locations, particularly in depressed areas of the relief. Sanitary protection zones should therefore be established around water sources to conserve water and improve its environmental quality.

Table 1

Sustainable use and conservation of the water resources of Ganjachay and Goshgarchay

Water resource / problem	Area of use	Main threat	Sustainable use and conservation measure
Ganjachay	Irrigation, domestic and economic use	Pollution, seasonal decline in water availability	Wastewater treatment, water conservation, and establishment of riparian protection zones
Goshgarchay	Water management and ecosystem	Seasonal decline in water availability and pollution	Flow monitoring and control of wastewater discharge
Groundwater	Drinking water and domestic use	Over-abstraction and pollution	Setting limits on water abstraction and conducting regular hydrogeological monitoring
Irrigation water	Agriculture	Water wastage and losses	Application of drip and sprinkler irrigation systems
River ecosystems	Biodiversity and ecological balance	Domestic and industrial waste	Prevention of waste discharge into rivers and strengthening environmental control
Overall water-resource management	Population and economic activity	Increasing aridity and water scarcity	Calculation of the water balance, water reuse, and public awareness

Constant attention should be paid to the maintenance and repair of the small water-regulating reservoirs constructed within the physical-geographical region. Otherwise, prolonged use may lead to water leakage from reservoirs. Population growth and increasing water demand are observed every year. Although water has traditionally been regarded as a renewable resource, there is a growing concern regarding the depletion of drinking-water resources. Water resources play an indispensable role in regulating the natural conditions and ecological processes of the physical-geographical region. Their most important ecological function is their participation in photosynthesis. Due to its multifunctional properties, water contributes to the formation of natural conditions and is regarded as an indispensable natural resource for meeting human needs.

Conclusion

The water resources of the Ganja Physical-Geographical Region are of major importance in terms of the area's natural conditions, the domestic needs of the population and agricultural development.

• The principal objective of sustainable water-resource use is to ensure that the quality and quantity of existing water resources are preserved for future generations while they are being utilized.

• In agriculture, it is necessary to reduce water losses, particularly losses in irrigation systems and canals, and to widely apply water-saving technologies.

• Pollution of Ganjachay and other water bodies in the Ganja Physical-Geographical Region should be prevented, particularly by preventing the discharge of domestic and industrial waste into rivers.

• Protective zones should be established along riverbanks, and regular environmental monitoring should be conducted.

• Particular attention should be paid to the protection of groundwater in the region. Excessive groundwater abstraction reduces reserves, while pollution creates problems for drinking-water supply.

• Among the water resources of the Ganja Physical-Geographical Region, Shamkirchay, Tovuzchay and Asrikchay are of particular importance and occupy an important position in the water-resource system. Water quality should be monitored to ensure the sustainable use of these rivers.

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РАЦИОНАЛЬНОЕ ИСПОЛЬЗОВАНИЕ И ОХРАНА ВОДНЫХ РЕСУРСОВ ГЯНДЖИНСКОГО ФИЗИКО-ГЕОГРАФИЧЕСКОГО РАЙОНА

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Резюме. В исследовании рассматриваются вопросы устойчивого использования и охраны водных ресурсов Гянджинского физико-географического района в условиях возрастающей потребности в воде и усиления воздействия факторов, связанных с изменением климата. Район характеризуется разнообразной гидрографической сетью, включающей горные реки, озёра, водохранилища, подземные воды и родники, которые играют важную роль в обеспечении питьевого водоснабжения, сельского хозяйства, промышленности, рекреационной деятельности и функционирования экосистем. Большинство рек берёт начало на северо-восточном склоне Малого Кавказа и относится к бассейну реки Куры. За исключением Агстафачая, их протяжённость, как правило, составляет менее 100 км. Результаты исследования показывают, что речной сток широко используется для орошения и регулируется посредством водохранилищ и гидротехнических сооружений. Вместе с тем горные озёра, особенно расположенные на территории Гёйгёльского национального парка, представляют собой важные ресурсы пресной воды и имеют значительную экологическую ценность. Одновременно сезонный дефицит воды, неэффективное использование водных ресурсов в оросительных системах, загрязнение и растущий спрос на воду создают существенную нагрузку на водные ресурсы региона. В связи с этим устойчивое управление водными ресурсами требует более широкого внедрения водосберегающих технологий орошения, совершенствования мониторинга речного стока и качества воды, усиления контроля за сбросом сточных вод, охраны подземных вод и приречных территорий, а также сохранения водных объектов в пределах особо охраняемых природных территорий. Реализация указанных мер имеет важное значение для долгосрочного сохранения экологических и социально-экономических функций водных ресурсов исследуемого района.

Ключевые слова: *Гянджинский физико-географический район, водные ресурсы, реки, озёра, водохранилища, подземные воды, устойчивое управление водными ресурсами*

GƏNCƏ FİZİKİ-COĞRAFİ RAYONUNUN SU EHTİYATLARINDAN DAYANIQLI İSTİFADƏ VƏ ONLARIN QORUNMASI

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Xülasə. Tədqiqatda suya tələbatın artması və iqlim dəyişmələri ilə əlaqədar təzyiqlərin güclənməsi şəraitində Gəncə fiziki-coğrafi rayonunun su ehtiyatlarından davamlı istifadə və onların mühafizəsi məsələləri araşdırılmışdır. Rayon içməli su təchizatı, kənd təsərrüfatı, sənaye, rekreasiya və ekosistemlərin fəaliyyəti üçün mühüm əhəmiyyət daşıyan dağ çayları, göllər, su anbarları, yeraltı sular və bulaqlardan ibarət zəngin və müxtəlif hidroqrafik şəbəkəyə malikdir. Çayların əksəriyyəti Kiçik Qafqazın şimal-şərq yamacından başlanır və Kür çayı hövzəsinə aiddir. Ağstafaçay istisna olmaqla, onların uzunluğu əsasən 100 km-dən azdır. Tədqiqat göstərir ki, çay sularından suvarma məqsədilə geniş istifadə olunur və onların axımı su anbarları və hidrotexniki qurğular vasitəsilə tənzimlənir. Bununla yanaşı, dağ gölləri, xüsusilə Göygöl Milli Parkının ərazisində yerləşən göllər mühüm şirin su mənbələri və ekoloji ehtiyatlar hesab olunur. Eyni zamanda, mövsümi su çatışmazlığı, suvarma sistemlərində sudan səmərəsiz istifadə, çirklənmə və suya tələbatın artması regionun su ehtiyatlarına ciddi təzyiq göstərir. Buna görə də su ehtiyatlarının davamlı idarə olunması suya qənaət edən suvarma texnologiyalarının daha geniş tətbiqini, çay axımı və suyun keyfiyyəti üzrə monitorinqin təkmilləşdirilməsini, tullantı sularının axıdılmasına nəzarətin gücləndirilməsini, yeraltı suların və çayboyu ərazilərin mühafizəsini, eləcə də xüsusi mühafizə olunan təbiət ərazilərində yerləşən su obyektlərinin qorunmasını tələb edir. Bu tədbirlərin həyata keçirilməsi rayonun su ehtiyatlarının ekoloji və sosial-iqtisadi funksiyalarının uzunmüddətli qorunub saxlanılması baxımından mühüm əhəmiyyət kəsb edir.

Açar sözlər: *Gəncə fiziki-coğrafi rayonu, su ehtiyatları, çaylar, göllər, su anbarları, yeraltı sular, su ehtiyatlarının dayanıqlı idarə edilməsi*

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SOLAR-ENERGY POTENTIAL OF OPTIMALLY ORIENTED AREAS OF THE WRINKLED TERRAIN ON THE NORTHERN COASTAL ZONE OF THE MINGECHEVIR RESERVOIR

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Keywords: *Mingechevir Reservoir, solar energy, photovoltaic orientation, terrain aspect, digital elevation model, Global Solar Atlas, ERA5, MERRA-2, time of use*

Summary. This study evaluates the solar-energy potential of naturally inclined terrain along a 200 m-wide landward strip of the wrinkled northern coast of the Mingechevir Reservoir, Azerbaijan. The study line extends from map-derived point A (41.0028° N, 46.6509° E) to point B (40.8000° N, 47.1127° E). The methodology combines the "time-of-use" optimal-orientation approach of Gardashov (2022), terrain slope and aspect screening, and long-term solar-resource information from the Global Solar Atlas, ERA5 and MERRA-2. To prevent positional uncertainty from including reservoir water or deep inland terrain, the endpoints are treated as along-shore anchors, the shoreline is traced between their nearest coastal positions, and a one-sided 200 m landward buffer defines the study polygon. Annual, spring/summer and autumn/winter target orientations were taken as 34°/180°, 19°/180°, and 56°/180° (tilt/azimuth), respectively, with stated angular tolerances. In the numerical terrain model, the georeferenced shoreline and the Copernicus GLO-30 DEM tiles were used. The screening indicates that the north shore is structurally favourable because many slopes face generally south towards the reservoir. The estimated suitable terrain area is largest for summer and spring-autumn orientations, smaller for the annual orientation, and limited for the steep winter orientation. The results support the concept of using naturally oriented coastal slopes for PV placement, while demonstrating that final engineering quantities require direct high resolution DEM, land-cover, geotechnical and grid-access data.

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1. Introduction

Mingechevir Reservoir is located on the Kura River in central-western Azerbaijan and was created as part of the Soviet-era hydroelectric and water-management development of the region. The reservoir and its dam-hydroelectric complex supported the establishment and growth of the modern city of Mingachevir. A total engineered capacity is approximately 16 billion m³ and there is a relationship between the reservoir, the dam and the city that developed around the power project (NASA Earth Observatory, 2010).

The reservoir remains economically important for hydropower, water regulation, irrigation, fisheries, recreation and regional development. Mingachevir is widely regarded as one of Azerbaijan's principal energy centres; official information indicates that a large share of the country's electricity generation is concentrated in Mingachevir, reflecting both its hydropower legacy and its later thermal-power infrastructure (President of the Republic of Azerbaijan, 2025). The reservoir is also Azerbaijan's largest and supports boating, fishing, tourism and biodiversity-related activities (Azerbaijan Tourism Board, 2026).

The northern coastal zone shown in Fig 1 consists of elongated, eroded hills and slopes that descend generally southwards towards the reservoir. This geometry is potentially favourable for fixed photovoltaic

installations because south-facing terrain can naturally approximate the azimuth and tilt of an optimally oriented PV panel. The current study aims to identify shares of the terrain whose slope and aspect fall within prescribed neighborhoods of annual or seasonal optimum panel orientations and to estimate their solar-resource characteristics.

The present work extends the "time-of-use" orientation concept proposed by Gardashov (2022) which is based on the research of Gardashov et al. (2000). In that approach, daily optimal tilt and incident direct solar energy are combined using energy weights to obtain the optimal orientation for any selected time interval. Here, the same concept is applied to the terrain itself: a DEM cell is considered naturally suitable when its tilt and azimuth are sufficiently close to the target PV orientation for the selected period.



Fig. 1. Google Earth view of the Mingechevir Reservoir and the map-derived northern-shore study line from A to B.

2. Description of the study area and data sources

The adopted endpoints are A = 41.0028° N, 46.6509° E and B = 40.8000° N, 47.1127° E. Their uncertainty is accepted only along the shoreline. Cross-shore uncertainty is removed by snapping the points to the northern water-land boundary and constructing a one-sided buffer extending 200 m landward. The preliminary traced shoreline length is approximately 45.3 km, giving a nominal corridor (coastal zone) area of about 9.07 km² before exclusions.

The Global Solar Atlas reports Azerbaijan-wide long-term ranges of approximately 3.44–4.80 $kWh\ m^{-2}\ day^{-1}$ for GHI, 3.82 − 5.56 $kWh\ m^{-2}\ day^{-1}$ for optimum-tilt irradiation and 29-37° for optimum annual tilt (World Bank/ESMAP and Solargis, 2026). The annual target tilt of 34° adopted here lies within that range. ERA5 and MERRA-2 are included in the final workflow to calculate monthly means, variability, minima and maxima, and to cross-check the atlas climatology (Gelaro et al., 2017; Hersbach et al., 2020). The information about data sources and their role in the current study is given in Table 1.

Table 1

Data sources and their role in the analysis

Source	Role	Important qualification
Supplied Google Earth map	A-B endpoints and visual shoreline geometry	Map-derived; approximate
Copernicus DEM GLO-30	Elevation, slope and aspect for final GIS model	30 m DSM; final recommended source
Global Solar Atlas	Long-term GHI, DNI, GTI and optimum tilt	1994/1999/2007-2018 climatology, source dependent
ERA5	Hourly surface solar radiation and meteorology	1940-present; reanalysis
MERRA-2	Hourly solar and atmospheric fields	1980-present; independent reanalysis
Gardashov (2022)	Energy-weighted "time-of-use" optimal orientation	Published mathematical/software method

3. Methodology

Shoreline-constrained terrain corridor

The shoreline is treated as the water-land boundary. The A-B shoreline segment is selected and a 200 m one-sided landward buffer is formed. Reservoir-water cells are excluded by the water mask, and all terrain beyond 200 m inland is removed. This procedure implements the clarification that endpoint uncertainty may act along the coastal line but must not place the study area in water or deep inland terrain.

Terrain tilt and azimuth

For a georeferenced elevation surface $z(x, y)$, the local gradients $\partial z/\partial x$ and $\partial z/\partial y$ are calculated.

Terrain tilt θ and downslope azimuth φ are obtained from $\beta = \arctan\sqrt{(\partial z/\partial x)^2 + (\partial z/\partial y)^2}$ and the four-quadrant aspect relation. Flat or unreliable water-mask cells are omitted. Copernicus GLO-30 is used because it provides open 30 m elevation data; it is technically a digital surface model and therefore may include vegetation and structures (Copernicus Programme, 2024).

"Time-of-use" optimal orientation

Gardashov (2022) defines the optimal tilt, $\theta_{opt\_time\ of\ use}$, for a selected time interval ("time-of-use") by weighting daily optimal tilts θ_{opt_i}, (i = 1,2, … ,365) with the corresponding incident direct solar energy S_i:

$$\theta_{opt\_time\ of\ use} = \sum_{i=i_1}^{i_2} \theta_{opt\_i} \cdot p_i\,,\quad p_i = S_i / \sum_{j=i_1}^{i_2} S_j$$

Where, i_1 and i_2 the day numbers of year between which optimal direction of panel for "time of use" should be found.

The same principle can be applied to azimuth through a circular energy-weighted mean. In Table 2 for the present calculation, the adopted south-facing target orientations and tolerances are listed.

Table 2

Target PV orientations and screening tolerances

Period	Target tilt (°)	Target azimuth (°)	Tilt tolerance, $\Delta\theta$	Azimuth tolerance, $\Delta\varphi$
Annual	34	180	±6°	±20°
Spring	19	180	±6°	±20°
Summer	19	180	±6°	±20°
Autumn	56	180	±6°	±20°
Winter	56	180	±6°	±20°

A terrain cell is classified as suitable when $|\theta - \theta_{opt}| \leq |\Delta\theta|$ and the circular azimuth difference $|\varphi - \varphi_{opt}| \leq |\Delta\varphi|$. Adjacent suitable cells are grouped into numbered regions. The area of the suitable region equals to the number of selected cells multiplied by the projected cell area.

Solar irradiation on selected relief

The final calculation uses hourly direct normal irradiation (DNI), diffuse horizontal irradiation and global horizontal irradiation, followed by a transposition model for each cell's tilt and azimuth. The beam component is obtained from DNI multiplied by the cosine of the incidence angle; diffuse and ground-reflected terms can be estimated with an isotropic, Hay-Davies or Perez model (Duffie & Beckman, 2013; Perez et al., 1990). Monthly and annual energy are summed over time. ERA5 and MERRA-2 provide independent long-term atmospheric forcing, whereas the Global Solar Atlas provides a high-resolution long-term benchmark.

For the preliminary numerical tables, an annual horizontal resource of approximately 1585 $kWh\ m^{-2}\ yr^{-1}$ and an annual optimum-plane resource of approximately 1875 $kWh\ m^{-2}\ yr^{-1}$ were adopted, consistent with the central part of the Azerbaijan-wide Global Solar Atlas ranges. Seasonal values were distributed using a representative monthly climatology. These values are assumptions and they are replaced by the extracted site-specific grids in the final version.

4. Results and discussion

Fig 2(a) presents the 3D terrain model of the 200m wide A-B landward corridor (coastal zone). In Fig. 2(b), the annual suitable areas indicated as 1 and 2, are shown. Fig. 2(c) presents these same areas 1 and 2 in geographical coordinates (latitude, longitude). Fig 3 and Fig 4 present the suitable areas for Autumn/Winter and Spring/Summer periods, respectively. Fig 5 represents monthly irradiation distribution. In Table 3 the annual suitable regions and their estimated areas are given. In Table 4 the Autumn/Winter and in Table 5 Spring/Summer -suitable regions and their estimated areas are presented. In Table 6, the solar energy resource indicators for the optimal orientation periods (annual, spring/summer, autumn/winter) are presented.

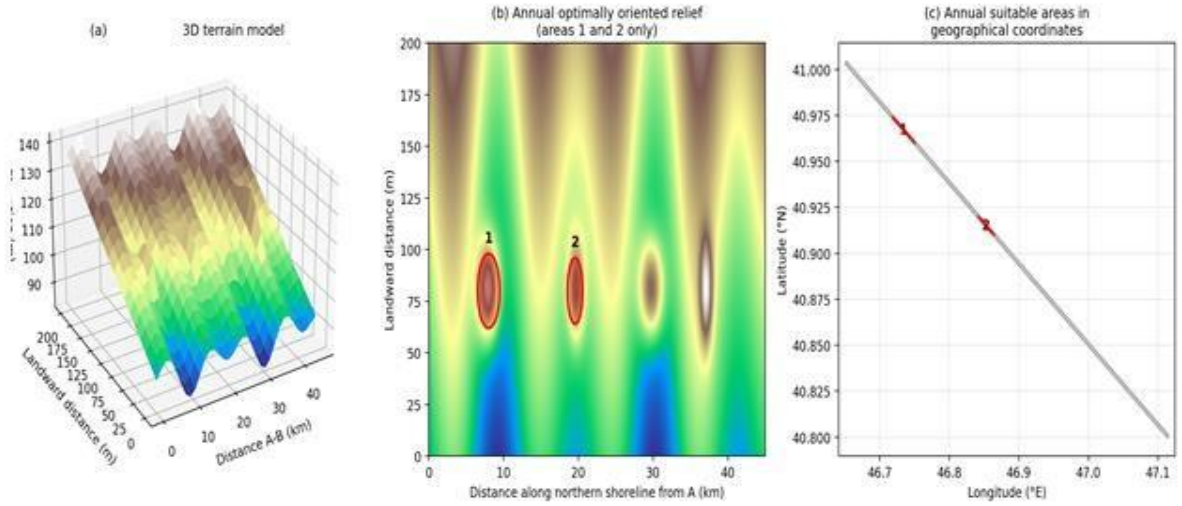


Fig. 2. (a) 3D model of the A-B landward corridor; (b) annual suitable areas 1 and 2; (c) annual suitable areas 1 and 2 presented in geographical coordinates (lat, lon).

Table 3

Annual suitable regions

Region No.	Start from A (km)	End from A (km)	Area (m²)
1	6.56	9.49	56,293
2	18.56	20.59	34,194

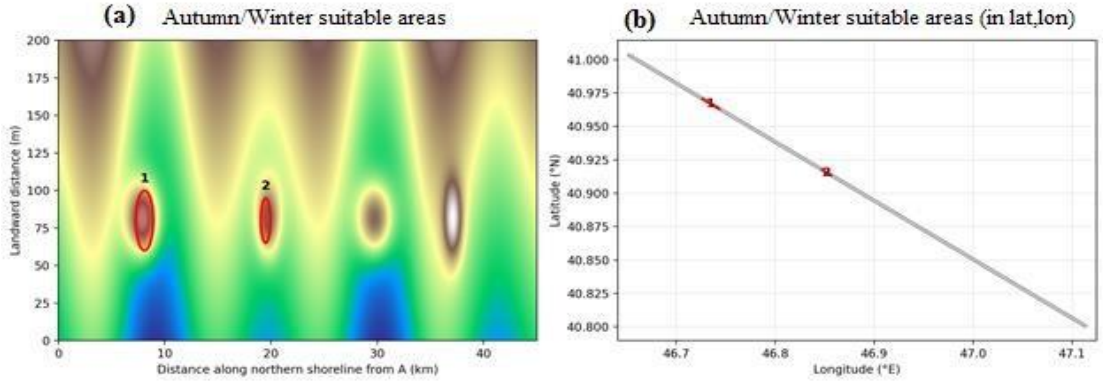


Fig 3. (a) Autumn/Winter suitable areas 1 and 2; (b) Autumn/Winter suitable areas 1 and 2 presented in geographical coordinates (lat, lon).

Table 4

Autumn/Winter -suitable regions

Region No.	Start from A (km)	End from A (km)	Area (m²)
1	7.29	8.93	35,823
2	19.05	19.96	14,655

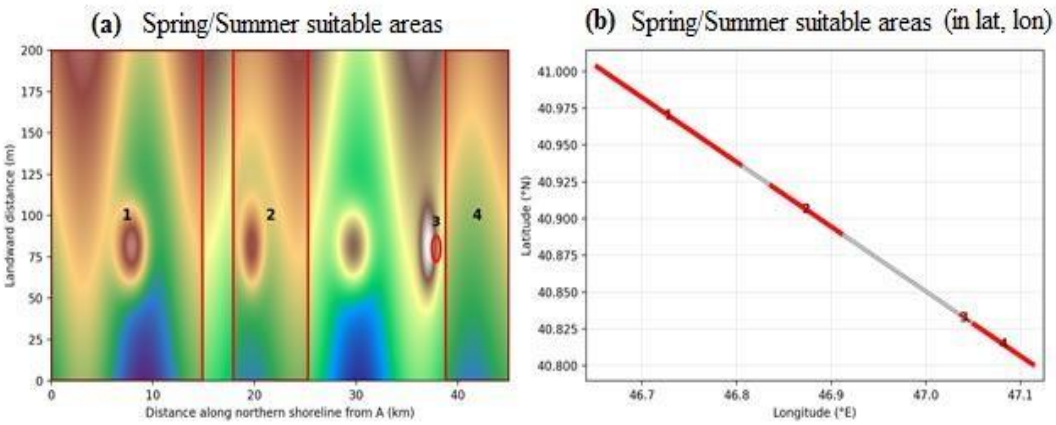


Fig 4. (a) Spring/Summer suitable areas 1, 2, 3 and 4; (b) Spring/Summer suitable areas 1, 2, 3 and 4 presented in geographical coordinates (lat, lon).

Table 5

Spring/Summer -suitable regions

Region No.	Start from A (km)	End from A (km)	Area (m²)
1	0.00	14.90	2,804,408
2	17.93	25.26	1,276,127
3	37.44	38.31	6,513
4	38.80	45.01	1,221,462

Table 6

Areas and solar-resource indicators for the annual and seasonal optimal orientation periods

Period	Target tilt (deg)	Target azimuth (deg)	Area (m²)	Mean energy (kWh m^{-2} $period^{-1}$)	Mean irradiance (W m^{-2})
Annual	34	180	90487	1875	214
Spring/Summer	19	180	5308510	659	305
Autumn/Winter	56	180	50477	422	195

As can be seen from Table 6, the optimal tilted area for spring/summer is approximately 50 times larger than the annual optimal tilted area and 100 times larger than the optimal tilted area for autumn/winter. At the same time, for autumn/winter period, the annual and autumn/winter optimally tilted areas receive approximately the same amount of irradiation; for summer period the annual and summer/spring optimally tilted (Fig. 5). As a result of information presented in Table 6 and in Fig 5, we obtain final assessment of solar energy potentially available for production (Table 7). The yearly produced solar energy is greater in summer/spring tilted areas and it is about 1.4 mil. MWh. This is enough to meet the electricity demands of approximately 226,000 businesses (residential buildings, infrastructure facilities, etc.) with a monthly consumption of 500 kWh. The Mingechevir Reservoir and its coastal zone are intensively used to support sport boating, fishing, tourism, and ecology-related activities, and therefore the use of clean energy is extremely important in that region.

The principal physical advantage of the northern shore is its generally south-facing downslope direction. Unlike a flat site, where mounting structures must create the complete tilt, naturally inclined terrain can reduce earthworks and support rows that follow the relief. However, favorable slope and aspect alone do not establish constructability. Geotechnical stability, erosion, drainage, access roads, vegetation, land ownership, protected zones, reservoir-level variation and grid distance must also be assessed.

The estimated areas depend strongly on angular tolerance. Narrower tolerances increase optical similarity to the ideal PV plane but reduce usable land and may fragment the selected regions. Wider tolerances increase area but can introduce shading, row-layout and non-uniformity problems. A final multi-criteria model should therefore optimize energy, grading cost, cable length, erosion risk and ecological constraints simultaneously.

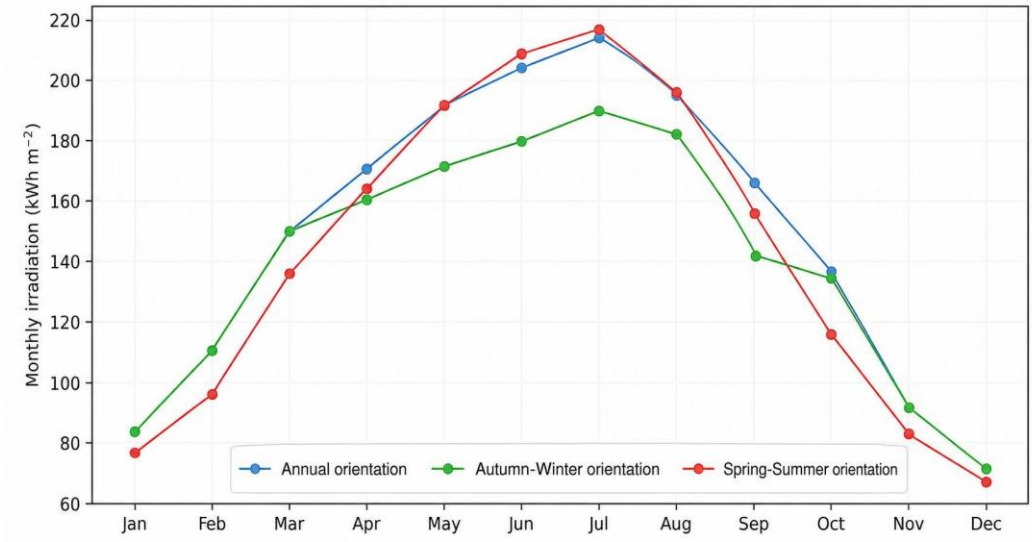


Fig 5. Monthly irradiation for optimally oriented areas in annual, autumn/winter, and spring/summer

Table 7

The Annual, Spring/Summer and Autumn/Winter optimal oriented areas solar energy indicators

Month	**Annual GTI opt** (kWh m^{-2})	**Annual GTI opt to Area** (MWh)	**Annual PV out, 15% eff** (MWh)	**Spring/ Summer GTI opt** (kWh·m^{-2})	**Spring/ Summer GTI opt to Area** (MWh)	**Spring/ Summer PV out, 15% eff** (MWh)	**Autumn/ Winter GTI opt** (kWh·m^{-2})	**Autumn/ Winter GTI opt to Area** (MWh)	**Autumn/ Winter PV out, 15% eff** (MWh)
Jan	84	7600	1140	77	408755	61313	84	4240	636
Feb	111	10044	1506	96	509616	76442	111	5602	840
Mar	150	13573	2035	136	721957	108293	150	7571	1135
Apr	171	15473	2320	164	870595	130589	161	8126	1218
May	192	17373	2605	192	1.019E+06	152850	172	8682	1302
Jun	204	18459	2768	209	1.109E+06	166350	180	9085	1362
Jul	214	19364	2904	217	1.152E+06	172800	190	9590	1438
Aug	195	17644	2646	196	1.04E+06	156000	182	9186	1377
Sep	166	15020	2253	156	828127	124219	142	7167	1075
Oct	137	12396	1859	116	615787	92368	135	6814	1022
Nov	92	8324	1248	83	440606	66090	92	4643	696
Dec	72	6515	977	67	355670	53350	72	3634	545
Yearly		161785	24261		9071113	1360666		84340	12651

The method has practical relevance beyond a conventional ground-mounted PV plant. Suitable natural slopes could host distributed arrays, agrivoltaic strips, reservoir-side auxiliary power, irrigationpumping systems, tourism facilities or hybrid land-floating PV schemes. The reservoir environment also creates possible cooling advantages, but humidity, corrosion and shoreline winds must be considered.

5. Conclusion

In the current study, the northern Mingechevir Reservoir shoreline between the map-derived A and B points is studied as a one-sided 200 m landward coastal zone without allowing coordinate uncertainty to extend into the water or deep inland. The time-of-use method of Gardashov (2022) has been adopted for the study of the annual, spring/summer, and autumn/winter optimally oriented areas of wrinkled terrain on the northern coastal zone of Mingechevir Reservoir. Future work should include high-resolution DEM validation, horizon/shadow analysis, hourly transposition modelling, PV rowlayout optimization, geotechnical and environmental screening, grid-connection analysis, and comparison with floating PV on the reservoir.

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ПОТЕНЦИАЛ СОЛНЕЧНОЙ ЭНЕРГЕТИКИ НА УЧАСТКАХ ХОЛМИСТОГО РЕЛЬЕФА С ОПТИМАЛЬНОЙ ОРИЕНТАЦИЕЙ СКЛОНОВ В СЕВЕРНОЙ ПРИБРЕЖНОЙ ЗОНЕ МИНГЯЧЕВИРСКОГО ВОДОХРАНИЛИЩА

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Резюме. В исследовании оценивается потенциал солнечной энергии на участках местности с естественным уклоном в пределах полосы суши шириной 200 м вдоль изрезанного северного побережья Мингячевирского водохранилища в Азербайджане. Линия исследования простирается между определёнными по картографическим данным точками A (41,0028° с. ш., 46,6509° в. д.) и B (40,8000° с. ш., 47,1127° в. д.). Методология объединяет предложенный Гардашовым (2022) подход к оптимальной ориентации с учётом времени использования солнечной энергии, оценку пригодности территории по крутизне и экспозиции склонов, а также многолетние данные о солнечных энергетических ресурсах из Global Solar Atlas, ERA5 и MERRA-2. Для предотвращения включения акватории водохранилища или удалённых от берега участков суши вследствие позиционной неопределённости начальная и конечная точки рассматриваются как опорные ориентиры вдоль побережья. Между ближайшими к ним береговыми позициями прослеживается береговая линия, после чего формируется односторонняя буферная зона шириной 200 м в направлении суши, определяющая границы исследуемого полигона. Целевые параметры ориентации для годового, весенне-летнего и осенне-зимнего периодов приняты соответственно равными 34°/180°, 19°/180° и 56°/180° (угол наклона/азимут) с учётом установленных допустимых угловых отклонений. При построении численной модели рельефа использовались геопривязанная береговая линия и соответствующие фрагменты цифровой модели рельефа Copernicus GLO-30. Оценка пригодности территории показывает, что северное побережье обладает благоприятными структурными

характеристиками, поскольку значительная часть склонов ориентирована преимущественно на юг, в сторону водохранилища. Расчётная площадь пригодных участков оказалась наибольшей для летнего и весенне-осеннего вариантов ориентации, меньшей для годового варианта и ограниченной для зимнего варианта, требующего более крутого угла наклона. Полученные результаты подтверждают перспективность размещения фотоэлектрических (PV) панелей на прибрежных склонах с естественно благоприятной ориентацией. Вместе с тем показано, что для окончательного определения инженерно-технических параметров необходимы непосредственные данные цифровой модели рельефа высокого пространственного разрешения, а также сведения о земельном покрове, геотехнических условиях и возможностях подключения к электрическим сетям.

Ключевые слова: *Мингячевирское водохранилище, солнечная энергия, ориентация фотоэлектрических установок, экспозиция склонов, цифровая модель рельефа, Global Solar Atlas, ERA5, MERRA-2, время использования*

MİNGƏÇEVİR SU ANBARININ ŞİMAL SAHİL ZONASINDA PARÇALANMIŞ RELYEFİN OPTİMAL SƏMTLƏNMİŞ SAHƏLƏRİNİN GÜNƏŞ ENERJİSİ POTENSİALI

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Xülasə. Tədqiqatda Azərbaycanın Mingəçevir su anbarının girintili-çıxıntılı şimal sahili boyunca qurunun içərisinə doğru uzanan 200 m enində zolaqda təbii meyilliyə malik ərazilərin günəş enerjisi potensialı qiymətləndirilmişdir. Tədqiqat xətti xəritə əsasında müəyyən edilmiş A (41,0028° şm. e., 46,6509° ş. u.) və B (40,8000° şm. e., 47,1127° ş. u.) nöqtələri arasında uzanır. Metodologiya Qardaşovun (2022) gün ərzində istifadə vaxtına əsaslanan optimal istiqamətləndirmə yanaşmasını, relyefin meyilliyi və yamacların ekspozisiyası üzrə uyğunluğun qiymətləndirilməsini, həmçinin Global Solar Atlas, ERA5 və MERRA-2 məlumat bazalarının uzunmüddətli günəş enerjisi ehtiyatlarına dair göstəricilərini birləşdirir. Mövqe qeyri-müəyyənliyi nəticəsində su anbarının akvatoriyasının və ya sahildən uzaqda yerləşən quru ərazilərin tədqiqat sahəsinə daxil edilməsinin qarşısını almaq məqsədilə başlanğıc və son nöqtələr sahilboyu istinad nöqtələri kimi qəbul edilmiş, onların sahil xəttinə ən yaxın mövqeləri arasında sahil xətti müəyyənləşdirilmiş və qurunun içərisinə doğru bir tərəfli 200 m-lik bufer zona yaradılaraq tədqiqat poliqonu formalaşdırılmışdır. İllik, yaz-yay və payız-qış dövrləri üçün hədəf istiqamətləndirmə parametrləri müvafiq olaraq 34°/180°, 19°/180° və 56°/180° (meyillik bucağı/azimut) qəbul edilmiş və bucaqlar üzrə yol verilən kənarlaşmalar nəzərə alınmışdır. Relyefin rəqəmsal modelində coğrafi koordinatlarla əlaqələndirilmiş sahil xəttindən və Copernicus GLO-30 rəqəmsal yüksəklik modelinin müvafiq fraqmentlərindən istifadə edilmişdir. Ərazilərin uyğunluq baxımından qiymətləndirilməsi göstərir ki, şimal sahili struktur baxımından əlverişlidir, çünki yamacların əhəmiyyətli hissəsi ümumilikdə cənuba, su anbarına doğru istiqamətlənmişdir. Günəş enerjisindən istifadə üçün uyğun hesab edilən ərazilərin təxmini sahəsi yay və yaz-payız istiqamətləndirmə variantlarında ən böyük, illik istiqamətləndirmə variantında nisbətən kiçik, daha böyük meyillik bucağı tələb edən qış variantında isə məhdud olmuşdur. Nəticələr təbii istiqamətlənmiş sahil yamaclarında fotovoltaik (PV) panellərin yerləşdirilməsi konsepsiyasının məqsədəuyğunluğunu təsdiqləyir. Bununla yanaşı, yekun mühəndis-texniki hesablamaların aparılması üçün yüksək məkan ayırdetməsinə malik birbaşa rəqəmsal yüksəklik məlumatlarının, torpaq örtüyünə, geotexniki şəraitə və elektrik şəbəkəsinə qoşulma imkanlarına dair məlumatların əldə edilməsinin zəruriliyi göstərilir.

Açar sözlər: *Mingəçevir su anbarı, günəş enerjisi, fotoelektrik qurğuların səmtlənməsi, yamacların ekspozisiyası, rəqəmsal yüksəklik modeli, Global Solar Atlas, ERA5, MERRA-2, istifadə vaxtı*

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ASSESSMENT OF THE IMPACT OF ROAD TRAFFIC NOISE ON THE URBAN ENVIRONMENT AND POPULATION HEALTH IN GABALA CITY

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Keywords *road traffic noise, environmental noise, urban environment, population health, noise pollution, traffic intensity, Gabala, Azerbaijan*

Summary. Road traffic noise is an increasingly important environmental concern in urban areas, particularly in cities experiencing growth in transport activity and tourism. This study assesses road traffic noise levels in Gabala City, Azerbaijan, and evaluates their potential implications for the urban environment and population health. Field measurements were conducted at selected monitoring points along major urban streets characterized by relatively high traffic intensity. Noise levels were measured using a SVAN 947 sound level meter, with observations focusing primarily on Category III and IV streets. The measured values were evaluated against the noise limits adopted in the study. The results indicate that average road traffic noise levels at most monitoring locations remained within or below the referenced limits; however, during peak traffic periods, noise levels along 28 May, V. Gahramanov, A. Javad, and H. Javid streets and avenues exceeded the reference level by approximately 7–10 dB. Particular attention is given to potentially vulnerable population groups, including children, older adults, and pregnant women. The findings demonstrate the importance of continuous urban noise monitoring, improved roadside green infrastructure, traffic management, and regular technical inspection of vehicles. The study provides an empirical basis for integrating environmental noise considerations into urban and transport planning in Gabala.

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Introduction

The rapid development of transportation infrastructure provides substantial economic and social benefits; however, it is also associated with increasing environmental pressures. Road transport, in particular, affects various components of the urban environment through atmospheric emissions and noise pollution. Unlike many natural environmental processes, anthropogenic impacts may occur rapidly and intensively, potentially exceeding the capacity of ecosystems to recover. The continuous growth of motorized transport therefore represents an important source of environmental pressure in urban areas.

Road vehicles are among the major mobile sources of urban environmental pollution. In addition to atmospheric emissions, increasing traffic volumes contribute substantially to environmental noise. In Azerbaijan, the number of motor vehicles has increased considerably in recent years. According to the statistical information cited in the study, the total number of motor vehicles in the country exceeded 1.95 million by the end of 2025, approximately 85% of which were passenger cars. The vehicle fleet increased by approximately 5.5%, or 94,934 vehicles, within one year. These trends highlight the growing importance of assessing transport-related environmental pressures in Azerbaijani cities.

Road traffic noise is generated by multiple components and processes, including engines, transmission systems, exhaust systems, vehicle horns, and tire–road interaction. Its intensity is additionally influenced by road surface characteristics, topography, vehicle condition, traffic speed and intensity, and the presence of urban vegetation. Consequently, traffic noise represents a complex environmental problem whose spatial and temporal characteristics may vary considerably within the same urban area.

Environmental noise is also relevant to public health. The source material associates prolonged exposure to elevated noise levels with adverse effects on the nervous and cardiovascular systems, chronic fatigue, reduced concentration and memory, and disturbances in rest and recovery. Such effects may be particularly important for vulnerable population groups, including children, older adults, and pregnant women.

Despite growing international attention to environmental noise, the source manuscript identifies a lack of sufficiently detailed research on road traffic noise in Azerbaijan. This research gap is particularly relevant for developing urban and tourism centers where increasing mobility may intensify environmental pressures. Gabala City, located on the southern slopes of the Greater Caucasus, represents an important case because of its tourism potential and relatively intensive road traffic. Accordingly, this study aims to measure and assess road traffic noise at selected locations in Gabala City and evaluate its potential implications for the urban environment and population health.

Literature review

Environmental noise is increasingly recognized as an important urban environmental and public-health concern. Road traffic is one of the principal sources of environmental noise exposure, particularly in densely populated urban areas. According to the World Health Organization (WHO), prolonged exposure to environmental noise is associated with adverse outcomes including annoyance, sleep disturbance, cardiovascular effects, cognitive impairment, and reduced well-being. WHO recommends reducing average road traffic noise exposure below 53 dB Lden and night-time exposure below 45 dB Lnight to minimize adverse health effects (World Health Organization, 2018).

Recent epidemiological evidence further supports the relevance of road traffic noise to population health. A systematic review and dose-response meta-analysis by Fu et al. (2023), incorporating 23 studies, found that each 10 dB increase in road traffic noise exposure was associated with an approximately 2% increase in overall cardiovascular disease risk, with stronger associations reported for some cardiovascular outcomes. More recent systematic evidence has similarly reported positive exposure-response relationships between long-term road traffic noise and myocardial infarction and stroke, reinforcing the importance of incorporating environmental noise into urban health assessments.

The magnitude of traffic noise is influenced by a combination of transport and environmental factors, including traffic volume, vehicle speed and composition, road-surface characteristics, vehicle condition, urban morphology, topography, and the spatial relationship between roads and residential areas. Consequently, effective noise assessment requires not only measurement of sound levels but also consideration of the characteristics of the surrounding urban environment. WHO guidance emphasizes interventions at both the noise source and transmission pathway, including traffic-flow management, appropriate road surfaces, vehicle-related measures, barriers, insulation, and urban planning interventions.

In Azerbaijan, previous research has addressed the environmental impacts of road transportation, including traffic intensity and associated anthropogenic pressures (Aliyev, 2013; Khalilov, 2006). However, the available literature remains limited with respect to instrument-based assessments of road traffic noise in regional urban centers. This research gap is particularly relevant for Gabala, where tourism development and increasing mobility may intensify transport-related environmental pressures. Therefore, field-based assessment of road traffic noise in Gabala provides an opportunity to establish baseline evidence for subsequent environmental monitoring and urban planning.

Materials and methods

Study area

The study was conducted in **Gabala City, Azerbaijan**, located on the southern slopes of the Greater Caucasus. Gabala is characterized by an expanding tourism sector and increasing road traffic activity, making traffic-related environmental noise an important issue for urban environmental assessment. According to the statistical data used in this study, the city covers an area of approximately **9.5 km²** and had a population of **15,319 in 2025**.

To obtain a spatially representative assessment of road traffic noise, monitoring locations were selected along streets characterized by different road categories and traffic conditions. Particular attention was given to **Category III and IV streets**, where relatively intensive traffic was observed. The monitoring network covered different parts of the urban road system in order to identify spatial variations in traffic-generated noise. The spatial distribution of the monitoring points and the corresponding noise-level classes is presented in **Figure 1**.

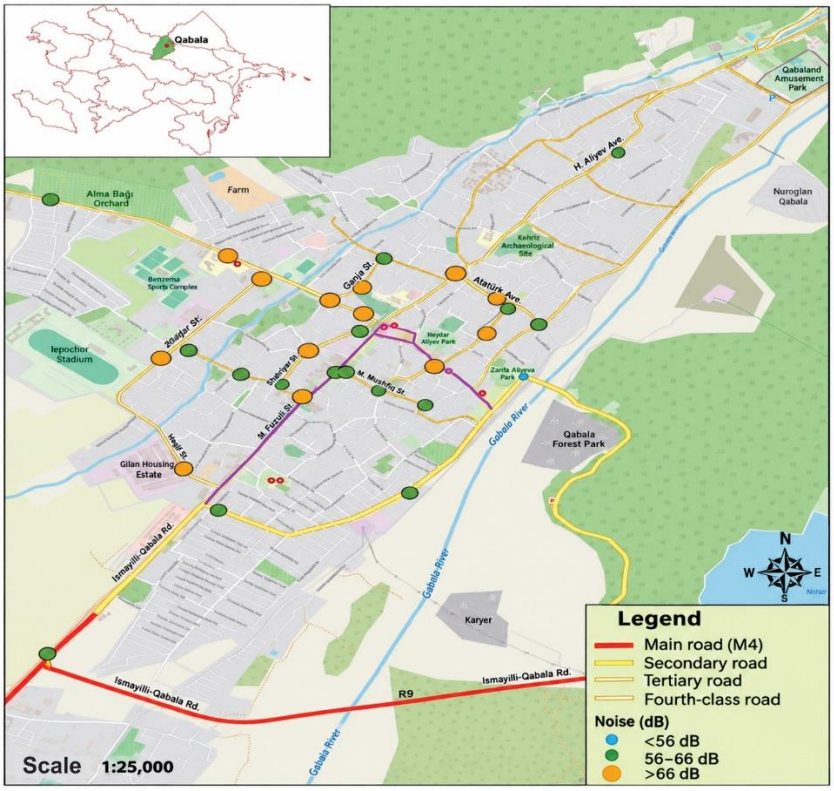


Fig. 1. Spatial distribution of road traffic noise monitoring points and measured noise levels in Gabala City, Azerbaijan

Noise measurement and assessment

Road traffic noise measurements were conducted using a SVAN 947 sound level meter at the selected monitoring locations. The measurements were subsequently processed to characterize the average noise conditions at the investigated sites. More than 36 observation records obtained during the field survey were analyzed to evaluate the spatial variation in road traffic noise across Gabala City.

For spatial interpretation, the measured noise levels were grouped into three classes: <56 dB, 56–66 dB, and >66 dB. These classes were used to visualize the distribution of relatively low, moderate, and high measured noise levels across the urban road network (Figure 1). The classification provides a spatial representation of locations where road traffic noise was comparatively elevated and facilitates comparison among different parts of the city.

The field observations focused on roads with relatively high traffic intensity and considered the influence of road and traffic characteristics on the urban acoustic environment. The resulting measurements were compared across monitoring locations to identify areas where elevated noise levels occurred, particularly during periods of intensive road traffic. The analysis therefore combined instrument-based field measurements and spatial assessment to characterize road traffic noise conditions in Gabala City.

Population-based assessment

To complement the environmental noise assessment, demographic data for Gabala City were examined to identify population groups potentially more sensitive to noise exposure. In 2025, the city had a population of 15,319, comprising 7,565 males (49.4%) and 7,754 females (50.6%). Children aged 0–14 accounted for 3,294 persons (21.5%), the working-age population aged 15–64 comprised 10,646 persons (69.5%), and residents aged 65 years and older accounted for 1,379 persons (9.0%).

These demographic characteristics were considered in interpreting the potential public-health relevance of traffic noise, with particular attention to children and older residents as potentially vulnerable population groups. However, because the study did not include individual-level clinical or epidemiological measurements, the health component was interpreted as an exposure-related assessment rather than evidence of direct causal health effects.

Results and discussion

Road traffic noise can have different effects on human health depending on the intensity and duration of exposure as well as individual susceptibility. The source material indicates that the response to environmental noise may vary according to age, sex, and health status, with children, older adults, and pregnant women considered particularly sensitive groups. It further notes that prolonged exposure to elevated noise levels may affect sleep and contribute to physiological responses involving the cardiovascular and nervous systems.

For a general representation of the relationship between noise intensity and the reported effects considered in the source study, noise levels ranging from 30 to 150 dB are presented in Figure 2.

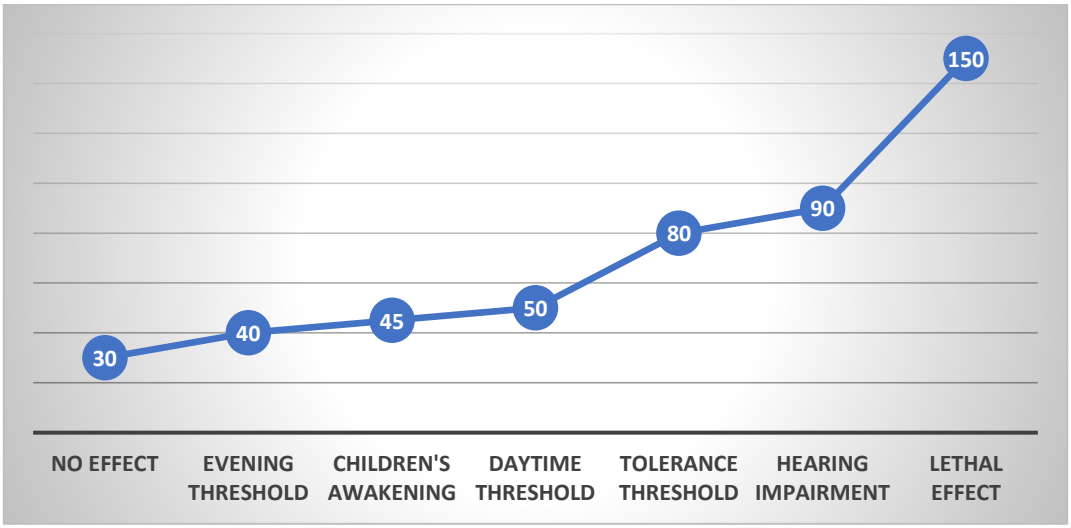


Fig. 2. Noise levels and their reported effects on human health (dB).

The information presented in Figure 2 illustrates that the potential effects associated with noise become progressively more severe as sound intensity increases. However, the health implications of environmental noise cannot be determined solely by a single sound-pressure level, as they also depend on exposure duration, frequency, time of day, individual susceptibility, and other environmental and health-related factors. Therefore, Figure 2 should be interpreted as a general representation of the noise-effect categories considered in the source study rather than as evidence of health outcomes among the population of Gabala.

The field measurements conducted in Gabala demonstrated spatial and temporal differences in road traffic noise levels. Along 28 May Street, V. Gahramanov Street, A. Javad Street, and H. Javid Avenue, average noise levels were generally within the reference range; however, during certain peak traffic periods, the measured values exceeded the reference level by approximately 7–10 dB. In contrast, measurements along 20 January Street, S. Vurgun Street, P. Hashimov Street, and H. Aliyev Avenue were generally at or below the reference level.

These findings demonstrate that road traffic noise is not uniformly distributed throughout Gabala City. Higher noise levels were associated with particular road sections and periods of increased traffic activity. This spatial variation may be influenced by several interacting factors, including traffic intensity and speed, vehicle condition, road-surface characteristics, topography, and the presence of roadside vegetation.

Analysis of more than 36 observation records indicates that the overall road traffic noise environment in Gabala was not characterized by uniformly elevated noise levels during the study period. Nevertheless, the occurrence of values exceeding the reference level during peak traffic periods identifies localized areas where continued environmental noise monitoring may be necessary.

Population exposure and potential health relevance

The demographic structure of Gabala City was also considered when evaluating the potential relevance of environmental noise exposure. In 2025, the city had a total population of 15,319, including 7,565 males (49.4%) and 7,754 females (50.6%). Children aged 0–14 years accounted for 3,294 residents (21.5%), while 10,646 residents (69.5%) were aged 15–64 years and 1,379 (9.0%) were aged 65 years or older.

As shown in Figure 3, females represent 50.6% and males 49.4% of the city's population, indicating a nearly balanced sex distribution. Children aged 0–14 years constitute more than one-fifth of the total population, while residents aged 65 years and older account for 9.0%. These demographic characteristics are relevant to environmental noise assessment because population groups may differ in their susceptibility to noise exposure.

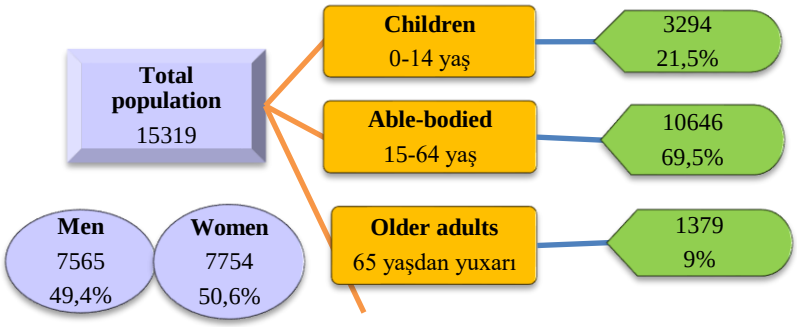


Fig. 3. Age and sex structure of the population of Gabala City in 2025.

However, the present study did not collect individual-level medical data or directly assess associations between measured noise exposure and specific diseases among Gabala residents. Therefore, the findings should be interpreted as an environmental exposure assessment with potential public-health relevance, rather than as evidence of a causal relationship between road traffic noise and health outcomes.

Conclusion

This study assessed road traffic noise in Gabala City, Azerbaijan, using instrument-based field measurements at selected locations representing different road categories and traffic conditions. The findings demonstrate that road traffic noise varies spatially and temporally across the city and is particularly influenced by periods of increased traffic intensity.

The measurements showed that average noise levels at many monitoring locations remained within or below the reference levels applied in the study. However, during peak traffic periods, noise levels along 28 May Street, V. Gahramanov Street, A. Javad Street, and H. Javid Avenue exceeded the reference level by approximately 7–10 dB. In comparison, measurements along 20 January Street, S. Vurgun Street, P. Hashimov Street, and H. Aliyev Avenue were generally within or below the reference range.

The spatial distribution of the measurements indicates that environmental noise in Gabala is characterized by localized traffic-related hotspots rather than uniformly high noise levels throughout the city. Although the observed conditions do not demonstrate direct health effects, elevated noise levels at specific locations may be environmentally relevant, particularly for potentially vulnerable population groups such as children and older residents. Therefore, the results should be interpreted as an assessment of environmental noise exposure rather than as evidence of a causal relationship between traffic noise and specific health outcomes.

Considering the continued development of Gabala as an urban and tourism center, increasing traffic volumes may intensify noise-related environmental pressures in the future. Consequently, systematic monitoring and the integration of environmental noise considerations into urban planning, transport management, and public-health protection strategies are important for maintaining a sustainable urban environment.

Recommendations

Based on the findings, regular road traffic noise monitoring should be conducted at locations characterized by intensive traffic, particularly during peak periods. Priority should be given to areas where elevated noise levels were identified during the field measurements.

Urban and transport planning should incorporate measures aimed at reducing traffic-related noise exposure. These should include the development and maintenance of roadside green belts, improvement of traffic-flow management, regular technical inspection of motor vehicles, and consideration of noise exposure when locating sensitive facilities such as schools and childcare institutions. These measures are consistent with the preventive actions proposed in the original study.

Particular attention should also be given to monitoring areas used frequently by potentially vulnerable population groups. Continued collection of standardized noise data would make it possible to identify long-term trends, evaluate changes associated with increasing traffic intensity, and provide a stronger scientific basis for future environmental and urban-management decisions.

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ОЦЕНКА ВОЗДЕЙСТВИЯ ШУМА АВТОМОБИЛЬНОГО ТРАНСПОРТА НА ГОРОДСКУЮ СРЕДУ И ЗДОРОВЬЕ НАСЕЛЕНИЯ ГОРОДА ГАБАЛЫ

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Резюме. Шум автомобильного транспорта становится всё более значимой экологической проблемой в городских районах, особенно в городах, характеризующихся ростом транспортной активности и развитием туризма. В исследовании оцениваются уровни шума автомобильного транспорта в городе Габала (Азербайджан) и рассматриваются их потенциальные последствия для городской среды и здоровья населения. Полевые измерения проводились в выбранных пунктах мониторинга вдоль основных городских улиц, характеризующихся относительно высокой интенсивностью транспортного движения. Уровни шума измерялись с помощью шумомера SVAN 947, при этом наблюдения были сосредоточены преимущественно на улицах III и IV категорий. Полученные значения оценивались путём сопоставления с предельными уровнями шума, принятыми в исследовании. Результаты показывают, что средние уровни шума автомобильного транспорта в большинстве пунктов мониторинга находились в пределах установленных в исследовании нормативных значений или ниже них. Однако в периоды пиковой транспортной нагрузки уровни шума на улицах и проспектах 28 Мая, В. Гахраманова, А. Джавада и Г. Джавида превышали принятый контрольный уровень приблизительно на 7–10 дБ. Особое внимание уделено потенциально уязвимым группам населения, включая детей, пожилых людей и беременных женщин. Полученные результаты свидетельствуют о важности непрерывного мониторинга городского шума, совершенствования придорожной зелёной инфраструктуры, управления транспортными потоками и регулярного технического осмотра транспортных средств. Исследование формирует эмпирическую основу для учёта экологических аспектов шумового воздействия при городском и транспортном планировании в Габале.

Ключевые слова: *автотранспортный шум, экологический шум, городская среда, здоровье населения, шумовое загрязнение, интенсивность движения, Габала, Азербайджан*

QƏBƏLƏ ŞƏHƏRİNDƏ AVTONƏQLİYYAT SƏS-KÜYÜNÜN ŞƏHƏR MÜHİTİNƏ VƏ ƏHALİNİN SAĞLAMLIĞINA TƏSİRİNİN QİYMƏTLƏNDİRİLMƏSİ

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Xülasə. Avtomobil nəqliyyatının yaratdığı səs-küy şəhər ərazilərində, xüsusilə nəqliyyat fəaliyyətinin və turizmin inkişaf etdiyi şəhərlərdə getdikcə daha mühüm ekoloji problemə çevrilir. Tədqiqatda Azərbaycanın Qəbələ şəhərində avtomobil nəqliyyatının yaratdığı səs-küy səviyyələri qiymətləndirilmiş və onların şəhər mühitinə və əhalinin sağlamlığına potensial təsirləri araşdırılmışdır. Çöl ölçmələri nəqliyyatın hərəkət intensivliyinin nisbətən yüksək olduğu əsas şəhər küçələri boyunca seçilmiş monitorinq məntəqələrində aparılmışdır. Səs-küy səviyyələri SVAN 947 səs səviyyəsi ölçən cihaz vasitəsilə ölçülmüş, müşahidələr əsasən III və IV kateqoriyalı küçələri əhatə etmişdir. Ölçülmüş göstəricilər tədqiqatda qəbul edilmiş səs-küyün yol verilən hədləri ilə müqayisəli şəkildə qiymətləndirilmişdir. Nəticələr göstərir ki, monitorinq məntəqələrinin əksəriyyətində avtomobil nəqliyyatının yaratdığı orta səs-küy səviyyələri istinad edilən hədlər daxilində və ya onlardan aşağı olmuşdur. Lakin nəqliyyatın pik hərəkət saatlarında 28 May, V. Qəhrəmanov, A. Cavad və H. Cavid küçə və prospektlərində səs-küy səviyyələri istinad göstəricisini təxminən 7–10 dB aşmışdır. Uşaqlar, yaşlı insanlar və hamilə qadınlar da daxil olmaqla, potensial həssas əhali qruplarına xüsusi diqqət yetirilmişdir. Tədqiqatın nəticələri şəhər mühitində səs-küyün davamlı monitorinqinin aparılmasının, yolkənarı yaşıl infrastrukturun təkmilləşdirilməsinin, nəqliyyatın hərəkətinin idarə edilməsinin və nəqliyyat vasitələrinin müntəzəm texniki baxışdan keçirilməsinin əhəmiyyətini göstərir. Tədqiqat Qəbələ şəhərində şəhərsalma və nəqliyyat planlaşdırılması proseslərinə ekoloji səs-küy amilinin inteqrasiyası üçün empirik əsas yaradır.

Açar sözlər: *avtonəqliyyat səs-küyü, ətraf mühit səs-küyü, şəhər mühiti, əhalinin sağlamlığı, səs-küy çirklənməsi, nəqliyyat hərəkətinin intensivliyi, Qəbələ, Azərbaycan*

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ENVIRONMENTAL ASSESSMENT OF THE EFFECTS OF AIR POLLUTION AND GEOMAGNETIC ACTIVITY ON HEMATOLOGICAL PARAMETERS IN CHILDREN WITH CONGENITAL HEART DEFECTS IN BAKU

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Keywords: *congenital heart defects, geomagnetic activity, Kp index, air pollution, PM2.5, hematological parameters, children*

Summary. Children with congenital heart defects (CHDs) may be particularly vulnerable to environmental stressors. This study investigated associations of geomagnetic activity and ambient air pollution with hematological parameters in 42 children aged 3 months to 15 years with echocardiographically confirmed CHDs in Baku, Azerbaijan. Participants were examined on 21 different days in 2023. Geomagnetic activity was characterized using the Kp index, while air pollution was assessed using daily indicators, particularly PM2.5 and particulate matter. Associations with leukocyte, erythrocyte, and platelet parameters were evaluated using Pearson's correlation coefficient. The Kp index was negatively correlated with PLT ($r = -0.414$, $p < 0.01$) and PCT ($r = -0.419$, $p < 0.01$). Particulate pollution showed positive correlations with WBC ($r = 0.321$), RDW-SD ($r = 0.360$), and RDW-CV ($r = 0.415$), and negative correlations with BAS% ($r = -0.434$), EOS# ($r = -0.444$), and EOS% ($r = -0.436$) ($p < 0.01$). PM2.5 was negatively correlated with PLT ($r = -0.374$), PCT ($r = -0.406$), BAS# ($r = -0.567$), BAS% ($r = -0.478$), and EOS# ($r = -0.334$) ($p < 0.01$). No significant correlations were found between geomagnetic activity and air-pollution indicators ($p > 0.05$). These findings suggest that geomagnetic activity and particulate air pollution are associated with distinct hematological variations in children with CHDs and warrant further investigation in larger longitudinal studies.

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1. Introduction

Environmental and geophysical stressors are increasingly investigated as potential modifiers of cardiovascular and hematological health. Among these factors, ambient air pollution and geomagnetic activity have attracted particular attention because of their reported associations with cardiovascular events and physiological responses. Previous studies have suggested relationships between geomagnetic disturbances and cardiovascular outcomes, including changes in hemostatic and platelet-related processes [1–4].

Children with congenital heart defects (CHDs) may represent a particularly vulnerable population because cardiovascular abnormalities and chronic hypoxia can influence compensatory and hematological mechanisms [5–8]. Environmental exposures may therefore be of particular relevance in this population. However, the hematological responses of children with CHDs to external physical and environmental factors remain insufficiently characterized.

Ambient air pollutants, particularly fine particulate matter (PM2.5) and other airborne particles, may also be associated with hematological and inflammatory responses. Although the effects of geomagnetic activity and air pollution have been investigated separately, considerably less is known about their relationships with hematological parameters in children with CHDs. Moreover, whether geomagnetic activity and local air-pollution indicators represent related exposures or act as independent environmental stressors remains unclear.

Baku provides a relevant setting for examining these relationships because children living in the city may be exposed to variations in both ambient air quality and geomagnetic conditions. Evaluation of these exposures

together with leukocyte, erythrocyte, and platelet indices may provide additional information on the hematological responses of children with CHDs.

Therefore, this study aimed to investigate the relationships between geomagnetic activity, represented by the Kp index, ambient air-pollution indicators, and hematological parameters in children with CHDs living in Baku, Azerbaijan. In addition, the study evaluated the relationship between geomagnetic activity and the investigated air-pollution indicators to determine whether their variations were statistically associated.

2. Materials and Methods

2.1. Study Population

The study included 42 children with congenital heart defects (CHDs) admitted to the Department of Pediatric Cardiac Surgery of the Scientific Surgery Center named after Academician M.A. Topchubashov, Ministry of Health of the Republic of Azerbaijan, on 21 different days in 2023. The participants ranged in age from 3 months to 15 years, with a mean age of 6.6 years. All participants were permanent residents of Baku, Azerbaijan.

CHD diagnoses were confirmed by echocardiography and included different structural cardiac abnormalities, such as atrial septal defect, ventricular septal defect, patent ductus arteriosus, and tetralogy of Fallot.

The inclusion criteria were permanent residence in the study area for at least six consecutive months and clinical and instrumental confirmation of CHD. Children with acute infectious diseases in the active phase, hematological or autoimmune diseases, or use of medications capable of directly affecting hematological parameters were excluded. Participation was based on formal ethical consent from the children and their parents or legal guardians.

2.2. Hematological Assessment

Venous blood samples were collected in the morning under fasting conditions from the antecubital vein into K3-EDTA tubes. Hematological measurements were performed using a fully automated hematology analyzer.

The investigated parameters included leukocyte indices (WBC, NEUT#, NEUT%, LYM%, BAS#, BAS%, EOS#, IG#, and IG%), erythrocyte indices (RBC, HGB, HCT, MCV, MCH, MCHC, RDW-CV, and RDW-SD), and platelet indices (PLT, PCT, MPV, PDW, and P-LCR).

2.3. Environmental and Geomagnetic Data

Daily environmental and medical data were recorded for the same 21 observation days in 2023. Geomagnetic activity was characterized using the Kp index, a global measure of disturbances in the Earth's magnetic field expressed on a scale from 0 to 9. Kp data were obtained from international monitoring sources.

Ambient air-pollution data were obtained from ground-level air-quality monitoring stations. The available environmental indicators included daily mean concentrations of carbon monoxide (CO) and PM2.5, together with particulate pollution data used in the subsequent analyses.

2.4. Statistical Analysis

Associations between geomagnetic activity, air-pollution indicators, and hematological parameters were evaluated using Pearson's correlation coefficient (r). Statistical calculations were performed using Microsoft Excel. A value of $p < 0.05$ was considered statistically significant.

3. Results

3.1. Relationship Between Geomagnetic Activity and Air Pollution

No statistically significant correlations were observed between the Kp index and the investigated air-pollution indicators, including CO, SO_2, NO_2, PM10, PM2.5, and particulate matter ($p > 0.05$). Thus, variations in geomagnetic activity during the observation period were not statistically associated with variations in the measured ambient air-pollution indicators.

3.2. Geomagnetic Activity and Hematological Parameters

Significant negative correlations were observed between the Kp index and PLT ($r = -0.414$, $p < 0.01$) and between the Kp index and PCT ($r = -0.419$, $p < 0.01$) (Figure 1). In contrast, correlations between the Kp index and RBC ($r = 0.203$, $p > 0.05$) and RDW-SD ($r = 0.266$, $p > 0.05$) were weak and not statistically significant. No correlation between the Kp index and MPV was reported.

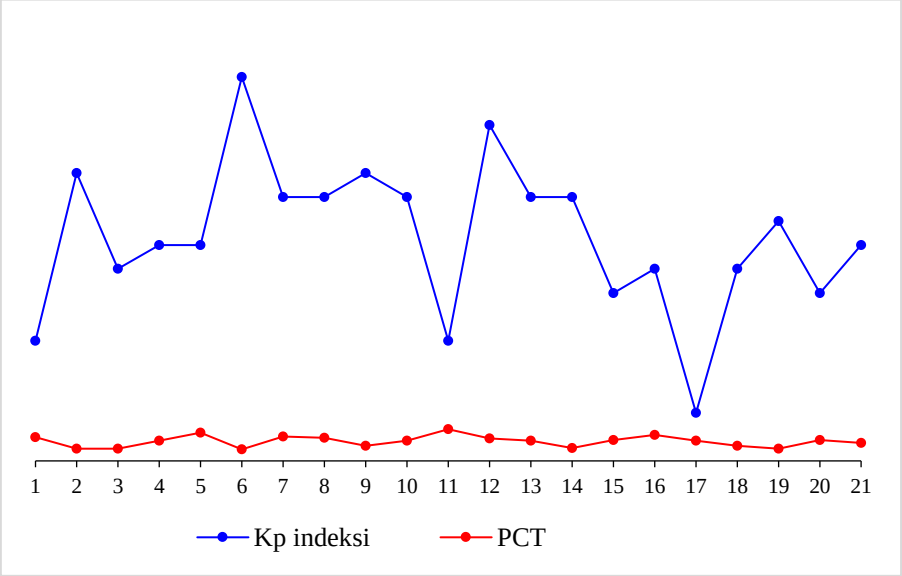


Fig. 1. Relationship between the Kp index and PCT in children with congenital heart defects in Baku

3.3. Particulate Pollution and Hematological Parameters

Particulate pollution showed significant positive correlations with WBC ($r = 0.321$, $p < 0.01$), RDW-SD ($r = 0.360$, $p < 0.01$), and RDW-CV ($r = 0.415$, $p < 0.01$). Significant negative correlations were observed with BAS% ($r = -0.434$, $p < 0.01$), EOS# ($r = -0.444$, $p < 0.01$), and EOS% ($r = -0.436$, $p < 0.01$). Positive correlations were also reported for NEUT# ($r = 0.305$, $p < 0.01$) and NEUT% ($r = 0.311$, $p < 0.01$). The relationships between particulate air pollution and WBC, RDW-SD, and RDW-CV in children with congenital heart defects are illustrated in Figure 2.

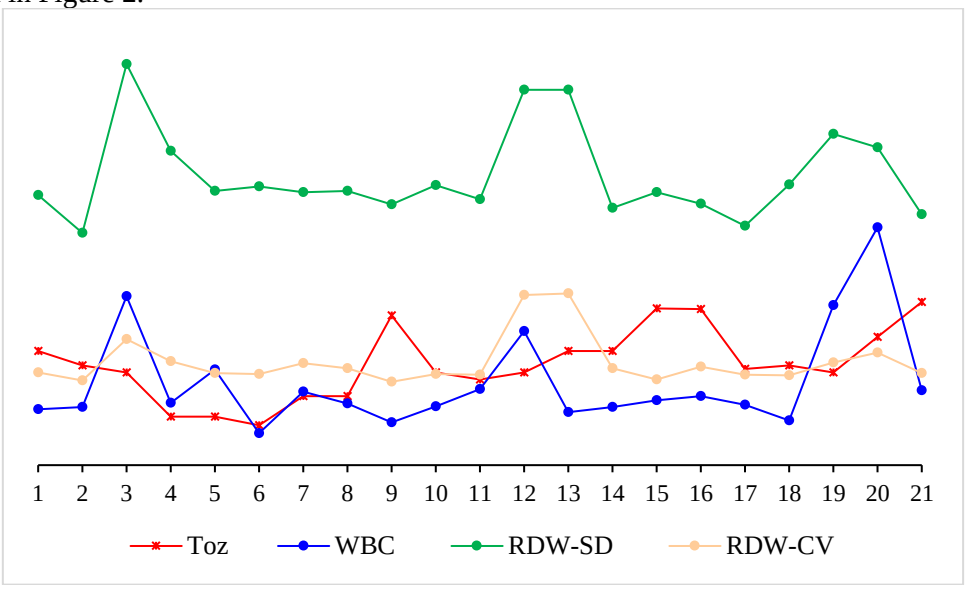


Fig. 2. Relationships of particulate pollution with WBC, RDW-SD, and RDW-CV in children with congenital heart defects in Baku

PM2.5 was negatively correlated with several hematological parameters, including PLT ($r = -0.374$, $p < 0.01$), PCT ($r = -0.406$, $p < 0.01$), BAS# ($r = -0.567$, $p < 0.01$), BAS% ($r = -0.478$, $p < 0.01$), and EOS# ($r = -0.334$, $p < 0.01$). Among these associations, the strongest reported correlation was observed between PM2.5 and BAS# ($r = -0.567$).

4. Discussion

The present study identified distinct associations between geomagnetic activity, particulate air pollution, and hematological parameters in children with congenital heart defects (CHDs) living in Baku. The principal findings were the negative correlations of the Kp index with PLT and PCT, as well as significant associations of particulate pollution and PM2.5 with several platelet, leukocyte, and erythrocyte-related indices. At the

same time, no statistically significant relationship was observed between geomagnetic activity and the investigated air-pollution indicators. Taken together, these findings suggest that geomagnetic variability and ambient particulate pollution may represent different environmental exposures associated with distinct patterns of hematological variation in children with CHDs.

One of the most notable findings was the negative association between geomagnetic activity and platelet-related parameters. The Kp index was negatively correlated with both PLT ($r = -0.414$, $p < 0.01$) and PCT ($r = -0.419$, $p < 0.01$), whereas no significant association with MPV was reported. Previous investigations have suggested that geomagnetic disturbances may be associated with cardiovascular and hemostatic responses [3–5]. Changes in platelet activity in relation to space-weather conditions have also been discussed in previous studies [3, 7]. The present results extend this line of investigation to a pediatric population with congenital cardiac abnormalities, in which the physiological response to external stressors may differ from that of healthy adults.

The simultaneous negative associations of the Kp index with PLT and PCT deserve particular attention. PLT reflects the circulating platelet count, whereas PCT represents the proportion of blood volume occupied by platelets. Their parallel associations with increasing Kp values may therefore indicate variation in the circulating platelet compartment during periods of increased geomagnetic activity. However, because the present study is observational and correlation-based, these findings should not be interpreted as evidence that geomagnetic activity directly causes platelet depletion or thrombocytopenia. Rather, they demonstrate a statistical relationship that requires confirmation in larger longitudinal studies.

The absence of a significant association between the Kp index and MPV may also be relevant. In the original hypothesis, this pattern was interpreted as potentially reflecting peripheral platelet consumption rather than impaired platelet production. Such an interpretation is biologically plausible in the context of CHDs, because chronic hypoxia and altered cardiovascular hemodynamics may influence platelet activation and microcirculatory processes [7, 8]. Nevertheless, MPV alone cannot distinguish peripheral platelet consumption from altered bone-marrow production. Therefore, the present findings should be regarded as supporting a hypothesis that can be tested using additional markers of platelet activation, coagulation, endothelial function, and bone-marrow response.

The vulnerability of children with CHDs may be particularly relevant when interpreting these observations. Congenital structural abnormalities of the heart can be accompanied by chronic or intermittent hypoxemia, altered blood flow, and compensatory hematological responses. Previous work has described hematological adaptation in pediatric patients with CHDs under chronic hypoxic conditions [8]. Against this background, additional environmental or geophysical stressors could potentially be associated with measurable changes in circulating blood-cell parameters. The present study does not establish the biological pathway responsible for such changes, but the observed platelet-related associations indicate that this question merits further investigation.

In contrast to the platelet-dominant pattern observed for the Kp index, particulate air pollution was associated with a broader spectrum of hematological parameters. Total particulate pollution showed positive correlations with WBC, RDW-SD, RDW-CV, NEUT#, and NEUT%, together with negative correlations with BAS%, EOS#, and EOS%. These findings indicate simultaneous variations in leukocyte and erythrocyte-distribution indices in relation to particulate exposure. The positive association with WBC and neutrophil indices may be consistent with an inflammatory response to airborne particulate exposure, although the cross-sectional correlation analysis used in this study cannot establish an inflammatory mechanism.

The associations involving RDW are also of interest. RDW-CV and RDW-SD characterize variation in erythrocyte size and are commonly used as indicators of erythrocyte heterogeneity. In the present study, particulate pollution was positively associated with both indices. This observation suggests that increased particulate exposure may coincide with greater variability in erythrocyte morphology in children with CHDs. However, RDW is influenced by multiple clinical and nutritional factors. Therefore, the observed relationships cannot specifically be attributed to iron deficiency, vitamin B12 deficiency, folate deficiency, anemia of chronic disease, or any other particular mechanism without corresponding biochemical measurements. The original data did not include these measurements, and these mechanisms should consequently be regarded as possible explanations rather than established outcomes.

PM2.5 demonstrated a somewhat different pattern. Negative correlations were observed between PM2.5 and PLT ($r = -0.374$), PCT ($r = -0.406$), BAS# ($r = -0.567$), BAS% ($r = -0.478$), and EOS# ($r = -0.334$), with all of these relationships reported at $p < 0.01$. The strongest reported association was between PM2.5 and BAS# ($r = -0.567$). The associations of PM2.5 with PLT and PCT are particularly noteworthy because the same platelet indices were also negatively associated with the Kp index. This convergence identifies platelet-

related parameters as potentially sensitive hematological indicators in the study population, although the mechanisms associated with the two exposures may differ.

Particulate matter, particularly fine particles such as PM2.5, has received substantial attention because of its potential cardiovascular effects. Previous research has established the broader relevance of particulate air pollution to cardiovascular health [1]. Fine particles may interact with the respiratory system and may be associated with systemic biological responses. In children already affected by congenital cardiac abnormalities, such environmental exposure could be particularly important. Nevertheless, the present study measured statistical associations rather than individual-level biological exposure, and therefore direct mechanistic conclusions cannot be drawn.

An additional finding was the absence of statistically significant correlations between the Kp index and the investigated air-pollution indicators ($p > 0.05$). This is important for interpreting the other results. Within the observation period, changes in geomagnetic activity were not statistically synchronized with variations in CO, SO_2, NO_2, PM10, PM2.5, or particulate pollution. Thus, the observed associations of the Kp index and particulate pollution with hematological parameters cannot simply be explained by a significant correlation between these two groups of environmental variables.

However, the absence of correlation between geomagnetic activity and air pollution should not be interpreted as proof that the two exposures act independently on the human body. Demonstrating independent effects would require multivariable statistical modelling in which geomagnetic activity, individual pollutants, meteorological conditions, demographic characteristics, CHD type and severity, and other potential confounders are evaluated simultaneously. The present Pearson correlation analysis does not provide such adjustment. Consequently, the results indicate distinct statistical associations, rather than confirmed independent biological effects.

This distinction is particularly important when considering the original observation that both higher Kp values and higher PM2.5 concentrations were negatively correlated with PLT and PCT. Although this pattern raises the possibility that platelet-related parameters may respond to multiple environmental stressors, the current analysis cannot determine whether their associations are additive, synergistic, or independent. A formal interaction analysis would be necessary to establish whether simultaneous elevations in geomagnetic activity and PM2.5 are associated with greater hematological changes than either exposure alone.

The study also has potential clinical relevance. Children with CHDs constitute a heterogeneous population, and their hematological status may be influenced by the type and severity of cardiac defect, oxygen saturation, surgical history, medication use, nutritional status, and other clinical factors. Identification of environmental conditions associated with variations in platelet and inflammatory-related indices may therefore contribute to a broader understanding of environmental vulnerability in this population. At the same time, the present results are not sufficient to support specific therapeutic interventions, including antioxidant treatment or changes in clinical management, without prospective clinical evidence.

From an environmental-health perspective, the findings support further investigation of air quality as a potentially relevant factor for vulnerable pediatric groups in Baku. The associations of particulate pollution with WBC, neutrophil indices, RDW indices, basophils, eosinophils, PLT, and PCT suggest that future studies should evaluate not only conventional cardiovascular outcomes but also detailed hematological profiles. Combining environmental monitoring with repeated individual blood measurements could help determine whether short-term changes in particulate exposure precede measurable hematological responses.

The present study also contributes to the comparatively limited literature examining geomagnetic activity in pediatric cardiovascular populations. Most previous research cited in this study has focused on cardiovascular events, mortality, hemostatic responses, or platelet activity in broader or adult populations [2–7]. By focusing specifically on children with CHDs, the present analysis identifies a population in which geomagnetic–hematological relationships have received substantially less attention. This represents one of the main potential contributions of the study, although the findings should be considered exploratory because of the relatively small sample and limited observation period.

4.1. Study limitations

Several limitations should be considered when interpreting the findings. First, the study included 42 children examined across 21 observation days, which limits statistical power and the generalizability of the results. Second, the analysis was based primarily on bivariate Pearson correlations and therefore did not control for potential confounding factors.

Third, children with different forms of CHD were analyzed together. Atrial septal defect, ventricular septal defect, patent ductus arteriosus, tetralogy of Fallot, and other CHDs may differ substantially in their hemodynamic characteristics and degree of hypoxia. Future studies should therefore stratify participants according to

CHD type, cyanotic status, disease severity, and oxygen saturation.

Fourth, the available analysis does not account for several potentially relevant individual-level variables, including sex, nutritional status, body mass index, iron status, vitamin B12 and folate levels, socioeconomic conditions, and previous surgical interventions. These variables may influence hematological parameters and should be incorporated into future multivariable analyses.

Fifth, ambient monitoring data represent environmental concentrations and may not accurately reflect individual exposure. Personal exposure to PM2.5 and other pollutants may vary according to residential location, indoor air quality, daily activity patterns, and time spent outdoors. Future studies would benefit from spatially resolved exposure assessment or individual monitoring.

Finally, the use of multiple correlations across a relatively large number of hematological parameters increases the possibility of chance findings. Future investigations should use larger samples, repeated-measures designs, multivariable regression models, and appropriate correction for multiple comparisons. These approaches would allow a more robust assessment of whether geomagnetic activity and air pollution are independently associated with hematological changes in children with CHDs.

4.2. Implications and future research

Future studies should integrate **geomagnetic, environmental, meteorological, and clinical data** within a unified analytical framework. Repeated hematological measurements in the same children before, during, and after periods of increased geomagnetic activity or elevated air pollution would provide stronger temporal evidence than cross-sectional correlations. Inclusion of platelet-activation markers, inflammatory biomarkers, coagulation parameters, oxygen saturation, and detailed CHD characteristics would also help clarify the biological pathways underlying the observed associations.

Larger multicenter studies involving children from both highly polluted and relatively less polluted areas could further determine whether the associations observed in Baku are reproducible in other environmental settings. Such studies may ultimately help identify environmental conditions associated with increased physiological stress in children with congenital cardiovascular disease.

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ОЦЕНКА ВЛИЯНИЯ ЗАГРЯЗНЕНИЯ АТМОСФЕРНОГО ВОЗДУХА И ГЕОМАГНИТНОЙ АКТИВНОСТИ НА ГЕМАТОЛОГИЧЕСКИЕ ПОКАЗАТЕЛИ У ДЕТЕЙ С ВРОЖДЁННЫМИ ПОРОКАМИ СЕРДЦА В ГОРОДЕ БАКУ

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Резюме. Дети с врождёнными пороками сердца (ВПС) могут быть особенно восприимчивы к стрессовым факторам окружающей среды. В исследовании изучались взаимосвязи геомагнитной активности и загрязнения атмосферного воздуха с гематологическими показателями у 42 детей в возрасте от 3 месяцев до 15 лет с эхокардиографически подтверждёнными врождёнными пороками сердца в городе Баку (Азербайджан). Обследование участников проводилось в течение 21 отдельного дня в 2023 году. Геомагнитная активность характеризовалась индексом Kp, тогда как загрязнение атмосферного воздуха оценивалось по суточным показателям, в частности PM2.5 и содержанию взвешенных частиц. Взаимосвязи с показателями лейкоцитов, эритроцитов и тромбоцитов оценивались с использованием коэффициента корреляции Пирсона. Установлена отрицательная корреляция индекса Kp с показателями PLT ($r = -0{,}414$; $p < 0{,}01$) и PCT ($r = -0{,}419$; $p < 0{,}01$). Загрязнение воздуха взвешенными частицами продемонстрировало положительные корреляции с WBC ($r = 0{,}321$), RDW-SD ($r = 0{,}360$) и RDW-CV ($r = 0{,}415$), а также отрицательные корреляции с BAS% ($r = -0{,}434$), EOS# ($r = -0{,}444$) и EOS% ($r = -0{,}436$) ($p < 0{,}01$). Выявлены отрицательные корреляции PM2.5 с PLT ($r = -0{,}374$), PCT ($r = -0{,}406$), BAS# ($r = -0{,}567$), BAS% ($r = -0{,}478$) и EOS# ($r = -0{,}334$) ($p < 0{,}01$). Статистически значимых корреляций между геомагнитной активностью и показателями загрязнения атмосферного воздуха не обнаружено ($p > 0{,}05$). Полученные результаты свидетельствуют о том, что геомагнитная активность и загрязнение атмосферного воздуха взвешенными частицами связаны с различными изменениями гематологических показателей у детей с врождёнными пороками сердца, что обусловливает необходимость дальнейших исследований с более крупными выборками и продольным дизайном.

Ключевые слова: *врожденные пороки сердца, геомагнитная активность, индекс Kp, загрязнение воздуха, PM2.5, гематологические показатели, дети*

BAKIDA ANADANGƏLMƏ ÜRƏK QÜSURLU UŞAQLARIN HEMATOLOJİ GÖSTƏRİCİLƏRİNƏ HAVA ÇİRKLƏNMƏSİNİN VƏ GEOMAQNİT AKTİVLİYİN TƏSİRİNİN EKOLOJİ QİYMƏTLƏNDİRİLMƏSİ

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Xülasə. Anadangəlmə ürək qüsurları (AÜQ) olan uşaqlar ətraf mühitin stress amillərinə qarşı xüsusilə həssas ola bilərlər. Tədqiqatda Azərbaycanın Bakı şəhərində exokardioqrafiya vasitəsilə anadangəlmə ürək qüsuru diaqnozu təsdiqlənmiş, 3 aylıqdan 15 yaşadək 42 uşaqda geomaqnit aktivliyi və atmosfer havasının çirklənməsi ilə hematoloji göstəricilər arasındakı əlaqələr araşdırılmışdır. İştirakçılar 2023-cü il ərzində 21 müxtəlif gündə müayinə olunmuşdur. Geomaqnit aktivliyi Kp indeksi əsasında, atmosfer havasının çirklənməsi isə gündəlik göstəricilər, xüsusilə PM2.5 və havadakı asılı hissəciklər əsasında qiymətləndirilmişdir. Leykosit, eritrosit və trombosit göstəriciləri ilə əlaqələr Pirsonun korrelyasiya əmsalı vasitəsilə təhlil edilmişdir. Kp indeksi ilə PLT ($r = -0{,}414$; $p < 0{,}01$) və PCT ($r = -0{,}419$; $p < 0{,}01$) arasında mənfi korrelyasiya müəyyən edilmişdir. Havadakı asılı hissəciklərlə çirklənmə WBC ($r = 0{,}321$), RDW-SD ($r = 0{,}360$) və RDW-CV ($r = 0{,}415$) göstəriciləri ilə müsbət, BAS% ($r = -0{,}434$), EOS# ($r = -0{,}444$) və EOS% ($r = -0{,}436$) göstəriciləri ilə isə mənfi korrelyasiya nümayiş etdirmişdir ($p < 0{,}01$). PM2.5 ilə PLT ($r = -0{,}374$), PCT ($r = -0{,}406$), BAS# ($r = -0{,}567$), BAS% ($r = -0{,}478$) və EOS# ($r = -0{,}334$) göstəriciləri arasında mənfi korrelyasiya aşkar edilmişdir ($p < 0{,}01$). Geomaqnit aktivliyi ilə atmosfer havasının çirklənmə göstəriciləri arasında statistik əhəmiyyətli korrelyasiya müəyyən edilməmişdir ($p > 0{,}05$). Əldə edilən nəticələr geomaqnit aktivliyi və atmosfer havasının asılı hissəciklərlə çirklənməsinin anadangəlmə ürək qüsurları olan uşaqlarda fərqli hematoloji dəyişikliklərlə əlaqəli olduğunu göstərir və daha geniş iştirakçı qruplarını əhatə edən uzunmüddətli tədqiqatların aparılmasını zəruri edir.

Açar sözlər: *anadangəlmə ürək qüsurları, geomaqnit aktivlik, Kp indeksi, hava çirklənməsi, PM2.5, hematoloji göstəricilər, uşaqlar*

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OPTIMIZING MINERAL NUTRITION FOR BEAN QUALITY AND SUSTAINABLE AGRICULTURAL PRODUCTION

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Keywords: *vegetable bean, mineral nutrition, fertilizer rate, nutrient uptake, phytomass, nutrient-use efficiency, sustainable agriculture*

Summary. The development of domestic agricultural production is an important component of national food security. In this context, optimizing plant mineral nutrition is essential for maintaining soil fertility, improving nutrient-use efficiency, and ensuring sustainable agricultural production. This study investigated the effects of different fertilizer rates on nutrient uptake by the pods and phytomass of vegetable bean (Phaseolus L.) during the growing season. The experiment included an unfertilized control, 10 t ha^{-1} manure, N30P30K30, N60P60K30, and N90P60K60 treatments. The results demonstrated that fertilizer application substantially affected nitrogen, phosphorus, and potassium removal by both pods and phytomass. Nutrient removal by bean pods was generally greater for nitrogen than for phosphorus. The highest nutrient removal by pods was recorded under the N60P60K30 treatment, reaching 51.5 kg ha^{-1} N, 27.2 kg ha^{-1} P, and 29.0 kg ha^{-1} K. The same treatment also resulted in the highest nutrient accumulation in phytomass, with 17.9 kg ha^{-1} N, 5.5 kg ha^{-1} P, and 7.5 kg ha^{-1} K. The lowest values were generally observed in the unfertilized control. Overall, the findings indicate that appropriate optimization of mineral fertilizer rates can improve nutrient uptake and productivity while supporting more efficient nutrient management in vegetable bean production.

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Introduction

Efficient fertilizer management requires the appropriate determination of nutrient application rates to achieve targeted crop yields. Plant nutrition is strongly influenced by soil nutrient reserves, moisture availability, soil reaction, and organic matter content, while the effectiveness of fertilizers and other agricultural practices is closely related to soil properties (Shafran, 2022a). Fertilization is one of the major factors contributing to agricultural productivity and may account for approximately 30–50% of additional crop yield (Korchenkina et al., 2017; Liu et al., 2020). Therefore, optimizing fertilizer application according to the physicochemical and agrochemical characteristics of soils is essential for efficient crop production (Kudeyarov, 2019; Shafran, 2022b).

Sustainable agricultural production also requires the maintenance and restoration of soil fertility (Utkin, 2022). Increasing the return of plant residues to soil and improving nutrient-use efficiency can contribute to more sustainable nutrient management (Sharkov et al., 2022). At the same time, fertilizer-induced changes in soil properties depend on fertilizer type, application rate, duration of use, and inherent soil characteristics (Yaroshenko et al., 2018). Consequently, improved agricultural technologies are needed to enhance the efficient use of soil resources and plant nutrients (Roeva et al., 2023). Although mineral fertilizers can substantially increase crop productivity, their application may also affect soil humus status, nutrient regimes, biological activity, and physicochemical properties (Borontov et al., 2019; Kosyakin, 2019). Both mineral and organic fertilizers therefore play an important role in managing crop productivity and maintaining soil fertility under intensive agricultural systems (Vasyuchkov et al., 2023).

For leguminous crops, biological nitrogen fixation and effective plant–rhizobia symbiosis are particularly important for vegetative growth and stable yield formation (Alyoshin & Zavalin, 2023). A well-functioning symbiotic system can substantially reduce the requirement for external nitrogen inputs; however, when nitrogen

fixation is insufficient, legumes increasingly depend on nitrogen supplied by the soil and fertilizers (Otieno et al., 2009).

Despite the agronomic importance of vegetable bean, the effects of different fertilizer rates on its productivity and technological quality under irrigated gray-brown soils in arid climatic conditions remain insufficiently studied. In particular, limited information is available on changes in the quality characteristics of green pods and seeds at different developmental stages in response to mineral nutrition. Therefore, this study aimed to evaluate the effects of mineral nutrition on the yield and technological quality of vegetable bean and to identify an optimal mineral fertilizer application rate during the growing season.

Materials and methods

The study was conducted on irrigated gray-brown soils at the Absheron Auxiliary Experimental Farm of the Research Institute of Vegetable Growing, Ministry of Agriculture of the Republic of Azerbaijan. The soils of the experimental area are characterized by a cultivated horizon with heavy- and light-loamy textures and a predominance of silt and clay fractions. Long-term agricultural use has altered the structure of the arable layer of these irrigated gray-brown soils, with silty fractions predominating throughout the soil profile and reaching higher proportions (43.7–55.0%) in the upper horizons. The soils are characterized by relatively low humus contents of 1.57% in the topsoil and 1.24% in the subsoil, relatively high carbonate contents (8.3–17.8%) in the middle horizons, and a slightly alkaline soil reaction.

The locally adapted Zulyal vegetable bean cultivar (*Phaseolus* L.) was used in the experiment. The experimental plots were plowed in autumn, followed by harrowing and sowing in spring. Planting furrows and irrigation channels were subsequently established. The major proportion of manure and mineral fertilizers was applied during autumn plowing, while the remaining portion was applied in spring. Vegetable beans were sown at a spacing of 45 × 10 cm, with 45 cm between rows and 10 cm between plants, at a sowing depth of 4–5 cm.

The field experiment consisted of five fertilizer treatments: (1) control without fertilizer; (2) 10 t ha^{-1} manure; (3) N30P30K30; (4) N60P60K30; and (5) N90P60K60. Manure was used as the organic fertilizer. Ammonium nitrate containing 34% active ingredient was used as the nitrogen fertilizer, superphosphate containing 20% active ingredient as the phosphorus fertilizer, and potassium chloride containing 45% active ingredient as the potassium fertilizer.

Plant samples were analyzed using standard analytical procedures. Ashing was performed according to the K. E. Ginzburg method. Nitrogen was determined using the Kjeldahl micromethod, phosphorus by the photoelectrocolorimetric method, and potassium by flame photometry.

The plant samples were further analyzed for total nitrogen, phosphorus, potassium, and crude protein. Total nitrogen was determined photocolorimetrically, phosphorus was determined photometrically according to GOST 26657-97, potassium was determined by flame photometry following dry ashing, and crude protein content was calculated using the corresponding analytical values.

Results and discussion

Effects of Organic and Mineral Fertilizers on Nutrient Removal by Vegetable Bean Pods and Phytomass

Crop growth and yield are influenced by the genetic potential of the cultivar, soil and climatic conditions, cultivation practices, fertilizer application, and biotic stresses (Khan et al., 2022). Organic and mineral fertilizers can improve nutrient availability and contribute to the replenishment of nutrients removed with harvested biomass (Kydyraliev & Bodoshov, 2014). For leguminous crops, nitrogen nutrition is particularly important because plant growth depends on the balance between biologically fixed nitrogen and nitrogen supplied by the soil and fertilizers (Alyoshin & Zavalin, 2023; Oldroyd & Dixon, 2014). Appropriate fertilizer management may also improve nutrient-use efficiency in legume-based production systems (Biswas et al., 2025).

The results demonstrated that nutrient removal by vegetable bean varied considerably among fertilizer treatments. Nitrogen removal by pods ranged from 29.5 to 51.5 kg ha^{-1}, phosphorus from 11.0 to 27.2 kg ha^{-1}, and potassium from 15.2 to 29.0 kg ha^{-1} (Table 1). In general, nutrient removal increased with fertilizer application, with nitrogen being removed in the greatest quantity and phosphorus in the lowest.

The highest nutrient removal by pods was recorded under the N60P60K30 treatment, reaching 51.5 kg ha^{-1} N, 27.2 kg ha^{-1} P, and 29.0 kg ha^{-1} K. Compared with the unfertilized control, these values represented increases of 22.0 kg ha^{-1} N, 16.2 kg ha^{-1} P, and 13.8 kg ha^{-1} K, respectively. Thus, increased pod yield was accompanied by greater nutrient removal (Table 1).

A similar response was observed for nutrient accumulation in the dry phytomass. Nitrogen accumulation was 8.7 kg ha^{-1} in the control, 12.2 kg ha^{-1} with 10 t ha^{-1} manure, 14.3 kg ha^{-1} under N30P30K30, 17.9 kg ha^{-1}

under N60P60K30, and 16.3 kg ha^{-1} under N90P60K60. The corresponding phosphorus values were 1.8, 2.5, 4.5, 5.5, and 5.9 kg ha^{-1}, while potassium accumulation was 3.7, 5.0, 6.4, 7.5, and 6.1 kg ha^{-1}, respectively. Overall, the N60P60K30 treatment produced the highest combined nutrient accumulation in phytomass, with 17.9 kg ha^{-1} N, 5.5 kg ha^{-1} P, and 7.5 kg ha^{-1} K (Table 1).

Nutrient removal by pods was substantially greater than nutrient accumulation in phytomass across all treatments. In the control, pod-to-phytomass ratios were 3.4 for N, 6.0 for P, and 4.1 for K. The corresponding ratios were 3.2, 7.8, and 4.3 with 10 t ha^{-1} manure; 3.4, 6.6, and 4.3 under N30P30K30; 2.9, 4.9, and 3.9 under N60P60K30; and 3.1, 5.2, and 4.7 under N90P60K60. These results confirm that a substantially greater proportion of absorbed nutrients was removed with harvested pods than retained in the remaining phytomass (Table 1 and 2).

Overall, the response did not increase continuously with fertilizer rate. Although nutrient removal generally increased relative to the control, increasing fertilizer application from N60P60K30 to N90P60K60 did not result in a further improvement in most measured parameters. This indicates that the N60P60K30 treatment provided a more favorable nutrient response under the experimental conditions and that increasing fertilizer rates beyond this level did not produce proportional benefits.

Table 1

Nutrient removal by vegetable bean pods and biomass (three-year average)

Treatments	Pod yield					Biomass				
	Yield, c ha^{-1}		Nutrient removal, kg ha^{-1}			Yield, c ha^{-1}		Nutrient removal, kg ha^{-1}		
	Pods	dry matter	N	P	K	Biomass	dry matter	N	P	K
Control	155.6	13.0	29.5	11.0	15.2	128.8	12.0	8.7	1.8	3.7
10 t ha^{-1} manure	180.2	15.0	38.7	19.5	21.5	150.4	13.3	12.2	2.5	5.0
$N_{30}P_{30}K_{30}$	213.7	17.4	48.6	25.3	27.0	179.7	14.2	14.3	4.5	6.4
$N_{60}P_{60}K_{30}$	223.4	17.6	51.5	27.2	29.0	220.9	15.8	17.9	5. 5	7.5
$N_{90}P_{60}K_{60}$	219.2	17.5	50.3	25.5	28.8	208.5	15.6	16.3	4.9	6.1

Correlation between yield and nutrient removal

Fertilizer application increased not only vegetable bean yield but also nutrient removal. Pod yield was strongly correlated with the removal of nitrogen (r = 0.999), phosphorus (r = 0.985), and potassium (r = 0.996). Similarly, biomass yield showed strong positive correlations with nitrogen (r = 0.988), phosphorus (r = 0.998), and potassium (r = 0.937) removal (Tables 1 and 2). These relationships indicate that fertilizer-induced increases in yield were accompanied by greater nutrient removal.

Effects of organic and mineral fertilizers on nutrient uptake

Plants do not fully utilize nutrients supplied through organic and mineral fertilizers; therefore, fertilizer application rates should be adjusted according to crop nutrient requirements and soil nutrient availability. Nitrogen, phosphorus, and potassium uptake depends on their availability in the soil, fertilizer application, and plant developmental stage. Previous studies have also emphasized the importance of maintaining an appropriate nutrient balance in agricultural soils (Sychev & Shafran, 2017). The efficiency of fertilizer-derived nutrient uptake is strongly influenced by the availability of readily accessible nutrient reserves in the soil (Gadjimammadov et al., 2019).

In the unfertilized control, vegetable bean production depended entirely on soil nutrient reserves. With fertilizer application, both native soil nutrients and fertilizer-derived nutrients contributed to crop nutrient uptake. Nitrogen removal by pods increased from 29.5 kg ha^{-1} in the control to 38.7–51.5 kg ha^{-1} in the fertilized treatments. Phosphorus removal increased from 11.0 to 19.5–27.2 kg ha^{-1}, while potassium removal increased from 15.2 to 21.5–29.0 kg ha^{-1}. The highest values were consistently recorded under N60P60K30.

Compared with the control, nitrogen removal by pods increased by 9.2 kg ha^{-1} under 10 t ha^{-1} manure, 19.1 kg ha^{-1} under N30P30K30, 22.0 kg ha^{-1} under N60P60K30, and 20.8 kg ha^{-1} under N90P60K60. The corresponding increases in phosphorus removal were approximately 8.5, 14.3, 16.2, and 14.5 kg ha^{-1}, while potassium removal increased by approximately 6.3, 11.8, 13.8, and 13.6 kg ha^{-1}, respectively. These results demonstrate that phosphorus was removed in smaller quantities than nitrogen and potassium and that increasing fertilizer rates beyond N60P60K30 did not result in further nutrient removal.

Nutrient accumulation in phytomass showed a similar response. Across the treatments, nitrogen accumulation ranged from 8.7 to 17.9 kg ha^{-1}, phosphorus from 1.8 to 5.5 kg ha^{-1}, and potassium from 3.7 to 7.5 kg

ha⁻¹, with the lowest values in the control and the highest values under N60P60K30. Overall, the results demonstrate that nutrient removal with harvested pods was substantially greater than nutrient accumulation in the remaining phytomass.

Table 2

Nutrient uptake by vegetable bean phytomass from soil and fertilizers (three-year average)

Treatment	Nitrogen, kg ha⁻¹	Of total, %		Phosphorus, kg ha⁻¹	Of total, %		Potassium, kg ha⁻¹	От общего, %	
		From soil	From fertilizers		From soil	From fertilizers		From soil	From fertilizers
Control	8,8	100		1,8	100,0		3,7	100	
10 t ha⁻¹ manure	12,2	72,1	27,9	2,5	72,0	28,0	5.0	74,0	26.0
$N_{30}P_{30}K_{30}$	14,3	61,5	38,5	3,8	47,4	52,6	6,3	58,7	41,3
$N_{60}P_{60}K_{30}$	17,9	49,2	50,8	5,5	32,7	67,3	7,5	49,3	50,7
$N_{90}P_{60}K_{60}$	16,3	54,0	46.0	4,9	36,7	63,4	6,1	60,7	39,3

Nutrient uptake from applied fertilizers

Based on the experimental results, nutrient uptake coefficients for vegetable bean were calculated considering nutrient removal by the main and secondary yield components, including roots, leaves, and stems, according to the established methodology (Narusheva, 2014).

In the unfertilized control, total nitrogen removal by above- and below-ground plant organs was 38.3 kg ha⁻¹. Fertilizer application increased total nitrogen removal to 50.9–69.4 kg ha⁻¹, depending on the treatment. The calculated nitrogen uptake coefficients were 25.2% for 10 t ha⁻¹ manure, 82.0% for N30P30K30, 51.8% for N60P60K30, and 31.4% for N90P60K60 (Table 3).

Total phosphorus removal was 12.8 kg ha⁻¹ in the control and increased to 22.0–32.7 kg ha⁻¹ following fertilizer application. The corresponding phosphorus uptake coefficients were 36.6, 54.4, 33.2, and 29.4% for the manure, N30P30K30, N60P60K30, and N90P60K60 treatments, respectively. Total potassium removal increased from 18.9 kg ha⁻¹ in the control to 26.5–36.5 kg ha⁻¹ in the fertilized treatments. Potassium uptake coefficients were 12.6% with manure, 48.0% under N30P30K30, 58.6% under N60P60K30, and 26.6% under N90P60K60 (Table 3).

Overall, nutrient uptake efficiency varied substantially with fertilizer rate. The highest nitrogen and phosphorus uptake coefficients were recorded under N30P30K30 (82.0 and 54.4%, respectively), whereas the highest potassium uptake coefficient occurred under N60P60K30 (58.6%). These results indicate that the N30P30K30 and N60P60K30 treatments provided the most favorable nutrient-use responses, while further increasing fertilizer application to N90P60K60 reduced the uptake efficiency of all three nutrients.

Table 3

Nutrient Uptake Coefficients of Vegetable Bean from Fertilizers
by Above- and Below-Ground Plant Organs (Three-Year Average)

Treatment	Nitrogen, kg ha⁻¹	Difference	Uptake coefficient, %	Phosphorus, kg ha⁻¹	Difference	Uptake coefficient, %	Potassium, kg ha⁻¹	Difference	Uptake coefficient, %
Control	38,3			12,8			18,9		
10 t ha⁻¹ manure	50,9	12,6	25,2	22,0	9,1	36,6	26,5	7,5	12,6
$N_{30}P_{30}K_{30}$	62,9	24,6	82,0	29,1	16,3	54,4	33,3	14,4	48,0
$N_{60}P_{60}K_{30}$	69,4	31,1	51,8	32,7	19,9	33,2	36,5	17,6	58,6
$N_{90}P_{60}K_{60}$	66,6	28,3	31,4	30,4	17,6	29,4	34,9	15,9	26,6

Conclusion

The results demonstrated that mineral nutrition significantly influenced nutrient removal and uptake by vegetable bean. Fertilizer application increased the removal of nitrogen, phosphorus, and potassium by both pods and phytomass compared with the unfertilized control. The N60P60K30 treatment produced the highest

pod yield and the greatest nutrient removal, reaching 51.5 kg ha^{-1} N, 27.2 kg ha^{-1} P, and 29.0 kg ha^{-1} K in pods and 17.9 kg ha^{-1} N, 5.5 kg ha^{-1} P, and 7.5 kg ha^{-1} K in phytomass. Increasing the fertilizer rate to N90P60K60 did not provide a further improvement in these parameters.

Nutrient uptake efficiency also varied among fertilizer treatments. The highest uptake coefficients for nitrogen (82.0%) and phosphorus (54.4%) were recorded under N30P30K30, whereas the highest potassium uptake coefficient (58.6%) occurred under N60P60K30. Overall, the results indicate that N30P30K30 and N60P60K30 provided the most favorable nutrient-use responses, while N60P60K30 was the most effective treatment for maximizing yield and nutrient removal under the experimental conditions.

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ОПТИМИЗАЦИЯ МИНЕРАЛЬНОГО ПИТАНИЯ ФАСОЛИ ДЛЯ ПОВЫШЕНИЯ КАЧЕСТВА ПРОДУКЦИИ И ОБЕСПЕЧЕНИЯ УСТОЙЧИВОГО СЕЛЬСКОХОЗЯЙСТВЕННОГО ПРОИЗВОДСТВА

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Резюме. Развитие отечественного сельскохозяйственного производства является важной составляющей национальной продовольственной безопасности. В этом контексте оптимизация минерального питания растений имеет существенное значение для сохранения плодородия почв, повышения эффективности использования питательных элементов и обеспечения устойчивого сельскохозяйственного производства. В исследовании изучалось влияние различных норм внесения удобрений на поглощение питательных элементов бобами и фитомассой овощной фасоли (Phaseolus L.) в течение вегетационного периода. Схема опыта включала контрольный вариант без внесения удобрений, внесение навоза в норме 10 т/га, а также варианты N30P30K30, N60P60K30 и N90P60K60. Результаты показали, что внесение удобрений существенно влияло на вынос азота, фосфора и калия как бобами, так и фитомассой растений. Вынос питательных элементов бобами фасоли в целом был выше по азоту, чем по фосфору. Наибольший вынос питательных элементов бобами отмечен в варианте N60P60K30 и составил 51,5 кг/га азота, 27,2 кг/га фосфора и 29,0 кг/га калия. В этом же варианте установлено максимальное накопление питательных элементов в фитомассе: 17,9 кг/га азота, 5,5 кг/га фосфора и 7,5 кг/га калия. Наименьшие значения преимущественно наблюдались в контрольном варианте без внесения удобрений. В целом полученные результаты свидетельствуют о том, что оптимизация норм внесения минеральных удобрений способствует улучшению поглощения питательных элементов и повышению продуктивности, одновременно обеспечивая более эффективное управление питательным режимом при выращивании овощной фасоли.

Ключевые слова: *овощная фасоль, минеральное питание, норма удобрений, поглощение питательных веществ, фитомасса, эффективность использования питательных веществ, устойчивое сельское хозяйство*

MƏHSULUN KEYFİYYƏTİNİN YÜKSƏLDİLMƏSİ VƏ DAYANIQLI KƏND TƏSƏRRÜFATI İSTEHSALININ TƏMİN EDİLMƏSİ ÜÇÜN LOBYANIN MİNERAL QİDALANMASININ OPTİMALLAŞDIRILMASI

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Xülasə. Yerli kənd təsərrüfatı istehsalının inkişafı milli ərzaq təhlükəsizliyinin mühüm tərkib hissəsidir. Bu baxımdan bitkilərin mineral qidalanmasının optimallaşdırılması torpaq münbitliyinin qorunması, qida elementlərindən istifadə səmərəliliyinin artırılması və dayanıqlı kənd təsərrüfatı istehsalının təmin edilməsi üçün mühüm əhəmiyyət kəsb edir. Tədqiqatda vegetasiya dövründə müxtəlif gübrə normalarının tərəvəz lobyasının (Phaseolus L.) paxlaları və fitokütləsi tərəfindən qida elementlərinin mənimsənilməsinə təsiri araşdırılmışdır. Təcrübəyə gübrə verilməyən nəzarət variantı, 10 t/ha peyin, N30P30K30, N60P60K30 və N90P60K60 gübrələmə variantları daxil edilmişdir. Nəticələr göstərmişdir ki, gübrələrin tətbiqi həm paxlalar, həm də fitokütlə tərəfindən azot, fosfor və kaliumun mənimsənilməsinə əhəmiyyətli dərəcədə təsir göstərmişdir. Lobya paxlaları tərəfindən qida elementlərinin mənimsənilməsi ümumilikdə azot üzrə fosfora nisbətən daha yüksək olmuşdur. Paxlalar tərəfindən qida elementlərinin ən yüksək mənimsənilmə göstəriciləri N60P60K30 variantında qeydə alınmış və azot üzrə 51,5 kq/ha, fosfor üzrə 27,2 kq/ha, kalium üzrə isə 29,0 kq/ha təşkil etmişdir. Eyni variantda fitokütlədə qida elementlərinin ən yüksək toplanma göstəriciləri müəyyən edilmişdir: azot üzrə 17,9 kq/ha, fosfor üzrə 5,5 kq/ha və kalium üzrə 7,5 kq/ha. Ən aşağı göstəricilər əsasən gübrə tətbiq edilməyən nəzarət variantında müşahidə olunmuşdur. Ümumilikdə, tədqiqatın nəticələri mineral gübrə normalarının düzgün optimallaşdırılmasının qida elementlərinin mənimsənilməsini və məhsuldarlığı artıra, eyni zamanda tərəvəz lobyasının becərilməsində qida elementlərinin daha səmərəli idarə olunmasına şərait yarada biləcəyini göstərir.

Açar sözlər: *tərəvəz lobyası, mineral qidalanma, gübrə norması, qida elementlərinin mənimsənilməsi, fitokütlə, qida elementlərindən istifadə səmərəliliyi, dayanıqlı kənd təsərrüfatı*

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SELECTIVE MANAGEMENT OF INFRASTRUCTURE SYSTEMS BASED ON RISK MONITORING AND SCENARIO MODELING

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Keywords: *infrastructure systems, selective management, risk monitoring, scenario modeling, risk assessment, decision support*

Summary. Infrastructure systems operate in increasingly unstable environments characterized by technological, economic, operational, and security-related risks. This study develops a selective management mechanism for infrastructure systems aimed at concentrating managerial attention and resources on critical elements while maintaining their overall sustainability. The research adopts a system-oriented conceptual approach and draws on scientific literature, regulatory materials, practical cases, and established risk-management practices. System analysis, SWOT analysis, Failure Mode and Effects Analysis (FMEA), and scenario modeling are incorporated into the proposed framework. The study distinguishes selective management from general infrastructure management and identifies the principal conditions and organizational mechanisms required for its implementation. The proposed mechanism comprises continuous risk monitoring, identification and ranking of critical infrastructure elements, risk identification and assessment, development of targeted management measures, decision-support information systems, and coordination and personnel training. Particular attention is given to automation, modularity and scalability, security, fault tolerance, continuous monitoring, and standardization as principles supporting selective infrastructure management. The framework also integrates adaptive management, resource redistribution, redundancy, recovery mechanisms, and scenario-based decision support. The proposed approach provides a structured basis for prioritizing vulnerable infrastructure components and allocating management resources according to their significance, condition, criticality, and exposure to risk. It can support more focused and adaptive infrastructure management under conditions of uncertainty.

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1. Introduction

Infrastructure constitutes a fundamental component of modern economic systems, supporting economic activity and the provision of essential services to society. Increasing environmental instability, technological change, and exposure to multiple risks have strengthened the need for management approaches capable of

maintaining the reliability and sustainability of infrastructure systems. Recent research emphasizes that infrastructure resilience requires the capacity to withstand disruptions, adapt to changing conditions, and restore essential functions following adverse events (Curt & Tacnet, 2018; Guo et al., 2021).

The concept of infrastructure has been interpreted from different theoretical perspectives. Bell (2004) and Schumpeter (2007) associated infrastructure with the conditions supporting economic activity and societal development, while Mallaev and Avramchikova (2017) emphasized its institutional dimension and its role in creating organizational and economic conditions for market functioning. Previous studies have also addressed specific aspects of infrastructure-related risk management, including energy-service systems (Guskova & Ulyankin, 2016), entrepreneurial risks within economic security systems (Barikaev, 2018), and IT infrastructure risks (Maslova, 2022). These studies demonstrate the importance of risk-oriented management but primarily address particular sectors or categories of risk.

Under conditions of uncertainty, managing individual infrastructure components in isolation may be insufficient because failures or imbalances in one element can affect the functioning of interconnected components. Risk-oriented and adaptive approaches are therefore increasingly important for maintaining system sustainability under changing operating conditions (Gridneva & Vasilevsky, 2025).

Accordingly, this study aims to develop a mechanism for selective management of infrastructure systems under risk conditions. The proposed approach integrates risk monitoring, prioritization of infrastructure elements, targeted managerial interventions, and scenario-based decision support to improve the adaptability and sustainability of infrastructure systems.

2. Materials and methods

The study adopts a system-oriented conceptual approach to the management of infrastructure systems under risk conditions. The analysis draws on scientific publications, regulatory and legal documents, research reports, practical cases, and other materials describing infrastructure management and risk-management practices.

The methodological framework combines system analysis with induction and deduction, analysis and synthesis, SWOT analysis, Failure Mode and Effects Analysis (FMEA), and scenario modeling. System analysis was used to examine infrastructure as an interconnected set of components, while SWOT analysis and FMEA provide tools for identifying vulnerabilities, assessing critical elements, and prioritizing risks. Scenario modeling was incorporated to support the evaluation of alternative management responses under changing conditions (Nevskaya et al., 2024).

Based on this framework, existing infrastructure-management practices were synthesized to develop a selective management mechanism comprising risk monitoring, prioritization of infrastructure elements, risk assessment, targeted management measures, and decision-support procedures.

3. Results and discussion

Infrastructure systems comprise interconnected technical, organizational, and managerial components whose reliable operation is essential for the functioning of the broader economic system. Their management therefore requires a combination of general and selective approaches. General management covers the system as a whole through common planning, organization, coordination, and control procedures, whereas selective management introduces targeted interventions for individual elements or groups of elements that require additional managerial attention.

In this study, selective management is understood as a complementary mechanism rather than a replacement for general infrastructure management. Its purpose is to identify problematic or vulnerable elements and concentrate managerial actions and resources on preventing failures, mitigating negative consequences, and supporting critical activities. Selective interventions can be incorporated at different stages of the management cycle, including goal setting, planning, organization, implementation, coordination, and control.

The proposed approach is particularly relevant under risk conditions because infrastructure components differ in their criticality, vulnerability, technical condition, and contribution to overall system performance. Selective management therefore allows management resources to be directed toward those elements where intervention is expected to have the greatest importance for system stability.

The expected benefits of selective management include reduced potential losses and operating costs, improved resource efficiency and management quality, and a better balance among the interests of infrastructure-system participants.

The proposed framework is based on six interrelated principles: automation, modularity and scalability, security and risk prevention, availability and fault tolerance, continuous monitoring and analysis, and documentation and standardization. Automation can reduce manual intervention and operational errors, while modularity supports adaptation to changing system requirements. Security and fault tolerance protect critical components and maintain service continuity, whereas continuous monitoring enables the early identification of anomalies and emerging risks. Documentation and standardization provide transparency and facilitate the integration and management of infrastructure components. These principles should be periodically reviewed as technological conditions, risks, and organizational requirements evolve. The principal types of selective infrastructure management are summarized in Figure 1.

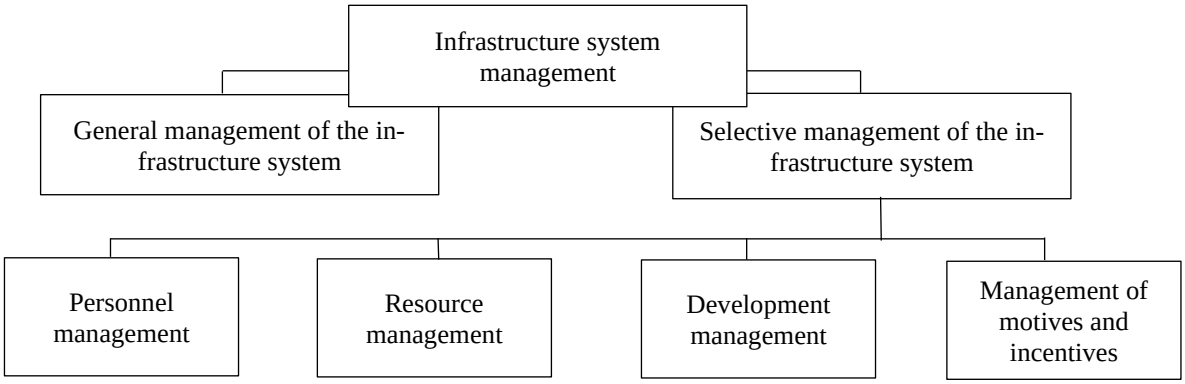


Fig. 1. Types of selective management of the infrastructure (compiled by the author)

Selective infrastructure management can be implemented through four main areas: personnel management, resource management, development management, and management of motives and incentives. Personnel management may employ role-, attribute-, behavior-, and rule-based approaches to regulate responsibilities, permissions, and access to infrastructure resources. Resource management focuses on targeted interventions that improve resource utilization and reduce the likelihood of operational problems, while development management directs goals, resources, and projects toward long-term system sustainability. Management of motives and incentives aims to align the interests of personnel and service users with infrastructure-management objectives. The appropriate combination of these approaches depends on organizational characteristics, security requirements, and the scale and complexity of the infrastructure system.

To implement selective management, it is advisable to have an appropriate mechanism in the management system of the infrastructure system.

The mechanism of selective management of the infrastructure system under risks is a comprehensive approach aimed at selectively influencing key elements of the infrastructure to minimize risks and increase the sustainability of its functioning.

The selective management mechanism uses a sample, selective approach to concentrate management actions and resources on the most critical infrastructure elements in order to minimize the negative consequences of risk impact.

It includes the following components.

1. Functional organization (or units) for the implementation of continuous monitoring of the state of the infrastructure system and risks (risk monitoring, timely response to threats, assessment of the effectiveness of risk identification, etc.). Risk management methods (SWOT analysis, FMEA, scenario modeling) can be used as tools.

2. Studying the condition and ranking of infrastructure elements. The main function is to determine the priority of infrastructure components and their condition (e.g., power supply systems, traffic centers, IT platforms) according to the criteria of significance (socio-economic, technical, etc.), condition and criticality for the functioning of the infrastructure, vulnerability to risks.

3. Implementation of systematization and determination of risks (identification, recognition and classification of risks).

4. Conducting risk analysis and assessment (determining possible damage from risk occurrence, clarifying the probability of risk occurrence).

5. Development of measures for selective risk management (definition of objects and elements subject to selective impact, development and planning of measures, programs, projects for selective impact, appointment of a responsible officer, determination of the results of selective impact).

6. Information system for decision support. This system should ensure the integration of current data from different sources (e.g., geographic information systems, Big Data, etc.) for scenario modeling and optimization of management decisions.

7. Interaction and personnel training. They are used for the purposes of personnel training to act in crisis situations, as well as for the coordination between departments (for example, the Ministry of Emergency Management, energy, logistics).

The following methods and tools can be used in the mechanism of selective management of the infrastructure system under risk conditions:

– adaptive management strategies; flexible plans of action for key elements in the form of redundancy (duplication of critical nodes), dynamic redistribution of resources (e.g., energy, personnel) in case of threats; localization of impact (isolation of damaged segments to prevent cascading failures), etc.

– implementation of a monitoring and feedback system that ensures continuous monitoring of the infrastructure state using sensors, IoT devices, analytical platforms, etc., which allow to forecast wearing of equipment and track anomalies in real time;

– mechanisms for redundancy and restoration to create "buffer zones" (in the form of reserve capacities, backup communications);

– plans for the fallback recovery, etc.

Selective management of the infrastructure system under risk conditions allows concentrating resources, focusing actions on key critical elements of the infrastructure, ensuring a sufficient level of stability of its functioning even in conditions of uncertainty. This approach should combine proactivity (risk prevention) and reactivity (quick response), which allows for an efficient and comprehensive solution to the problem of effective management of the infrastructure system.

Selective management of the infrastructure system under risk conditions is an innovative approach aimed at increasing the sustainability and efficiency of the key elements functioning. The main focus is on selective effect on the most vulnerable components, such as traffic centers, power supply systems and IT platforms, which allows minimizing risks and reducing costs. The use of SWOT analysis, FMEA and scenario modeling techniques ensures accuracy in assessing threats and developing adaptive strategies.

An important aspect is the implementation of special devices and analytical platforms for continuous monitoring of the infrastructure condition. This allows for prompt detection of anomalies and prevention of cascading failures. The principles of modularity, scalability and security ensure the flexibility of the system in a changing external environment.

Selective management also involves the creation of "buffer zones" and reserve capacities, which increases fault-tolerance. However, successful implementation of the approach requires regular updating of the methodology and adaptation to new challenges. Thus, the proposed mechanism contributes not only to reducing risks, but also to increasing the competitiveness of infrastructure systems.

4. Conclusion

This study proposes a selective management mechanism for infrastructure systems operating under risk and uncertainty. Unlike general management, selective management focuses managerial attention and resources on infrastructure elements according to their criticality, vulnerability, and current condition. The proposed mechanism integrates continuous risk monitoring, prioritization of infrastructure elements, risk identification and assessment, targeted management measures, decision-support tools, and personnel coordination and training.

The framework combines proactive risk prevention with responsive measures and incorporates adaptive management, monitoring and feedback systems, redundancy, and recovery mechanisms. Its application can support more focused allocation of management resources and strengthen the ability of infrastructure systems to respond to disruptions and changing operating conditions. The proposed mechanism provides a conceptual basis for further development and practical testing of selective infrastructure management approaches in different infrastructure contexts.

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ДИФФЕРЕНЦИРОВАННОЕ УПРАВЛЕНИЕ ИНФРАСТРУКТУРНЫМИ СИСТЕМАМИ НА ОСНОВЕ МОНИТОРИНГА РИСКОВ И СЦЕНАРНОГО МОДЕЛИРОВАНИЯ

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Резюме. Инфраструктурные системы функционируют во всё более нестабильной среде, характеризующейся технологическими, экономическими, операционными рисками и рисками, связанными с безопасностью. В исследовании разрабатывается механизм селективного управления инфраструктурными системами, направленный на концентрацию управленческого внимания и ресурсов на критически важных элементах при сохранении общей устойчивости систем. Исследование основывается на системно-ориентированном концептуальном подходе с использованием научной литературы, нормативных материалов, практических примеров и сложившихся методов управления рисками. В предлагаемую концептуальную модель включены системный анализ, SWOT-анализ, анализ видов и последствий отказов (FMEA), а также сценарное моделирование. В исследовании проводится разграничение селективного и общего управления инфраструктурой, определяются основные условия и организационные механизмы, необходимые для его реализации. Предлагаемый механизм включает непрерывный мониторинг рисков, выявление и ранжирование критически важных элементов инфраструктуры, идентификацию и оценку рисков, разработку целевых управленческих мероприятий, информационные системы поддержки принятия решений, а также координацию и подготовку персонала. Особое внимание уделяется автоматизации, модульности и масштабируемости, безопасности, отказоустойчивости, непрерывному мониторингу и стандартизации как принципам, обеспечивающим селективное управление инфраструктурой. Предлагаемая модель также объединяет адаптивное управление, перераспределение ресурсов, резервирование, механизмы восстановления и поддержку принятия решений на основе сценариев. Предложенный подход формирует структурированную основу для определения приоритетности уязвимых компонентов инфраструктуры и распределения управленческих ресурсов в соответствии с их значимостью, состоянием, критичностью и подверженностью рискам. Данный подход может способствовать более целенаправленному и адаптивному управлению инфраструктурой в условиях неопределённости.

Ключевые слова: *инфраструктурные системы, селективное управление, мониторинг рисков, сценарное моделирование, оценка рисков, поддержка принятия решений*

RİSKLƏRİN MONİTORİNQİ VƏ SSENARİ MODELLƏŞDİRİLMƏSİ ƏSASINDA İNFRASTRUKTUR SİSTEMLƏRİNİN SELEKTİV İDARƏ EDİLMƏSİ

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Xülasə. İnfrastruktur sistemləri texnoloji, iqtisadi, əməliyyat və təhlükəsizliklə bağlı risklərlə səciyyələnən, getdikcə daha qeyri-sabit mühitdə fəaliyyət göstərir. Tədqiqatda infrastruktur sistemlərinin ümumi dayanıqlığını qorumaqla yanaşı, idarəetmə diqqətinin və resurslarının kritik elementlər üzərində cəmləşdirilməsinə yönəlmiş selektiv idarəetmə mexanizmi işlənib hazırlanmışdır. Tədqiqat sistem yönümlü konseptual yanaşmaya əsaslanır və elmi ədəbiyyata, normativ materiallara, praktiki nümunələrə və formalaşmış risklərin idarə edilməsi təcrübələrinə istinad edir. Təklif olunan çərçivəyə sistem təhlili, SWOT təhlili, nasazlıq növlərinin və təsirlərinin təhlili (FMEA), həmçinin ssenari modelləşdirilməsi daxil edilmişdir. Tədqiqatda selektiv idarəetmə infrastrukturun ümumi idarə edilməsindən fərqləndirilmiş, onun həyata keçirilməsi üçün tələb olunan əsas şərtlər və təşkilati mexanizmlər müəyyən edilmişdir. Təklif olunan mexanizm risklərin davamlı monitorinqini, kritik infrastruktur elementlərinin müəyyənləşdirilməsini və ranqlaşdırılmasını, risklərin müəyyən edilməsi və qiymətləndirilməsini, məqsədyönlü idarəetmə tədbirlərinin hazırlanmasını, qərarların qəbuluna dəstək verən informasiya sistemlərini, eləcə də koordinasiya və kadr hazırlığını əhatə edir. Selektiv infrastruktur idarəetməsini dəstəkləyən prinsiplər kimi avtomatlaşdırmaya, modulluğa və miqyaslana bilməyə, təhlükəsizliyə, nasazlıqlara davamlılığa, fasiləsiz monitorinqə və standartlaşdırmaya xüsusi diqqət yetirilmişdir. Təklif olunan çərçivə adaptiv idarəetməni, resursların yenidən bölüşdürülməsini, ehtiyatlılığı təmin edən mexanizmləri, bərpa mexanizmlərini və ssenarilər əsasında qərarların qəbuluna dəstəyi də özündə birləşdirir. Təklif olunan yanaşma həssas infrastruktur komponentlərinin prioritetləşdirilməsi və idarəetmə resurslarının onların əhəmiyyətinə, vəziyyətinə, kritikliyinə və risklərə məruz qalma səviyyəsinə uyğun bölüşdürülməsi üçün strukturlaşdırılmış əsas yaradır. Bu yanaşma qeyri-müəyyənlik şəraitində infrastrukturun daha məqsədyönlü və adaptiv idarə edilməsini dəstəkləyə bilər.

Açar sözlər: *infrastruktur sistemləri, selektiv idarəetmə, risklərin monitorinqi, ssenari modelləşdirilməsi, risklərin qiymətləndirilməsi, qərar qəbuluna dəstək*

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CONTROL OF FINANCIAL RESOURCES OF INFRASTRUCTURE FACILITIES WITH THE ACCEPTION OF HAZARD ANALYSIS

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Keywords: *infrastructure systems, economic efficiency, economic potential and risks, strategic management, sustainability, management*

Summary. The purpose of this study is to investigate the methods of regulating the economic resource of infrastructure complexes, taking into account the impact of risk factors. Infrastructure complexes play an important role in the progress of the economy, but they are subject to various dangers, such as financial, environmental and operational difficulties. The present study identifies the basic components of infrastructure complexes, their economic potential and the risks associated with their regulation. Based on an analysis of existing scientific views and relevant publications, the study suggests a unified framework for regulating infrastructure complexes with a focus on hazard reduction and cost-effectiveness. The results include a mathematical model of an economic resource, a systematization of infrastructure complexes, and a detailed analysis of risk management principles. The study argues that effective regulation of infrastructure complexes requires a strategic approach combining hazard assessment, economic analysis, and adaptive management. This work contributes to this field by providing a comprehensive understanding of infrastructure regulation and offering applied advice to all stakeholders.

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Introduction

Infrastructure complexes, including transport networks, energy systems, water supply, and communications, are a vital foundation for economic development. Effective management of these systems is critical for sustaining economic growth and improving the living standards of the population. Over the years of research, numerous scientific approaches to infrastructure management have been proposed. For example, Bertalanffy's Systems Theory emphasizes the interrelationship of infrastructure components and their combined impact on economic indicators. E. Hollnagel's Resilience Engineering concept is similarly aimed at increasing the resilience of infrastructure systems to failures and their ability to recover. These approaches are widely discussed in the scientific literature, particularly in the works of L Hong, M Ouyang, M Xu, P Hu, Terje Aven, Enrico

Zio and other authors who emphasize the importance of adapting to change and reducing risks in infrastructure management. (Hollnagel et al., 2006; Hong et al., 2020)

Russian scientists are also actively studying various aspects of managing the economic potential of infrastructure systems, considering the impact of risks. For example, S.P. Kirilchuk, S.M. Yergin, E.V. Nalivaychenko, and I.V. Artukhova have investigated methods for assessing the development of the region's production infrastructure, justifying the impact of production infrastructure drivers on economic growth. (Kirilchuk et al., 2022)

E.A. Trofimov and T.I. Trofimova emphasized the need to divide social production into material production (identified with the real sector of the economy) and the infrastructure complex, which includes diverse components such as production, energy, social, institutional, information, and environmental elements. This approach necessitates a rethinking of the traditional understanding of a region's economic potential and the approaches to its assessment. (Trofimov & Trofimova, 2021)

Y.I. Mikhailov, V.P. Semenov and N.V. Mikhailova examined methods for assessing the effectiveness of the production infrastructure of mining enterprises.

Research in the fields of information technology, drivers of economic growth, high-tech industries, social infrastructure, features of digital economy development etc., has indicated the existence of numerous connections, factors, and phenomena between industries and infrastructure systems, uniting them into a single socio-economic system that requires a comprehensive approach.

Analysis of scientific sources revealed a variety of methodologies for determining the economic potential of both the infrastructure as a whole and its individual components. These methodologies primarily reveal the economic aspects of infrastructure potential, although increasing attention is also being paid to social, environmental, and other aspects, and the methods are based on mathematical calculations, discounting, and complex mathematical models. The assessment of economic potential, in a general sense, is primarily considered as the determination of the totality of resources, opportunities, and conditions available to the infrastructure.

The aim of this study is to address these gaps by developing a comprehensive framework for managing the economic potential of infrastructure systems, with a focus on minimizing risks.

Methods

The theoretical and methodological basis of the study were the works of domestic and foreign scientists in the field of economic geography, geopolitics, location of production, network economy, development of regions and clusters, as well as works revealing methodological issues of identification, structural construction of clusters, mechanisms of formation and state support of cluster development. The article uses methods of system, logical, comparative analysis, methods of determining efficiency, groupings, cluster analysis, etc.

Results

For the uninterrupted functioning of the economy a developed infrastructure is necessary. It ensures the unity of production and consumption processes, deepens the specialization of activities, and increases the efficiency of the division of labor. The concept of “infrastructure” is multifaceted and encompasses a set of conditions for economic development, a complex of interconnected industries, the non-productive sector, the service sector, etc. In this context, infrastructure is viewed as a complex, organized system of interconnected economic entities that provide services to support socio-economic activity. Infrastructure systems are divided into transport, energy, heat and water supply, information and communication systems, and others.

There are many classifications of infrastructure systems based on various criteria. In the field of design and management, it is possible to present an original classification of infrastructure systems, based on the criterion of their hierarchy (4 levels) in ensuring the life of the population, functional role, and relationship with the urban environment.

The first level includes essential services for the population, such as water supply, sewage systems, electricity supply, heating, trade, healthcare, security, and others that provide for the basic needs of the population and the economy, supporting the functioning of the urban environment.

The second level of infrastructure covers transport systems, including roads, railways, public transport and airports. They provide mobility for the population and economic entities, the transportation of goods, connecting different parts of the city and regions.

The third level of infrastructure is represented by information and communication systems, such as radio, television, communication networks, the Internet, data management systems, etc. They facilitate the transmission of information, access to knowledge, and coordination of various areas of activity.

At the fourth level of infrastructure formations are waste management systems, such as landfills, waste processing plants, and waste recycling systems, which ensure environmental safety and sustainable development of the urban environment.

Infrastructure systems provide services to the population and businesses, and participate in the creation of tangible and intangible goods and values. They provide access to markets and all types of resources and information, and create favorable conditions (including institutional ones) for business and entrepreneurship development. Developed infrastructure systems influence economic performance by contributing, for example, to lower transaction costs, increased labor productivity, and faster capital turnover, thereby stimulating investment activity. In addition, infrastructure plays a vital role in ensuring social stability and improving the quality of life of the population by providing access to education, healthcare, and other social services.

Like any economic object (element), infrastructure systems possess characteristics and indicators that reflect their features, state, and dynamics of change, and which serve the purposes of management, planning, and development. One of the most important characteristics of infrastructure systems, which has not yet been sufficiently studied, is economic potential, reflecting their ability to sustain themselves and develop independently. Furthermore, the economic potential of the infrastructure system is considered as a combination of resources, opportunities, and factors capable of ensuring sustainable economic growth and improving the living standards of the population in a given territory. It includes not only the physical presence of infrastructure facilities, such as transport networks, energy systems, and communication lines, but also their qualitative characteristics, operational efficiency, and ability to adapt to the changing needs of the economy.

Assessing the economic potential of an infrastructure system requires a comprehensive approach that considers both quantitative and qualitative indicators. For example, it is important to consider not only the volume of investment in infrastructure, but also its effectiveness.

The economic potential of an infrastructure system is its ability to generate economic value by supporting production, exchange, and consumption. This potential is determined by characteristics such as productivity, efficiency, and sustainability.

Based on this definition of an infrastructure system, economic potential consists of the following key components:

Physical (tangible) assets, which include infrastructure facilities such as roads, canals, power supply networks, buildings, structures, as well as equipment, raw materials, etc.

Intangible assets mean the elements that do not have a physical form but generate economic profit (e.g., patents, service marks, trademarks, licenses, etc.).

Human resources, which is represented by qualified specialists involved in the creation of the infrastructure system, maintaining its operation, and managing it.

Financial resources include the investments and funding necessary to ensure the operation and development of the infrastructure.

Technological advancements are progressive technologies that improve the performance and productivity of infrastructure.

The combination of components and the structure of an infrastructure system determine the size and characteristics of its economic potential. Given the importance and influence of potential, it can be argued that economic potential also affects the composition of components and the structure of the infrastructure system.

For management and planning purposes, the economic potential of an infrastructure system (EPIS) can be represented by the following mathematical expression:

$$EPIS = \sum(TA + IA + HC + FR + TI)\text{xRxEMSxS}, \quad (1)$$

where TA denotes tangible assets; IA – intangible assets; HC – human capital; FR – financial resources; TI – technological innovations; R – risk-based losses (value in the range 0-1); EMS – efficiency of the management system of infrastructure (value in the range 0-1); S – socio-economic situation in the region (value in the range 0-1).

To determine the volume (value) of the economic potential of an infrastructure system, relevant economic indicators (cost, prices, revenues, etc.), as well as expert assessments, can be used. The determination of expert assessment values can be illustrated using Table 1 as an example.

Table 1

Scale of expert assessment values (in scores)

Range of the assessment	Criteria	Description
0-0.2	Low level	Minimal influence
0.2-0.5	Average risk level	Insignificant influence
0.5-0.8	High level of risks	Significant impact
0.8-1	Critical level of risks	High impact

The management of the infrastructure system must ensure the creation of conditions and the application of such methods, in which the formation and use of economic potential, considering risk and the need to achieve the required level of competitiveness, should strive for maximum values in each period of time:

$$EPIS \rightarrow max. \quad (2)$$

Infrastructure risks are the probability of events occurring that threaten the functioning of key infrastructure elements (transport, energy, water supply, communications, IT).

It is important to synchronize the management of infrastructure and the industries it serves. Infrastructure serves as the foundation for the successful functioning of these industries. Therefore, management should be aimed at maintaining operational efficiency, development, and adaptation to the needs of the industry, which is achieved through planning, design, construction, operation, and modernization.

There is a close relationship between the economic potential of infrastructure and the industry it serves. Infrastructure creates the conditions for the efficient operation of the industry, reducing costs and ensuring reliable access to resources. In turn, the growth of the industry stimulates the development of infrastructure.

It is important to distinguish between strategic, tactical, and operational management of the economic potential of infrastructure, considering the impact of risks. Strategic management focuses on long-term goals and risk prevention, while tactical and operational management address short-term tasks. Strategic management defines the mission and direction of development, tactical management develops specific measures, and operational management ensures uninterrupted operation. Risk management is an integral part of strategic management, while tactical and operational management consider risks in the context of current tasks.

Let's consider the key aspects of the goals and objectives associated with managing the economic potential of the infrastructure system, considering the impact of risks. The main goal in this context is to maximize the socio-economic impact of the infrastructure system while ensuring its high resilience in the face of various risk situations.

Achieving this overall goal requires fulfilling a number of conditions:

1) the staff of the infrastructure system must ensure the effective attraction, allocation, and rational use of resources aimed at maintaining current operations and development;

2) an essential condition is the consideration of risks and the development of measures to eliminate negative consequences following the adoption of management decisions;

3) realizing economic potential involves implementing innovations, including in the technological sphere. This makes it possible to increase the efficiency and quality of services through modernization;

4) it is very important to use a variety of tools and methods to improve efficiency in the field of management, such as diversifying sources of funding or establishing partnerships between the state and the private sector;

5) the coordination of measures undertaken by all participants in infrastructure complexes and the transparency of the entire process are absolutely essential for realizing human resource potential in various areas of the economy and for effective risk management.

The results obtained highlight the importance of developing a strategy in the field of infrastructure potential management. This includes analyzing and preventing threats, minimizing risks, and ensuring the rationality of financial investments. This study presents a framework that considers the diversity of risks and their potential consequences for economic growth.

Conclusion

1. Infrastructure complexes play a key role in economic progress, but they are subjected to serious risks.

2. Effective management involves applying a strategic model that combines risk analysis and cost-effective solutions.

3. The proposed model for managing the economic potential of infrastructure, which considers the impact of risks, provides valuable insights for industry stakeholders.

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УПРАВЛЕНИЕ ФИНАНСОВЫМИ РЕСУРСАМИ ИНФРАСТРУКТУРНЫХ ОБЪЕКТОВ С УЧЁТОМ АНАЛИЗА РИСКОВ

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Резюме. Целью данного исследования является изучение методов регулирования экономических ресурсов инфраструктурных комплексов с учётом воздействия факторов риска. Инфраструктурные комплексы играют важную роль в развитии

экономики, однако подвержены различным угрозам, включая финансовые, экологические и операционные трудности. В исследовании определяются основные компоненты инфраструктурных комплексов, их экономический потенциал и риски, связанные с их регулированием. На основе анализа существующих научных подходов и соответствующих публикаций предлагается единая концептуальная основа регулирования инфраструктурных комплексов с акцентом на снижение угроз и обеспечение экономической эффективности. Результаты включают математическую модель экономического ресурса, систематизацию инфраструктурных комплексов и подробный анализ принципов управления рисками. В исследовании обосновывается, что эффективное регулирование инфраструктурных комплексов требует стратегического подхода, объединяющего оценку угроз, экономический анализ и адаптивное управление. Данная работа вносит вклад в развитие рассматриваемой области, обеспечивая комплексное понимание регулирования инфраструктуры и предлагая практические рекомендации всем заинтересованным сторонам.

Ключевые слова: *инфраструктурные системы, экономическая эффективность, экономический потенциал и риски, стратегическое управление, устойчивость, управление*

RİSKLƏRİN TƏHLİLİ NƏZƏRƏ ALINMAQLA İNFRASTRUKTUR OBYEKTLƏRİNİN MALİYYƏ RESURSLARININ İDARƏ EDİLMƏSİ

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Xülasə. Tədqiqatın məqsədi risk amillərinin təsirini nəzərə almaqla infrastruktur komplekslərinin iqtisadi resurslarının tənzimlənməsi üsullarını araşdırmaqdır. İnfrastruktur kompleksləri iqtisadiyyatın inkişafında mühüm rol oynayır, lakin maliyyə, ekoloji və əməliyyat çətinlikləri kimi müxtəlif təhlükələrə məruz qalır. Tədqiqatda infrastruktur komplekslərinin əsas komponentləri, onların iqtisadi potensialı və tənzimlənməsi ilə bağlı risklər müəyyən edilmişdir. Mövcud elmi yanaşmaların və müvafiq nəşrlərin təhlili əsasında təhlükələrin azaldılmasına və iqtisadi səmərəliliyə xüsusi diqqət yetirilməklə infrastruktur komplekslərinin tənzimlənməsi üçün vahid konseptual çərçivə təklif olunur. Nəticələr iqtisadi resursun riyazi modelini, infrastruktur komplekslərinin sistemləşdirilməsini və risklərin idarə edilməsi prinsiplərinin ətraflı təhlilini əhatə edir. Tədqiqatda əsaslandırılır ki, infrastruktur komplekslərinin səmərəli tənzimlənməsi təhlükələrin qiymətləndirilməsini, iqtisadi təhlili və adaptiv idarəetməni birləşdirən strateji yanaşma tələb edir. Bu tədqiqat infrastrukturun tənzimlənməsinin hərtərəfli anlaşılmasını təmin etməklə və bütün maraqlı tərəflərə praktiki tövsiyələr təqdim etməklə müvafiq sahəyə töhfə verir.

Açar sözlər: *infrastruktur sistemləri, iqtisadi səmərəlilik, iqtisadi potensial və risklər, strateji idarəetmə, dayanıqlıq, idarəetmə*

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A SYSTEM-SCENARIO MULTIFACTOR MODEL FOR OPTIMIZING MESO-LEVEL ECONOMIC POTENTIAL USING MATRIX METHODS

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Keywords: *economic potential, meso-level, matrix modeling, system-scenario model, optimization, textile industry*

Summary. This study develops a system-scenario multifactor model for optimizing meso-level economic potential using matrix methods. The model considers an industry as a complex socio-economic system in which resource and institutional components interact under internal and external influences. It integrates indicators of potential profitability, return, and intensity within a hierarchical matrix framework to support strategic decision-making. The empirical analysis uses data from leading enterprises in the Belarusian light and textile industry, incorporating 42 indicators of local resource potential and 72 indicators of local institutional potential. The methodology involves constructing state and index matrices, aggregating indicators at three analytical levels, and positioning enterprises within a strategic decision-making matrix. The results reveal differences in resource and institutional potential, with an integral economic potential index of 0.963 for the analyzed enterprise. Institutional potential demonstrated stronger performance than resource potential. The proposed model provides a quantitative framework for identifying constraints, comparing development scenarios, and selecting strategies to improve economic efficiency and adaptability at the meso-level.

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1. Introduction

The optimization of economic potential has become increasingly important for industrial systems operating under uncertainty, globalization, integration, and digital transformation (Kostikova et al., 2016). At the meso-level, an industry represents a complex socio-economic system comprising interconnected enterprises and multiple resource, institutional, and managerial components. These components interact dynamically and are influenced by both internal and external factors (Andrianov & Grebnev, 2015; Kvyatkovskaya & Frenkel, 2009).

Existing approaches to economic potential optimization do not fully capture the complex relationships among its structural components. In particular, limited attention has been paid to the dynamic interdependence of resource and institutional parameters and their combined influence on industrial development. This limitation complicates the assessment of economic potential and the selection of appropriate development strategies.

Matrix modeling provides a useful analytical framework for addressing this problem because it enables multiple economic indicators and their interrelationships to be represented within an integrated quantitative system (Brinza et al., 2016; Romanenko, 2007; Yaroshevich, 2023). Combined with scenario analysis, this approach can support the assessment of alternative development trajectories and the selection of strategies for improving economic potential.

2. Methodology

This study applies a system-scenario multifactor modeling approach to assess and optimize economic potential at the meso-level. The methodological framework is based on matrix modeling, which enables the

interrelationships among multiple parameters of economic potential to be represented and analyzed within an integrated system (Brinza et al., 2016; Romanenko, 2007; Yaroshevich, 2023).

The model distinguishes between two principal components of economic potential: local resource potential and local institutional potential. Their performance is evaluated through three analytical dimensions: potential profitability, potential return, and potential intensity. These dimensions provide the basis for assessing changes in economic potential and comparing the relative efficiency of its structural components.

The modeling procedure consists of three analytical levels. At the first level, state matrices are constructed from the initial economic parameters. The local resource potential matrix comprises 42 specific indicators, calculated from all possible paired ratios of seven initial parameters. The local institutional potential matrix comprises 72 specific indicators reflecting institutional and external-environment factors relevant to industrial development.

At the second level, dynamic index matrices are constructed to measure changes in the indicators over time. Individual indicators are subsequently aggregated using a hierarchical procedure to obtain composite measures of resource and institutional potential. At the third level, the resulting indices are normalized and used to position industrial entities within a strategic decision-making matrix. This positioning provides the basis for identifying appropriate development scenarios according to the relative performance of resource and institutional potential.

The empirical application was conducted using economic data from enterprises of the Belarusian light and textile industry. The detailed calculation is illustrated for JSC Mogotex, while the strategic analysis also incorporates other enterprises within the industry. The matrix calculations were performed using spreadsheet-based computational procedures.

The calculation module is based on a number of microsystems, claterized by the level of economic potential development (microsystems can be grouped according to other criteria in accordance with the objectives of the IAS of the RPR (for example, by the level of contribution to sectoral GDP, financial level, level of innovation sensitivity, and others).

3. Results and discussion

The proposed model was applied to economic data from leading enterprises of the Belarusian light and textile industry. JSC Mogotex (Microsystem 1) was selected to illustrate the detailed matrix calculations. The analysis distinguishes between local resource and local institutional potential and evaluates both components in terms of potential profitability, return, and intensity. The selection and application of matrix modeling procedures were informed by established approaches to assessing the economic efficiency of industrial enterprises (Romanenko, 2007). The matrix model for the scenario analysis of local resource potential in Microsystem 1 (JSC Mogotex) for 2016 and 2017 is presented in Table 1.

Table 1

Matrix Model for the Scenario Analysis of Local Resource Potential (Microsystem 1)

2016							
Designations	PR	OP	VR	OPF	OS	HR	FOT
PR	1	21,454	24,591	14,060	10,383	0,585	3,532
OP	**0,047**	1	1,146	0,655	0,484	0,027	0,165
VR	**0,041**	**0,872**	1	0,572	0,422	0,024	0,144
OPF	**0,071**	**1,526**	**1,749**	1	0,738	0,042	0,251
OS	**0,096**	**2,066**	**2,368**	1,354	1	0,056	0,340
HR	**1,710**	**36,690**	**42,055**	24,046	17,756	1	6,040
FOT	**0,283**	**6,074**	**6,963**	3,981	2,940	0,166	1
2017							
Designations	PR	OP	VR	OPF	OS	HR	FOT
PR	1	14,421	27,027	16,330	7,580	0,316	1,964
OP	**0,069**	1	1,874	1,132	0,526	0,022	0,136
VR	**0,037**	**0,534**	1	0,604	0,280	0,012	0,073
OPF	**0,061**	**0,883**	**1,655**	1	0,464	0,019	0,120
OS	**0,132**	**1,902**	**3,565**	2,154	1	0,042	0,259
HR	**3,160**	**45,566**	**85,397**	51,599	23,951	1	6,206
FOT	**0,509**	**7,342**	**13,760**	8,314	3,859	0,161	1
PR – profit from sales; OP – volume of production; VR – revenue from sales; OPF – fixed assets; OS – working capital; HR – number of employees; FOT – wage fund							

Source: *compiled by the author*

The corresponding matrix model for the scenario analysis of local institutional potential in Microsystem 1 for 2016 and 2017 is presented in Table 2.

Table 2

Matrix Model for the Scenario Analysis of Local Institutional Potential (Microsystem 1)

2016									
Designations	PR	OP	VR	RM	NIR	E	RU	I	IP
PR	1	21,454	24,591	0,181	1,614	11,479	1,734	0,051	3,124
OP	**0,047**	1	1,146	0,008	0,075	0,535	0,081	0,002	0,146
VR	**0,041**	**0,872**	1	0,007	0,066	0,467	0,071	0,002	0,127
RM	**5,522**	**118,459**	**135,782**	1	8,912	63,384	9,574	0,282	17,250
NIR	**0,620**	**13,292**	**15,236**	0,112	1	7,112	1,074	0,032	1,936
E	**0,087**	**1,869**	**2,142**	0,016	0,141	1	0,151	0,004	0,272
RU	**0,577**	**12,374**	**14,183**	0,104	0,931	6,621	1	0,029	1,802
I	**19,592**	**420,320**	**481,789**	3,548	31,623	224,904	33,969	1	61,206
IP	**0,320**	**6,867**	**7,872**	0,058	0,517	3,675	0,555	0,016	1
2017 г.									
Designations	PR	OP	VR	RM	NIR	E	RU	I	IP
PR	1	14,421	27,027	0,120	1,027	11,086	1,152	0,035	2,037
OP	**0,069**	1	1,874	0,008	0,071	0,769	0,080	0,002	0,141
VR	**0,037**	**0,534**	1	0,004	0,038	0,410	0,043	0,001	0,075
RM	**8,319**	**119,976**	**224,850**	1	8,548	92,226	9,588	0,294	16,944
NIR	**0,973**	**14,036**	**26,305**	0,117	1	10,790	1,122	0,034	1,982
E	**0,090**	**1,301**	**2,438**	0,011	0,093	1	0,104	0,003	0,184
RU	**0,868**	**12,514**	**23,452**	0,104	0,892	9,619	1	0,031	1,767
I	**28,268**	**407,657**	**763,996**	3,398	29,044	313,367	32,577	1	57,573
IP	**0,491**	**7,081**	**13,270**	0,059	0,504	5,443	0,566	0,017	1
RM – marketing expenses; NIR – expenses on scientific and information resources; E – export volume; RU – management expenses; I – investment volume; IP – volume of sales of innovative products based on the criteria of "new product" and "with new functions"									

Source: *compiled by the author*

To assess changes over time, the state matrices were transformed into dynamic index matrices. The resulting indices capture changes in potential profitability, return, and intensity and provide the basis for subsequent aggregation. Because the individual matrix elements represent intermediate calculations, the analysis below focuses on the aggregated indicators that are directly relevant to evaluating economic potential and selecting development strategies.

The multidimensional nature of the resulting indicators requires hierarchical aggregation to facilitate comparison among industrial entities. Accordingly, the model applies a three-level aggregation procedure, beginning with the first-level indices of resource and institutional potential presented in Table 3.

Table 3

First-Level Aggregated Indices of Resource and Institutional Potential

Industry entity	Index	Local resource potential			Local institutional capacity		
		potential output	potential intensity	potential profitability	potential output	potential intensity	potential profitability
Microsystem 1	2013 / 2012	1,289	1,240	0,544	1,151	1,071	0,498
	2014 / 2013	0,873	1,010	0,453	0,830	0,951	0,431
	2015 / 2014	0,992	0,960	0,028	1,377	1,411	0,038
	2016 / 2015	1,016	1,034	30,529	1,293	1,367	37,739
	2017 / 2016	0,867	1,546	1,321	0,895	1,559	1,350
	I_{rpi}	**0,997**	**1,140**	**0,774**	**1,088**	**1,251**	**0,839**
I_{rpi} – the aggregated index of the first level of generalization according to indicators of potential output, potential intensity, potential profitability							

Source: *compiled by the author*

The results reveal substantial variation in the development of resource and institutional potential over the analyzed period. Changes in profitability were particularly pronounced, reflecting fluctuations in sales profits

and the financing of marketing, innovation, investment, and information-related activities. Export performance also influenced the observed dynamics, as the analyzed enterprise operated with a substantial share of export-oriented production.

At the first aggregation level, the resource potential profitability index was 0.774, indicating an average annual decline of 22.6%, whereas the potential intensity index reached 1.140, corresponding to an average annual increase of 14%. Institutional potential demonstrated comparatively stronger performance: the aggregated indices of potential return and potential intensity reached 1.088 and 1.251, respectively. However, the institutional profitability index remained below unity at 0.839. These results indicate that improvements in institutional capacity were not accompanied by comparable growth in profitability.

The results of analytical calculations of the aggregated indices of the second level of generalization and the integral index of the level of development of economic potential (the third level of generalization) for microsystem 1 are presented in Table 4.

Table 4

Aggregated Indices of the Second and Third Levels of Economic Potential Assessment

Industry entity	The indicator	Local resource potential			Local institutional capacity		
		potential output	potential intensity	potential profitability	potential output	potential intensity	potential profitability
Microsystem 1	I_{rpi}	**0,997**	**1,140**	**0,774**	**1,088**	**1,251**	**0,839**
	ki	0,067	0,218	0,715	0,067	0,218	0,715
	I_{rpi}^{ki}	1,000	1,029	0,833	1,006	1,050	0,882
	$I_{rp\ (ip)}$	**0,950**			**0,977**		
	I_{ep}	**0,963**					

I_{rpi} – aggregated index of the first level of generalization; ki – significance coefficient; $I_{rp\ (ip)}$ – aggregated index of the second level of generalization; I_{ep} – the integral index of the level of realization of economic potential (the third level of generalization).

Source: *compiled by the author*

The second- and third-level aggregation confirms the stronger performance of institutional potential compared with resource potential. The corresponding second-level aggregated indices were 0.950 for resource potential and 0.977 for institutional potential, resulting in an integral economic potential index of 0.963. Although the analyzed enterprise did not reach the reference value of unity, the results indicate that institutional factors contributed more strongly to overall economic potential than resource factors. A comparable calculation procedure was previously applied to other microsystems of the Bellegprom concern according to their contribution to industry GDP (Narkevich, 2024a). The present results further demonstrate the usefulness of hierarchical aggregation for identifying imbalances between the resource and institutional components of economic potential.

At the final stage, the aggregated indices were normalized and used to construct a strategic decision-making matrix. The relative positions of resource and institutional potential determine the location of each industrial entity within the matrix and provide the basis for selecting an appropriate development scenario. This approach builds on the author's previous application of a strategic decision-making matrix to economic potential optimization (Narkevich, 2024b) and extends the analysis through the system-scenario multifactor framework used in the present study.

Table 5

Strategic Positioning of Industrial Enterprises Based on Economic Potential

Industrial entity	**Normalized coordinates**	**Matrix quadrant**	**Recommended strategic orientation**
Microsystem 1 (JSC Mogotex)	0.765; 0.378	d	Concentrated growth and product/market development
Microsystem 2 (JSC BPHO)	0.673; 0.469	b	Vertical integration and integrated growth
Microsystem 3 (JSC Lenta)	1.000; 0.745	c	Investment- and innovation-oriented development

Source: *compiled by the author*

As shown in Table 5, the analyzed industrial enterprises occupy different positions within the strategic decision-making matrix, reflecting variations in their economic potential and corresponding development strategies.

The strategic positioning demonstrates that the analyzed enterprises require different development trajectories. JSC Mogotex is characterized by comparatively stronger institutional than resource potential and therefore requires strategies aimed at strengthening resource efficiency, market position, and product development. JSC BPHO is associated with an integrated-growth trajectory emphasizing vertical integration, whereas JSC Lenta requires a stronger investment and innovation orientation. These differences demonstrate the ability of the proposed model to translate quantitative assessments into differentiated strategic recommendations.

4. Recommendations

The proposed system-scenario multifactor model can be used to support strategic decision-making in complex industrial systems by integrating resource and institutional components of economic potential within a unified analytical framework. Its application enables industrial entities to identify imbalances between these components, assess alternative development trajectories, and select strategies consistent with their current economic potential.

For practical implementation, priority should be given to the components that constrain overall economic performance. Enterprises with comparatively weaker resource potential should focus on improving production efficiency, technological modernization, and resource utilization, while stronger institutional capacity can be used to support innovation, investment, and market development. Where institutional potential is comparatively weak, greater attention should be paid to marketing, innovation, investment, scientific and information resources, and management mechanisms.

The matrix-based calculations can be implemented using spreadsheet software, making the approach accessible for routine analytical and decision-support purposes. The framework may also be adapted to different industrial systems by modifying the initial indicators and their relative significance according to sector-specific characteristics.

5. Conclusion

This study developed and applied a system-scenario multifactor model for assessing and optimizing economic potential at the meso-level using matrix methods. The framework integrates resource and institutional components of economic potential and evaluates their dynamics through potential output, intensity, and profitability indicators. Hierarchical aggregation and strategic positioning enable the transformation of multiple economic indicators into interpretable measures for decision-making.

The empirical application to enterprises in the Belarusian light and textile industry demonstrated differences between resource and institutional potential. For JSC Mogotex, the second-level aggregated indices were 0.950 for resource potential and 0.977 for institutional potential**,** resulting in an integral economic potential index of 0.963. The results therefore indicate comparatively stronger institutional potential and identify resource efficiency as an area requiring greater attention. Strategic positioning further demonstrated that the analyzed enterprises require differentiated development trajectories depending on the balance between their resource and institutional components.

The proposed approach provides a quantitative basis for diagnosing structural imbalances, comparing development scenarios, and supporting the selection of industrial development strategies. Its matrix structure also allows the indicator system to be adapted to the characteristics of different industrial contexts. Further research should test the framework using more recent data, additional industries, and longer observation periods to assess its robustness and broader applicability.

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СИСТЕМНО-СЦЕНАРНАЯ МНОГОФАКТОРНАЯ МОДЕЛЬ ОПТИМИЗАЦИИ ЭКОНОМИЧЕСКОГО ПОТЕНЦИАЛА НА МЕЗОУРОВНЕ С ИСПОЛЬЗОВАНИЕМ МАТРИЧНЫХ МЕТОДОВ

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Резюме. В исследовании разработана системно-сценарная многофакторная модель оптимизации экономического потенциала на мезоуровне с использованием матричных методов. Модель рассматривает отрасль промышленности как сложную социально-экономическую систему, в которой ресурсные и институциональные компоненты взаимодействуют под влиянием внутренних и внешних факторов. Для поддержки принятия стратегических решений показатели потенциальной рентабельности, доходности и интенсивности объединяются в рамках иерархической матричной структуры. Эмпирический анализ основан на данных ведущих предприятий лёгкой и текстильной промышленности Беларуси и охватывает 42 показателя локального ресурсного потенциала и 72 показателя локального институционального потенциала. Методология предусматривает построение матриц состояний и индексов, агрегирование показателей на трёх аналитических уровнях и позиционирование предприятий в матрице принятия стратегических решений. Результаты выявили различия между ресурсным и институциональным

потенциалом, при этом интегральный индекс экономического потенциала анализируемого предприятия составил 0,963. Институциональный потенциал продемонстрировал более высокие показатели по сравнению с ресурсным потенциалом. Предлагаемая модель представляет собой количественную основу для выявления ограничений, сопоставления сценариев развития и выбора стратегий, направленных на повышение экономической эффективности и адаптивности на мезоуровне.

Ключевые слова: *экономический потенциал, мезоуровень, матричное моделирование, системно-сценарная модель, оптимизация, текстильная промышленность.*

MATRİS METODLARINDAN İSTİFADƏ ETMƏKLƏ MEZOSƏVİYYƏDƏ İQTİSADİ POTENSİALIN OPTİMALLAŞDIRILMASININ SİSTEM-SƏNARİ ƏSASLI ÇOXAMİLLİ MODELİ

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Xülasə. Tədqiqatda matris metodlarından istifadə etməklə mezosəviyyədə iqtisadi potensialın optimallaşdırılması üçün sistem-sənari əsaslı çoxamilli model işlənib hazırlanmışdır. Model sənaye sahəsini resurs və institusional komponentlərin daxili və xarici amillərin təsiri altında qarşılıqlı əlaqədə olduğu mürəkkəb sosial-iqtisadi sistem kimi nəzərdən keçirir. Strateji qərarların qəbulunu dəstəkləmək məqsədilə potensial rentabellik, gəlirlilik və intensivlik göstəriciləri iyerarxik matris strukturu çərçivəsində birləşdirilir. Empirik təhlil Belarusun yüngül və toxuculuq sənayesinin aparıcı müəssisələrinin məlumatlarına əsaslanır və lokal resurs potensialının 42, lokal institusional potensialın isə 72 göstəricisini əhatə edir. Metodologiya vəziyyət və indeks matrislərinin qurulmasını, göstəricilərin üç analitik səviyyədə aqreqasiyasını və müəssisələrin strateji qərarların qəbulu matrisində mövqeləndirilməsini nəzərdə tutur. Nəticələr resurs və institusional potensial arasında fərqləri aşkar etmiş, təhlil edilən müəssisə üzrə iqtisadi potensialın inteqral indeksi 0,963 təşkil etmişdir. İnstitusional potensial resurs potensialı ilə müqayisədə daha yüksək göstəricilər nümayiş etdirmişdir. Təklif olunan model məhdudiyyətlərin müəyyənləşdirilməsi, inkişaf ssenarilərinin müqayisəsi və mezosəviyyədə iqtisadi səmərəliliyin və adaptasiya qabiliyyətinin artırılmasına yönəlmiş strategiyaların seçilməsi üçün kəmiyyət əsaslı qiymətləndirmə çərçivəsi təqdim edir.

Açar sözlər: *iqtisadi potensial, mezosəviyyə, matris modelləşdirilməsi, sistem-senari modeli, optimallaşdırma, toxuculuq sənayesi*

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ASSESSMENT OF THE RISKS AND EXPECTED ECONOMIC IMPACT OF SMALL BUSINESS GROWTH BASED ON AN ADAPTED BALANCED SCORECARD (BSC)

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Keywords: *digital economy, small business, efficiency, assessment, trends, development, problems, infrastructure*

Summary. This study examines the impact of digital transformation on small business efficiency in Russia and proposes an assessment methodology based on an adapted Balanced Scorecard (BSC). The analysis considers major digital trends, including e-commerce, artificial intelligence, digital platforms, cloud technologies, and automation, as well as key constraints such as regional digital inequality, dependence on imported technologies, cybersecurity risks, and shortages of qualified personnel. The proposed methodology integrates five dimensions of business performance: economic, operational, marketing, innovation, and social efficiency, while also accounting for the costs of implementing digital technologies. A practical calculation for a small retail enterprise demonstrates the applicability of the model and indicates that economic and marketing performance make the greatest contribution to overall efficiency, whereas high digitalization costs may reduce the final result. The findings show that cost optimization, process automation, digital marketing, and innovative technologies can improve small business efficiency and competitiveness in the digital economy.

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Introduction

Digital transformation has become an important factor in the development and competitiveness of small businesses in Russia. Its growing influence is associated with globalization, changing consumer preferences, cost optimization, and the need to improve operational efficiency. Digital tools enable small enterprises to overcome limitations related to business scale and geographical location, expand market access, and interact with customers through electronic platforms and digital payment systems.

Changing consumer behavior further accelerates this transformation. In 2023, 42% of consumers made more than half of their purchases through digital channels, increasing the need for small businesses to adapt traditional business models. Digital technologies also contribute to cost reduction: business process automation can reduce accounting costs by approximately 50% and transportation costs by 10%. Moreover, predictive analytics and artificial intelligence applied to supply-chain management can increase labor productivity by 18–22%.

Against this background, the study aims to assess the efficiency of small businesses in Russia under digital economy conditions, identify major challenges, and develop an adapted approach for evaluating and improving their performance.

Materials and methods

The study applies theoretical analysis, synthesis, observation, and comparison to assess the efficiency of small businesses under digital economy conditions. The research is based on relevant scientific literature, statistical data, and Internet sources. Particular attention is given to digital transformation trends, their impact on small business performance, and the adaptation of the Balanced Scorecard (BSC) approach to the digital business environment.

Theoretical approaches

Recent research emphasizes the growing influence of digital transformation on small and medium-sized enterprises. Domestic studies examine the current state of the digital economy (Abashkin et al., 2024), digitalization opportunities and project-management tools for SMEs (Arutyunyan et al., 2023; Bagdykov et al., 2023), and the opportunities, mechanisms, and barriers associated with small business digital transformation (Myzrova et al., 2024; Stepanov, 2022).

International research conceptualizes the digital economy from several complementary perspectives. Tapscott (1996) interprets it through the development of the network economy, while Schwab (2016) associates contemporary digital transformation with the Fourth Industrial Revolution. Frey and Osborne (2013) emphasize its implications for employment, whereas Goi et al. (2023) examine the influence of digital technologies on companies' strategic management. Together, these approaches provide the theoretical basis for assessing how digital transformation affects small business efficiency.

Results

The retrospective analysis identifies three main stages in the development of Russia's digital economy. The formation stage (1990s–early 2000s) was characterized by the emergence of Internet infrastructure, e-commerce, and the first digital services; by 2005, Internet penetration in the business environment had reached 35%. The active development stage (2000s–early 2010s) involved the rapid expansion of mobile communications, social networks, and digital business tools, with the share of companies using CRM systems increasing from 12% to 48%. The current stage (2010s–present) is characterized by deeper integration of e-commerce, digital platforms, big data, blockchain, and ecosystem-based business models, together with government programs supporting digital transformation.

Recent trends indicate a rapid expansion of Russia's digital economy, particularly in e-commerce, digital platforms, artificial intelligence (AI), and digital infrastructure. In 2023, the e-commerce market reached 7.9 trillion rubles, representing a 48% increase, with approximately 5.03 billion orders (Data Insight, 2024). Digital platforms are also expanding across transport, finance, education, and healthcare, while B2B platforms contribute to greater competitiveness and lower transaction costs (Pashkin, 2024; RAEC, 2024).

AI adoption is another major trend, particularly in process automation, customer service, and predictive analytics. The Russian AI market was expected to exceed 300 billion rubles in 2024, approximately 1.5 times the 2023 level, while exports by domestic AI vendors were also projected to increase substantially (Smart Ranking, 2024a, 2024b). The adoption of advanced AI technologies in industry is expected to increase by a further **12%** (Smart Ranking, n.d.). At the same time, broadband infrastructure has expanded, with the share of the population having broadband Internet access increasing from 70% in 2020 to 85% in **2024** (Ministry of Digital Development, Communications and Mass Media of the Russian Federation, n.d.). The growing use of the Internet of Things, cloud computing, big data, and cybersecurity technologies further supports digital infrastructure and enables smaller firms to access technologies such as chatbots and predictive analytics.

Despite these developments, Russia's digital transformation faces several constraints, including regional inequality, dependence on imported technologies, cybersecurity risks, and shortages of qualified personnel. In 2023, the level of digitalization in Moscow and St. Petersburg was reported to be 60% higher than the regional average, while approximately 72% of business software was reported to be of foreign origin. Moreover, demand for IT specialists among small businesses is estimated to be only 54% satisfied (Ministry of Digital Development, Communications and Mass Media of the Russian Federation, n.d.). These limitations may restrict technological adoption and increase risks associated with digital dependence and security.

Nevertheless, digitalization provides substantial opportunities for small businesses by improving customer interaction, reducing operating costs, expanding access to alternative financing, and supporting data-driven decision-making. The institutional environment also contributes to this process through subsidies, financing mechanisms, and educational initiatives. The article reports that digitalization subsidies may cover up to 50% of SME costs, crowdlending platforms have increased access to financing by 35%, and the "Digital Professions" program has trained approximately 120,000 specialists.

These developments highlight the need for an assessment methodology that reflects the specific characteristics of small businesses operating in the digital economy. Traditional financial indicators alone may not adequately capture the effects of digital transformation. Therefore, an adapted Balanced Scorecard (BSC) approach is proposed to integrate financial and non-financial dimensions, including economic performance, customer-related outcomes, business-process efficiency, innovation, and development potential. Such an approach provides the basis for a more comprehensive assessment of small business efficiency and for identifying opportunities to improve competitiveness and sustainable development.

The formula for assessing the effectiveness of a small business entity in the digital economy may have the following form:

$$E = \frac{(Ce * We + Co * Wo + Cm * Wm + Ci * Wi + Cs * Ws)}{Tc},$$

where: E is the general effectiveness of small business in the digital economy; Ce is the coefficient of economic efficiency; We is the weight of economic efficiency in the overall assessment; Co is the coefficient of operational efficiency; Wo is the weight of operational efficiency in the overall assessment; Cm is the coefficient of marketing efficiency; Wm is the weight of marketing efficiency in the overall assessment; Ci is the coefficient of innovation efficiency; Wi is the weight of innovation efficiency in the overall assessment; Cs is the coefficient of social efficiency; Ws is the weight of social efficiency in the overall assessment; Tc is the total costs of implementing and using digital technologies.

Let's consider the concepts of the coefficients used in the formula.

1. The coefficient of economic efficiency Ce reflects the financial performance of the business due to the implementation of digital technologies. It includes the following elements: revenue growth, cost saving, payability and profitability.

Calculation example:

$$Ce = \frac{(PR_2 - PR_1)}{C},$$

where PR1 and PR2 are profits before and after digitalization; C are digitalization costs.

2. The coefficient of operational efficiency Co characterizes the optimization of internal processes due to digitalization. It includes the speed of operations, reduction of errors, automation of routine tasks.

Calculation example:

$$Co = \frac{(T_2 - T_1)}{T_1},$$

where T1 and T2 denote the time before and after optimization.

3. The coefficient of marketing efficiency Cm shows the impact of digital tools on promotion and sales. It includes conversion, audience reach, ROI advertisement, and social media engagement.

Calculation example:

$$Cm = \frac{Im}{Em},$$

where Im is income from marketing; Em is expenditures for marketing.

4. The coefficient of innovation efficiency Ci evaluates the ability of a business to implement and use new technologies. It includes the number of implemented innovations, patents, the share of digital products in revenue.

Calculation example:

$$Ci = \frac{Ni}{Np},$$

where Ni is the number of innovations; Np is the total number of projects.

5. The coefficient of social efficiency Cs determines the contribution of business to society through digital technologies. It includes the level of digital literacy of employees, the environmental friendliness of processes, customer satisfaction.

An example of the calculation method:

$$Cs = \frac{Npr}{Nr},$$

where Npr is the number of positive reviews; Nr is the total number of reviews.

The costs (Tc) for implementing digital technologies in a small business may include hardware (server systems, computers, sensors), software (licenses, subscriptions, CRM systems), personnel education (courses, trainings), implementation and configuration (IT specialist services), technical support (maintenance, updates), cybersecurity (data protection, antiviruses).

The following is an example of calculating the efficiency of a small business in one of the regions of Russia. The clothes shop implemented online sales and a CRM system.

Total costs (Tc) amounted to 500 000 rubles.

Weights: We=0.3; Wo=0.2; Cm=0.25; Ci=0.15; Cs=0.1.

Calculation of coefficients:

Ce = (1 200 000 – 800 000) / 500 000 = 0.8.

Co = (10 days - 5 days) / 10 = 0.5.

Cm = (400 000 rubles of income / 200 000 rubles of expenditures) = 2.0.

Ci = (2 new digital services / 5 projects) = 0.4.

Cs = (85% positive reviews / 100%) = 0.85.

The final efficiency will be:

$$E = \frac{(0.8 * 0.3 + 0.5 * 0.2 + 2.0 * 0.25 + 0.4 * 0.15 + 0.85 * 0.1)}{500\,000} = 0.00000197\,.$$

Conclusion: Marketing (Cm) and economics (Ce) contributed the most to efficiency, but high costs reduce the overall indicator. Cost optimization can increase E.

Based on the results of the project implementation, a number of measures can be proposed to improve the overall effectiveness of a small business entity in the digital economy.

1. Cost optimization (↓Tc):

– using cloud solutions instead of purchasing server systems (for example, renting CRM in SaaS format);

– gradual introduction of digital tools (not all at once);

– use of free and cheap software analogues (for example, Tilda instead of an expensive CMS).

Reducing costs by 30-40% will increase efficiency (E) even at current coefficients.

2. Increase in the coefficient of economic efficiency (↑Ce):

– implementation of the “dynamic pricing” method (demand analysis and automatic price adjustment);

– using AI analytics to forecast purchases (reducing surplus);

– development of a “subscription and repeat sales” program (loyalty programs).

It is assumed that the increase in profit will increase Ce and provide an increase in the contribution to efficiency.

3. Improving operational efficiency (↑Co):

– warehouse automation (1C + mobile terminals for accounting);

– implementation of chatbots for processing orders and returns;

– integration of online and offline sales (unified database of balances).

As a result, acceleration of processes should reduce labor costs and increase the value of the coefficient of operational efficiency (Co).

4. Enhancing the marketing efficiency (↑Cm):

– targeted advertising in social networks (VK, Telegram);

– implementation of gamification (promotional offers, quests, referral programs);

– use of UGC content (reviews, styles from buyers).

The expected effect is that an increase in conversion and marketing ROI will raise the value of the coefficient of marketing efficiency (Cm).

5. Development of innovations (↑Ci):

– implementation of a VR (virtual) fitting room on the website;

– using NFT (digital tokens) to verify brand authenticity;

– launch of AI stylist (selection of looks based on preferences).

These unique technologies are expected to increase Ci and attract new audiences.

6. Improving social efficiency (↑Cs):

– implementation of a program for environmentally friendly packaging and clothing recycling;

– training employees in digital skills through free courses;

– support for local designers (collaborations).

It is expected that the company's reputation will improve and customer loyalty will increase. The expected effect will increase the value of the coefficient of social efficiency (Cs).

Final efficiency forecast. If we reduce costs (Tc) to 300 000 rubles and increase coefficients by 20-30%, then:

$$\text{Eproject} = \frac{(0.96 * \ 0.3 + \ 0.6 * 0.2 + 2.4 * 0.25 + 0.48 * 0.15 + \ 1.0 * 0.1)}{300\,000} = 0.000003$$

As can be seen, as a result of the project implementation, the efficiency increase will be 1.5 times.

The greatest effect will be achieved by measures for reducing costs (cloud technologies, gradual implementation), enhance marketing and automation (targeting, chatbots), and introduce innovations (VR fitting room, AI analytics), which will make the business more profitable, technologically advanced, and competitive in the digital economy.

Conclusion

The present research confirms that digital transformation has a significant impact on the effectiveness of small businesses in Russia. The development of e-commerce, the introduction of artificial intelligence and cloud technologies create new opportunities for growth. However, the key problems, such as uneven digitalization in regions, dependence on foreign technologies, a shortage of qualified specialists and cybersecurity risks, still remain.

The proposed methodology for assessing efficiency, based on the adapted BSC model, allows for a comprehensive consideration of both financial and non-financial performance indicators of small enterprises. A practical calculation using a retail store as an example showed that marketing activity and economic efficiency make the greatest contribution to efficiency, but high digitalization costs can reduce the overall indicator.

To improve efficiency, the following is recommended:

– Cost optimization through cloud solutions and gradual implementation of technologies.

– Automation of operational processes (CRM, chatbots, data analytics).

– Development of digital marketing (targeted advertising, gamification).

– Implementation of innovative solutions (AI, VR, blockchain).

– Improving social responsibility and digital literacy of employees.

Prospects for further research are related to the development of more accurate metrics for assessing the digital maturity of small businesses and the analysis of the long-term effects of digitalization in various industries.

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ОЦЕНКА РИСКОВ И ОЖИДАЕМОГО ЭКОНОМИЧЕСКОГО ЭФФЕКТА ОТ РАЗВИТИЯ МАЛОГО БИЗНЕСА НА ОСНОВЕ АДАПТИРОВАННОЙ СИСТЕМЫ СБАЛАНСИРОВАННЫХ ПОКАЗАТЕЛЕЙ (ССП)

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Резюме. В исследовании рассматривается влияние цифровой трансформации на эффективность малого бизнеса в России и предлагается методика оценки, основанная на адаптированной системе сбалансированных показателей (Balanced Scorecard – BSC). В ходе анализа рассматриваются основные цифровые тенденции, включая электронную коммерцию, искусственный интеллект, цифровые платформы, облачные технологии и автоматизацию, а также ключевые ограничения, такие как региональное цифровое неравенство, зависимость от импортных технологий, риски кибербезопасности и дефицит квалифицированных кадров. Предлагаемая методика объединяет пять направлений оценки эффективности деятельности бизнеса: экономическую, операционную, маркетинговую, инновационную и социальную эффективность, одновременно учитывая затраты на внедрение цифровых технологий. Практический расчёт на примере малого предприятия розничной торговли демонстрирует применимость модели и показывает, что наибольший вклад в общую эффективность вносят экономические и маркетинговые показатели, тогда как высокие затраты на цифровизацию могут снижать конечный результат. Результаты исследования показывают, что оптимизация затрат, автоматизация процессов, цифровой маркетинг и инновационные технологии могут способствовать повышению эффективности и конкурентоспособности малого бизнеса в условиях цифровой экономики.

Ключевые слова: *цифровая экономика, малый бизнес, эффективность, оценка, тенденции, развитие, проблемы, инфраструктура*

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UYĞUNLAŞDIRILMIŞ BALANSLAŞDIRILMIŞ GÖSTƏRİCİLƏR SİSTEMİ (BGS) ƏSASINDA KİÇİK BİZNESİN İNKİŞAFINDAN YARANAN RİSKLƏRİN VƏ GÖZLƏNİLƏN İQTİSADİ SƏMƏRƏNİN QİYMƏTLƏNDİRİLMƏSİ

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Xülasə. Tədqiqatda rəqəmsal transformasiyanın Rusiyada kiçik biznesin səmərəliliyinə təsiri araşdırılır və uyğunlaşdırılmış Balanslaşdırılmış Göstəricilər Sisteminə (Balanced Scorecard – BSC) əsaslanan qiymətləndirmə metodologiyası təklif olunur. Təhlildə elektron ticarət, süni intellekt, rəqəmsal platformalar, bulud texnologiyaları və avtomatlaşdırma da daxil olmaqla əsas rəqəmsal tendensiyalar, eləcə də regional rəqəmsal bərabərsizlik, idxal texnologiyalarından asılılıq, kibertəhlükəsizlik riskləri və ixtisaslı kadr çatışmazlığı kimi başlıca məhdudiyyətlər nəzərdən keçirilir. Təklif olunan metodologiya rəqəmsal texnologiyaların tətbiqi xərclərini də nəzərə almaqla biznes fəaliyyətinin səmərəliliyinin beş istiqamətini – iqtisadi, əməliyyat, marketinq, innovasiya və sosial səmərəliliyi birləşdirir. Kiçik pərakəndə ticarət müəssisəsi üzrə aparılmış praktiki hesablama modelin tətbiq oluna biləcəyini nümayiş etdirir və ümumi səmərəliliyə ən böyük töhfənin iqtisadi və marketinq göstəriciləri tərəfindən verildiyini, rəqəmsallaşmaya çəkilən yüksək xərclərin isə yekun nəticəni azalda biləcəyini göstərir. Tədqiqatın nəticələri xərclərin optimallaşdırılmasının, proseslərin avtomatlaşdırılmasının, rəqəmsal marketinqin və innovativ texnologiyaların rəqəmsal iqtisadiyyat şəraitində kiçik biznesin səmərəliliyini və rəqabət qabiliyyətini artıra biləcəyini göstərir.

Açar sözlər: *rəqəmsal iqtisadiyyat, kiçik biznes, səmərəlilik, qiymətləndirmə, meyillər, inkişaf, problemlər, infrastruktur*

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SUSTAINABLE DEVELOPMENT AND GREEN ECONOMY: A PROPOSAL OF INDEX FOR AZERBAIJAN

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Keywords: *green economy, sustainable development, green economy index, Azerbaijan, environmental performance*

Summary. This study evaluates Azerbaijan's progress toward a green economy that integrates economic growth, social well-being, and environmental protection. Since conventional indicators such as GDP fail to reflect environmental and social dimensions, a composite Green Economy Index is developed for a more comprehensive assessment. Using national data from 1990 to 2023, the index is constructed from 21 economic, social, and environmental indicators obtained from the World Bank. Indicators are normalized using the min–max method and aggregated into dimension-specific sub-indices, which are then averaged to obtain the overall index. The results show a general upward trend in Azerbaijan's green economy performance over the study period. Progress is mainly driven by economic and social improvements, including higher income levels, better access to electricity, education, and health services. Environmental performance improves over the long term but remains volatile and contributes less consistently. The findings underline the need to strengthen environmental policies, expand renewable energy investment, and improve resource efficiency. The index provides a practical tool for monitoring green economy performance and supporting sustainable policy design.

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Introduction

The relationship between economic development and environmental sustainability has been widely discussed since the 1970s. The Limits to Growth emphasized that continuous population growth, industrialization, pollution, and resource consumption could eventually constrain economic development, highlighting the need to consider the interdependence between economic activity and the natural environment (Meadows et al., 1972). This perspective contributed to the development of sustainability-oriented approaches based on the rational use of natural resources and intergenerational equity (Diniz & Bermann, 2012).

Growing concerns about climate change, environmental degradation, and resource depletion have further demonstrated that conventional economic growth cannot be evaluated independently of environmental and social conditions. Although environmental protection measures may impose short-term economic costs, maintaining ecological balance can support sustainable long-term growth and social welfare (Akyazı & Başoğlu, 2015).

These developments have also intensified the Beyond GDP debate. GDP remains a fundamental measure of economic performance but does not adequately capture income inequality, environmental degradation, resource depletion, or broader social well-being. Consequently, alternative measures have emerged, including GDP-adjusted indicators, non-GDP indices, and composite indices integrating economic, social, and environmental dimensions (Özsoy & Tosunoğlu, 2017).

Within this framework, the green economy has emerged as a multidimensional approach integrating economic development, social well-being, and environmental protection. Its measurement is particularly

important for assessing national progress and supporting policies related to low-carbon development, green investment, resource efficiency, and sustainable economic growth.

Problem statement

Sustainable development was formally defined in the Brundtland Report as development that meets present needs without compromising the ability of future generations to meet their own needs. The approach integrates economic growth, basic human needs, natural-resource protection, and environmental considerations into development policy, emphasizing the quality as well as the quantity of growth (Brundtland, 1987; Soussan, 1992). This principle was further reinforced at the 1992 Rio Conference, where sustainable development was recognized as a common global objective.

Within this framework, green growth and green economy have emerged as approaches that integrate economic progress with environmental sustainability and human well-being. The foundations of green growth were strengthened through international initiatives, including the 2005 Seoul Conference and the Rio+20 process, which recognized green growth as an important pathway toward sustainable development (Kararach et al., 2018; UNESCAP, 2012). Green growth emphasizes economic development alongside efficient resource use, environmental protection, and lower emissions (OECD, 2011; Yalçın, 2016; GGGI, 2012).

The green economy similarly aims to improve human well-being and social equity while reducing environmental risks. Its principal objectives include reducing carbon emissions, waste and pollution, preserving biodiversity, increasing energy and resource efficiency, and promoting social welfare (UNEP, 2011). Public and private investment can support these objectives by generating employment and income while improving resource efficiency (Diyar et al., 2014). Although definitions vary, green economy and green growth are generally regarded as closely related components of sustainable development (Bowen, 2012).

From economic, social, and environmental perspectives, green economy performance therefore depends on **resource efficiency, social equity, ecological sustainability, resilience, and responsible management of natural resources** (EEA Report, 2013; Bass, 2013). These interrelated dimensions are summarized in Figure 1.

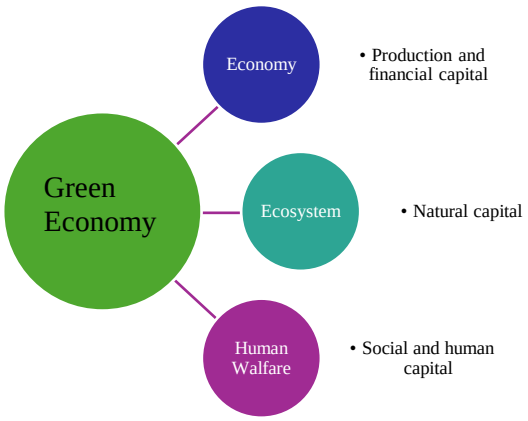


Fig. 1. Green Economy
Source: EEA (2013, p.5)

Therefore, the economic dimension covers production and financial capital; the human welfare dimension encompasses social and human capital; and the ecological dimension includes natural capital.

Materials and methods

GDP does not fully account for the environmental and social consequences of economic activity; therefore, alternative measures such as the Environmental Sustainability Index, Environmental Performance Index, Environmental Vulnerability Index, Index of Sustainable Economic Welfare, and Green Net National Product have been developed. However, these measures often emphasize particular economic or environmental dimensions rather than providing a comprehensive assessment of the green economy.

Several composite approaches have subsequently been proposed. The Global Green Economy Index (GGEI), calculated by Dual Citizen since 2010, incorporates 20 variables related to climate change, sector efficiency, investment, and the environment. Nahman et al. (2016) developed a green economy index based on 26 economic, social, and ecological indicators for 196 countries, while Kararach et al. (2018) constructed

a green growth index using 48 variables in five categories for 22 African countries. However, limited historical data restrict the use of these indices for long-term performance analysis.

Other studies have applied smaller indicator sets to improve temporal comparability. Teixeira et al. (2015) assessed the socioeconomic and environmental performance of the United States and China using selected indicators, including CO_2 emissions, access to drinking water, public health, human development, and renewable energy. Similar approaches have been applied to Brazil and Latin American countries using indicators such as income per capita, CO_2 emissions, renewable energy, the Gini coefficient, GDP per capita, and fossil-fuel consumption (Vilasboas & Teixeira, 2017; Velame & Teixeira, 2017). Schlor et al. (2017) developed a Green Economy Innovation Index for Germany using 46 variables and sub-indices covering the food, energy, and water sectors.

Research

Composite indices provide a practical means of aggregating multiple variables into a single measure for decision-making and policy evaluation. Their construction generally involves four stages: variable selection, transformation, weighting, and evaluation (OECD, 2002).

For assessing green economy development, variables should represent the interaction between economic activity, social welfare, and environmental conditions. Accordingly, indicator selection should consider three main areas: (1) green-economy-related investment, employment, and production, including renewable energy; (2) economic growth and associated environmental pressures, including energy intensity, resource use, and waste generation; and (3) broader development and welfare indicators, including poverty reduction and natural-resource consumption. Such indicators allow conventional economic measures to be assessed together with environmental degradation and resource depletion (Jones, 2011).

Discussion

Since the values of variables generally have different scales and units, these values need to be normalized. Normalization is essentially a mathematical transformation that arranges raw values with different scales and units into a common scale. Thus, all values are scaled to a specified range (0-1, 0-10, 0-100, etc.), preventing one variable from dominating others when the final index value is calculated. Although various normalization methods exist in the literature, the max-min normalization method used in the World Bank's Human Development Index has been chosen for this work. In this method, raw data is normalized within the framework of the following equations (Nahman et al., 2016):

If the raw values of a variable are desirable to be high (e.g., income per capita), the normalization is done as follows:

$$Xi' = \frac{Xi - min\,(x)}{max\,(x) - min\,(x)} \quad (1)$$

If high raw values are not desirable (e.g., the ratio of government debt to GDP), the normalization is done as follows:

$$Xi' = \frac{max\,(x) - Xi}{max\,(x) - min\,(x)} \quad (2)$$

Equation (1) and (2), Xi' represents the normalized value, Xi is the raw value of the variable, and max(x) and min(x) are the maximum and minimum values of the variable, respectively. Thus, all numerical values of the variables are brought into a defined range. If the normalized values are closer to the lower end of the range, it indicates poor performance, while values closer to the upper end of the range indicate good performance. Since the range used in this case is 0-1, a normalized value of 0 represents the worst condition, and 1 represents the best condition.

Weighting is the process of evaluating the relative importance of the various components within an index. In an index, it is possible to assign different weights according to the significance of each variable. This helps to assess the role of each variable in the index more accurately and in a balanced manner.

Obtaining azerbaijan's green economy index

In this study, Azerbaijan's green economy index was calculated for the period 1990-2023. The most important limitation of the study is the lack of data. The lack of regular data for many variables caused the study to be limited to the period in question. For example, although the Gini coefficient in Azerbaijan has been calculated for some years.

In order to create the index, a total of 21 variables, which are thought to represent economic, social and environmental dimensions in the context of the relevant literature, were used and the data were obtained from the World Bank (WB) databases. Information and sources of the variables are presented in Table 1.

Table 1

Economic, Social and Environmental Variables Included in the Green Economy Index

DIMENSION	VARIABLE
ECONOMIC	Net National Income (current, US Dollar) Net National Income per Capita (Current, US Dollar) Net National Income Growth Rate (Annual, %) GDP by Purchasing Power Parity (Current US Dollar) Gross fixed capital formation (current US$) Gross fixed capital formation (% of GDP) Agriculture, forestry, and fishing, value added (current US$)
SOCIAL	Life expectancy at birth, total (years) Mortality rate, infant (per 1,000 live births) Government expenditure (GE) on education, total (% of GE) School enrollment, primary (% net) Poverty rate (% of population) Access to electricity (% of population)
ENVIROMENTAL	Electricity production from renewable sources, excluding hydroelectric (% of total) Renewable energy consumption (% of total final energy consumption) Fossil fuel energy consumption (% of total) Adjusted savings: natural resources depletion (% of GNI) Energy intensity level of primary energy (MJ/$2017 PPP GDP) Total greenhouse gas emissions excluding LULUCF (Mt CO2e) Forest area (% of land area) Arable land (% of land area)

In the index creation process, first the raw data of all variables were normalized with the max-min method and each variable was brought to a 0-1 scale. Then, economic, social and environmental sub-indices were calculated by taking the arithmetic average of the normalized values of the variables in each group. Finally, the scores for the green economy index were obtained by taking the arithmetic average of the sub-indexes obtained. The graphs below show the normalized economic, social and environmental variables of Azerbaijan between 1990 and 2023 taken from the World Bank data.

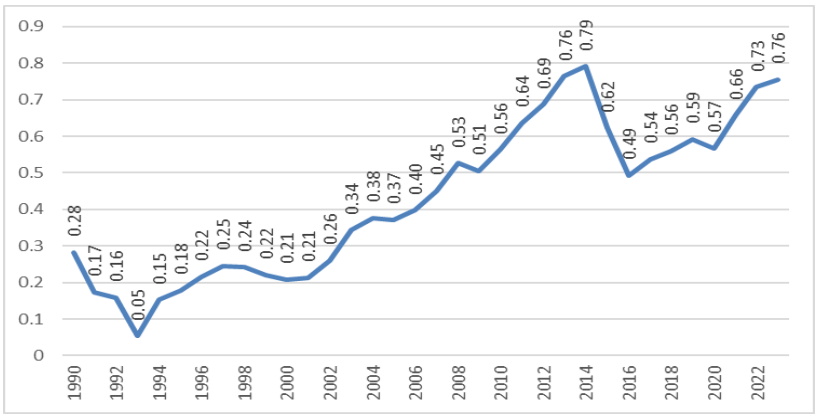


Fig. 2. Normalized economic index of Azerbaijan for 1990-2023

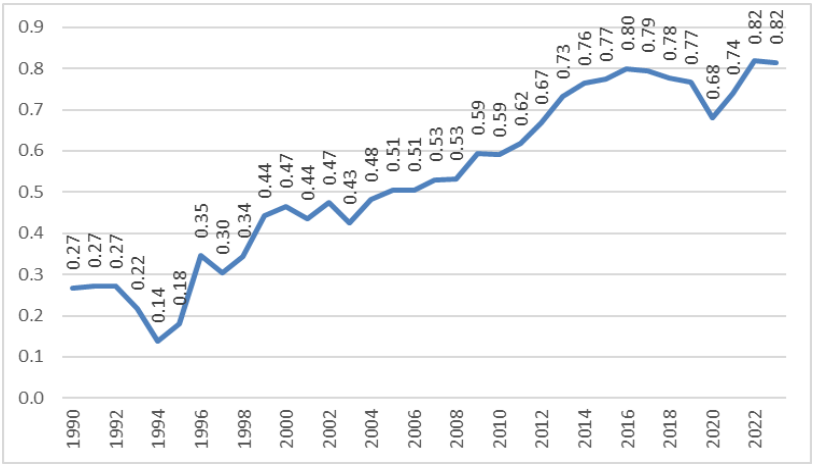


Fig. 3. Normalized social index of Azerbaijan for 1990-2023

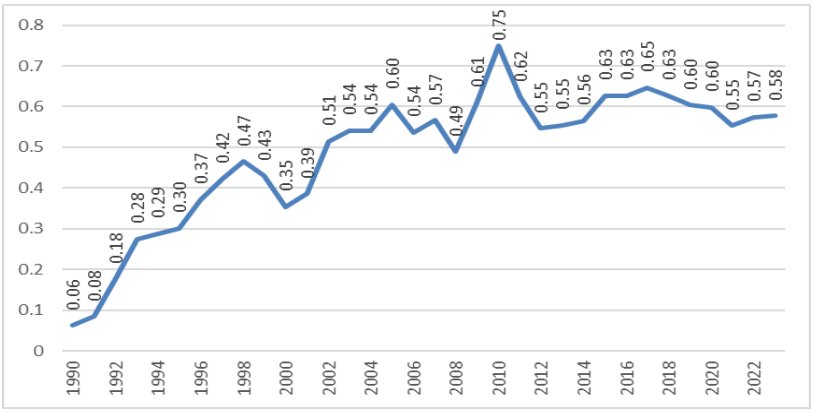


Fig. 4. Normalized enviromental index of Azerbaijan for 1990-2023

As depicted in figures, Azerbaijan's economic performance decreased in 1990-1993, it showed a long-term growth in 1993-2013 and the oil price slump of 2014 caused a drastic economic slowdown with all economic indicators and economic performance has declined but with the increasing oil prices in the following years, after 2016, it again followed a growth rate. Azerbaijan's social indicators also showed a decline between 1990-1994, fluctuations were observed in 1994-2003, and although it showed a decrease in 2019-20 due to the Covid pandemic, it was at a growth rate in the following years. But talking about a trend for environmental performance it is not possible. Azerbaijan's environmental performance increased until 1998, 1998-2008 it fluctuated during the period, showed a large increase in 2008-2010, and had a decreasing trend in the post-2010 period compared to the previous period. But in general, we can see that environmental performance is also increasing in the long term.

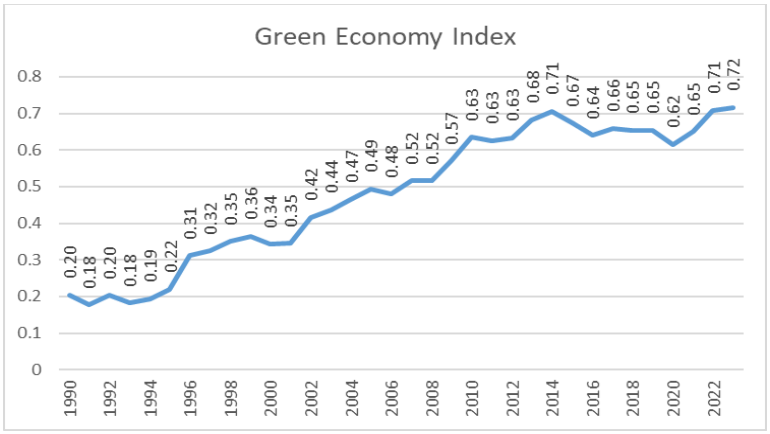


Fig. 5. Green economy index of Azerbaijan for 1990-2023

The development of Azerbaijan's green economy index for the 1990-2023 period is presented in Figure 5. We can say that Azerbaijan's green economy performance is generally on an upward trend. Although this upward trend became more pronounced in the 1990-2014 period, it followed a stable course in the 2014-2020 period and has been on an upward trend in the following years.

Conclusions

In this study evaluating the green economy performance of Azerbaijan, first of all, a green economy index consisting of 21 variables belonging to economic, social and environmental dimensions was created. According to the index scores obtained, it can be said that the green economy performance of Azerbaijan has increased in the period under consideration. This increase was mainly driven by the progress in the economic and social dimensions. On the other hand, it is not possible to say that it has shown an adequate performance in the environmental dimension. This is because the environmental performance index has shown a more fluctuating course than the others in the period under consideration.

In addition to progress in economic and social variables, implementing social policies to increase equitable income distribution and reduce poverty, and increasing investments in health, education and infrastructure that contribute to the development of human capital can improve the social index and hence the country's green economy performance.

In particular, positive developments in environmental variables will further improve the performance of the green economy. In this context, the development of green technologies that will also contribute to the economy, the creation of green jobs, the efficient use of natural resources and energy, the rehabilitation of agricultural land and increasing productivity can improve both economic and environmental performance. In this context, developing incentives for wind and solar energy investments and accelerating natural gas exploration efforts will contribute to Azerbaijan's current account balance and economic growth by reducing energy dependency, and will also contribute positively to environmental performance by preventing environmental pollution. However, in making these investments, it is also important to determine the correct location of the establishment and to choose the methods that will cause the least damage to the environment. It is also important to develop and expand recycling practices, which are widely practiced in many countries.

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УСТОЙЧИВОЕ РАЗВИТИЕ И ЗЕЛЁНАЯ ЭКОНОМИКА: РАЗРАБОТКА ИНТЕГРАЛЬНОГО ИНДЕКСА ДЛЯ АЗЕРБАЙДЖАНА

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Резюме. В исследовании оценивается прогресс Азербайджана в направлении перехода к зелёной экономике, объединяющей экономический рост, социальное благополучие и охрану окружающей среды. Поскольку традиционные показатели, такие как валовой внутренний продукт (ВВП), не отражают экологические и социальные аспекты, для более комплексной оценки разработан составной Индекс зелёной экономики. На основе национальных данных за 1990–2023 годы индекс сформирован из 21 экономического, социального и экологического показателя, полученного из базы данных Всемирного банка. Показатели нормализованы методом минимакса и агрегированы в субиндексы по отдельным направлениям, после чего путём вычисления их среднего значения получен общий индекс. Результаты свидетельствуют об общей тенденции роста показателей зелёной экономики Азербайджана в течение исследуемого периода. Прогресс обусловлен главным образом улучшениями в экономической и социальной сферах, включая повышение уровня доходов, расширение доступа к электроэнергии, образованию и медицинским услугам. Экологические показатели улучшаются в долгосрочной перспективе, однако сохраняют нестабильный характер и вносят менее устойчивый вклад в общий прогресс. Полученные результаты подчёркивают необходимость усиления экологической политики, расширения инвестиций в возобновляемую энергетику и повышения эффективности использования ресурсов. Разработанный индекс представляет собой практический инструмент для мониторинга показателей зелёной экономики и поддержки формирования политики устойчивого развития.

Ключевые слова: *зелёная экономика, устойчивое развитие, индекс зелёной экономики, Азербайджан, экологическая результативность*

DAYANIQLI İNKİŞAF VƏ YAŞIL İQTİSADİYYAT: AZƏRBAYCAN ÜÇÜN İNDEKS TƏKLİFİ

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Xülasə. Tədqiqatda Azərbaycanın iqtisadi artımı, sosial rifahı və ətraf mühitin mühafizəsini özündə birləşdirən yaşıl iqtisadiyyata keçid istiqamətində irəliləyişi qiymətləndirilir. Ümumi daxili məhsul (ÜDM) kimi ənənəvi göstəricilər ekoloji və sosial aspektləri əks etdirmədiyindən daha əhatəli qiymətləndirmə üçün kompozit Yaşıl İqtisadiyyat İndeksi hazırlanmışdır. Dünya Bankından əldə edilmiş 1990–2023-cü illərə aid milli məlumatlardan istifadə edilməklə indeks 21 iqtisadi, sosial və ekoloji göstərici əsasında formalaşdırılmışdır. Göstəricilər min–maks metodu ilə normallaşdırılmış və ayrı-ayrı istiqamətlər üzrə subindekslərdə birləşdirilmiş, daha sonra onların orta qiyməti hesablanaraq ümumi indeks əldə edilmişdir. Nəticələr tədqiqat dövründə Azərbaycanın yaşıl iqtisadiyyat

göstəricilərində ümumi artım meylinin müşahidə olunduğunu göstərir. İrəliləyiş əsasən gəlir səviyyəsinin yüksəlməsi, elektrik enerjisinə, təhsilə və səhiyyə xidmətlərinə çıxış imkanlarının yaxşılaşması da daxil olmaqla iqtisadi və sosial sahələrdəki müsbət dəyişikliklərlə şərtlənir. Ekoloji göstəricilər uzunmüddətli dövrdə yaxşılaşsa da, dəyişkən olaraq qalır və ümumi irəliləyişə daha az sabit töhfə verir. Əldə edilən nəticələr ekoloji siyasətin gücləndirilməsi, bərpa olunan enerji mənbələrinə investisiyaların genişləndirilməsi və resurslardan istifadə səmərəliliyinin artırılması zərurətini vurğulayır. İndeks yaşıl iqtisadiyyatın inkişaf göstəricilərinin monitorinqi və dayanıqlı siyasətin formalaşdırılmasının dəstəklənməsi üçün praktiki vasitə təqdim edir.

Açar sözlər: *yaşıl iqtisadiyyat, dayanıqlı inkişaf, yaşıl iqtisadiyyat indeksi, Azərbaycan, ekoloji nəticəlilik*

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GREEN ENERGY TRANSITION AND REGIONAL ECONOMIC RESILIENCE

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Keywords: *renewable energy adoption, sustainable development, low-carbon transformation, green investment, environmental innovation*

Summary. As regions increasingly face environmental challenges, energy security concerns, and economic transformation pressures, understanding how green energy transition contributes to sustainable and resilient regional development has become an important research priority. This study aims to examine the influence of green energy transition on regional economic resilience by analyzing the mediating role of green investment and its effect on green innovation capability. Using survey data collected from 364 professionals representing energy sectors, industrial organizations, public institutions, universities and sustainability-related organizations in Azerbaijan, Structural Equation Modeling was applied to evaluate the proposed relationships. The results reveal that green energy transition has a significant positive impact on both regional economic resilience and green innovation capability. The findings further confirm that green investment partially mediates the relationship between green energy transition and regional economic resilience, indicating that financial mechanisms are essential for converting renewable energy initiatives into sustainable regional development outcomes. The study contributes to sustainability transition literature by demonstrating that successful green transformation depends not only on renewable energy adoption but also on investment capacity and innovation development. These findings suggest that policymakers and regional stakeholders should integrate green energy strategies with investment mechanisms to enhance long-term regional adaptability and sustainable economic development.

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1. Introduction

The global transition toward green energy systems has become a key response to climate change and the pursuit of sustainable economic development. Efforts to reduce carbon emissions, decrease fossil fuel dependence, and enhance energy security have accelerated the adoption of renewable energy, making the green energy transition (GET) both an environmental necessity and a strategic driver of economic transformation and regional development (Markard, 2018).

Regional economic resilience (RER) refers to a region's ability to adapt to structural change, withstand disruptions, and sustain long-term growth. GET can strengthen resilience by promoting economic diversification, structural transformation, and reduced reliance on conventional energy systems, particularly in resource-dependent economies such as Azerbaijan.

Although previous studies have examined the effects of renewable energy on economic growth and environmental outcomes (Saidi & Omri, 2020; Mukhtarov et al., 2023), limited attention has been given to the relationship between GET and RER and the mechanisms underlying this relationship.

Therefore, this study examines the direct effect of GET on RER and the mediating role of green investment (GI), providing an integrated framework for understanding how green investment translates energy transition into stronger regional economic resilience.

2. Literature review and hypotheses development

2.1. Green energy transition, regional economic resilience, and green innovation capability

GET is reshaping regional development through renewable energy adoption, energy efficiency, technological modernization, and low-carbon transformation. As a strategic response to environmental and economic challenges, GET strengthens regional adaptability, competitiveness, and sustainable development (Sovacool, 2016; Hasanov & Safarli, 2023). From a socio-technical perspective, energy transitions involve interactions among technologies, institutions, industries, and society, driving structural transformation and innovation across multiple sectors (Geels et al., 2017).

RER refers to the ability of regional economies to withstand disruptions, adapt to change, and sustain long-term development. GET enhances RER by reducing fossil fuel dependence, improving energy security, promoting economic diversification, and supporting green industries (Dincer, 2000). At the same time, GET creates technological opportunities that stimulate green innovation capability (GIC) by encouraging knowledge creation, technological learning, and capability development (Rennings, 2000; Chen, 2008; Huang & Li, 2017).

GIC reflects the capacity of regions and organizations to develop and apply environmentally oriented innovations. Its development depends on internal capabilities, external pressures, technological readiness, and continuous innovation (Cai & Li, 2018; Song et al., 2019). Although previous studies have examined renewable energy, innovation, and economic growth, limited attention has been given to the role of GET in simultaneously strengthening RER and GIC.

Drawing on the preceding discussion, the following hypotheses are proposed:

H1. Green energy transition positively influences regional economic resilience.

H2. Green energy transition positively affects green innovation capability.

2.2. The mediating role of green investment

GI is a key financial mechanism through which the GET contributes to RER. By financing renewable energy, clean technologies, sustainable infrastructure, and environmentally responsible projects, GI supports long-term economic transformation (Chen et al., 2023; Ristanović et al., 2024).

Beyond financing, GI promotes technological upgrading, industrial restructuring, and sustainable development. Previous studies show that green finance accelerates technological progress, low-carbon development, and sustainability-oriented strategies (Zhang et al., 2021; Wang et al., 2022). However, GET alone is unlikely to strengthen regional resilience without investment mechanisms that transform renewable energy initiatives into innovation and sustainable industrial development (Tan & Zhou, 2025; Guliyeva et al., 2021).

GI also enhances RER by encouraging economic diversification, reducing vulnerability to energy-related shocks, and supporting green development. Institutional frameworks, financial systems, environmental regulations, and investment incentives are essential for mobilizing resources for sustainable transformation (Tao, 2026; Zeynalova, 2019). Despite its importance, the mediating role of GI between GET and RER remains underexplored, as previous studies have focused mainly on its direct effects on sustainability and green growth (Feng & Li, 2025).

Therefore, this study proposes that GI serves as a transmission mechanism linking GET to stronger regional economic resilience.

H3. Green investment mediates the relationship between green energy transition and regional economic resilience.

3. Materials and methods

3.1. Research design, measurement and data collection

Data were collected through a structured questionnaire based on validated scales for green energy transition, green innovation, green investment, and sustainable regional development. The survey was conducted in Azerbaijan between January and March 2026 using purposive sampling to select respondents with relevant expertise in energy transition, investment, innovation, and regional development.

All items were measured on a five-point Likert scale ranging from 1 (“strongly disagree”) to 5 (“strongly agree”). After data screening, 364 valid questionnaires were retained for analysis. Respondents' demographic characteristics are presented in Table 1.

Table 1

Demographic profile of respondents

Variable	Category	Sample size	%
Gender	Male	188	51.6
	Female	176	48.4
Age	18–35	95	26.1
	36–65	232	63.7
	65 and above	37	10.2
Experience with Sustainability	Less than 1 year	72	19.8
	1–5 years	205	56.3
	More than 5 years	87	23.9
Field Knowledge	Renewable energy transition	111	30.5
	Green innovation activities	103	28.3
	Regional economic development	95	26.1
	Environmental/sustainability projects	55	15.1

3.2. Data Analysis Procedures

Data analysis was performed using SPSS 26 and SEM. A multi-stage analytical procedure was applied to evaluate the reliability and validity of the measurement model and to test the proposed hypotheses.

First, descriptive statistics were calculated to summarize respondents' demographic characteristics. The reliability of the constructs was assessed using Cronbach's alpha (α) and CR). Values exceeding the recommended threshold of 0.70 indicated acceptable internal consistency reliability.

CFA was conducted to assess the measurement model. Convergent validity was evaluated using standardized factor loadings and AVE. Factor loadings above 0.60 and AVE values greater than 0.50 were considered acceptable indicators of convergent validity. Discriminant validity was assessed using the Fornell–Larcker criterion and the HTMT ratio.

The overall model fit was evaluated using multiple goodness-of-fit indices, including χ^2/df, CFI, TLI, RMSEA, and SRMR.

After confirming the adequacy of the measurement model, SEM was applied to examine the hypothesized structural relationships. The direct effect of GET on RER was analyzed to test H1, while the effect of GET on GIC was examined to test H2.

Finally, the mediating role of GI in the relationship between GET and RER (H3) was tested using a bootstrapping procedure with 5000 resamples and bias-corrected 95% confidence intervals. The indirect effect was considered statistically significant when the confidence interval did not include zero.

4. Results

The results of the structural model examining the relationships among GET, GIC, GI, and RER are presented in Figure 1. The structural model illustrates the estimated path coefficients for the proposed hypotheses, including the direct relationships and the mediating mechanism of GI.

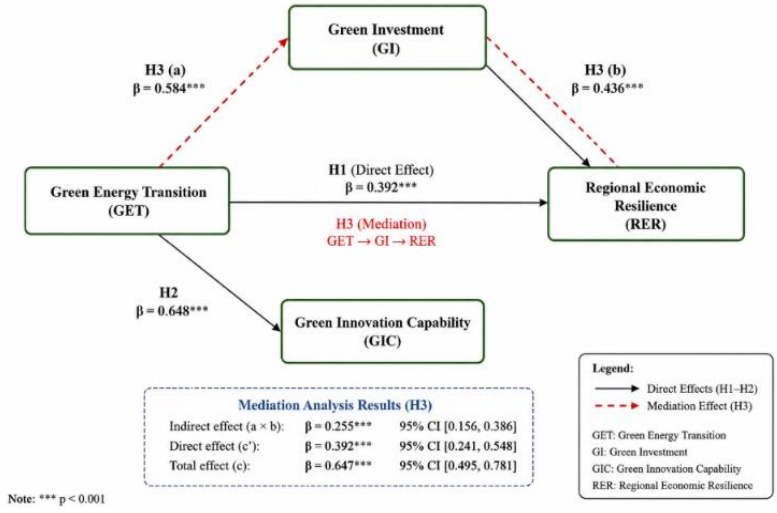


Fig. 1. Structural model results

The detailed results of the structural relationships are presented in Table 2. The findings show that all estimated structural paths are positive and statistically significant.

Table 2

Results of the structural relationships

Path Relationship	Path Coefficient (β)	S.E.	C.R.	Hypothesis Result
GET → RER	0.392	0.079	5.762	H1 Supported
GET → GIC	0.648	0.073	8.657	H2 Supported
GET → GI	0.584	0.068	7.914	H3 mediation path (a) Supported
GI → RER	0.436	0.071	6.325	H3 mediation path (b) Supported

The results indicate that GET has a significant positive influence on RER ($\beta = 0.392$, $p < 0.001$), supporting H1. This result suggests that the development of renewable energy systems, improvements in energy efficiency, and low-carbon transformation processes contribute to strengthening regional adaptability and sustainable economic development.

The results also demonstrate that GET has a strong positive effect on GIC ($\beta = 0.648$, $p < 0.001$), confirming H2. This finding indicates that the transition toward cleaner energy systems encourages technological development, environmental innovation practices, and the creation of new green capabilities.

Furthermore, GET significantly enhances GI ($\beta = 0.584$, $p < 0.001$), and GI contributes positively to RER ($\beta = 0.436$, $p < 0.001$).

The explanatory power of the structural model was evaluated using R^2 values. GET explains 45% of the variance in GIC ($R^2 = 0.45$), indicating its important role in promoting environmentally oriented innovation capacity. Additionally, GET and GI together explain 59% of the variance in RER ($R^2 = 0.59$), demonstrating strong explanatory capability of the proposed model.

After examining the direct structural relationships, mediation analysis was conducted to evaluate the indirect effect of GET on RER through GI. The results are presented in Table 3.

Table 3

Mediation analysis results

Effect Type	Path	Standardized Effect (β)	S.E.	95% Bootstrap CI
Direct effect (c′)	GET → RER	0.392	0.079	[0.241, 0.548]
Indirect effect (a × b)	GET → GI → RER	0.255	0.061	[0.156, 0.386]
Total effect (c)	GET → RER	0.647	0.072	[0.495, 0.781]

The mediation results presented in Table 3 confirm the mediating role of GI in the relationship between GET and RER. The indirect effect of GET on RER through GI is positive and statistically significant ($\beta = 0.255$, $p < 0.001$), and the 95% bootstrap confidence interval does not include zero.

Since both the direct effect of GET on RER and the indirect effect through GI are significant, the findings indicate a partial mediation effect. Therefore, H3 is supported.

5. Discussion

5.1. Green energy transition, regional economic resilience, and green innovation capability

The findings confirm that GET has significant positive effects on both RER (H1) and GIC (H2). These results indicate that GET is not merely a shift from fossil fuels to renewable energy but a broader socio-economic transformation that reshapes industrial structures, investment patterns, and regional development.

GET strengthens regional resilience by reducing dependence on conventional energy sources, improving energy security, promoting economic diversification, and enhancing regions' capacity to respond to environmental and economic shocks. At the same time, the transition stimulates technological learning, knowledge creation, and the development of sustainable production processes, thereby strengthening regional green innovation capability.

These findings support environmental innovation theory by demonstrating that sustainability-oriented energy transitions create favorable conditions for technological advancement and capability development. Unlike previous studies that primarily emphasized the effects of renewable energy on economic growth, emissions, or existing innovation capacity, this study shows that GET simultaneously enhances both the adaptive capacity

of regional economies and the development of green innovation capability, highlighting its broader contribution to sustainable regional transformation.

5.2. The Mediating Role of Green Investment

The mediation analysis confirms that GI partially mediates the relationship between GET and RER (H3). This finding indicates that GET strengthens regional resilience both directly and indirectly through investment-driven mechanisms.

From a theoretical perspective, GI serves as a strategic mechanism that transforms renewable energy initiatives into technological progress, sustainable infrastructure, and regional competitiveness. Renewable energy transition alone is insufficient to enhance resilience without adequate investment to support clean technologies, energy efficiency, and sustainable industrial transformation.

These findings extend the sustainability literature by showing that GI is not only a financial resource but also a key mechanism linking energy transition to regional adaptation, structural transformation, and long-term economic resilience.

6. Conclusion

The transition toward sustainable energy systems is a key driver of regional transformation. This study developed and tested a structural framework explaining how the GET enhances RER through the mediating role of GI. Using structural equation modeling, the study provides empirical evidence on the mechanisms linking energy transition to long-term regional development.

The findings indicate that GET is not only an environmental initiative but also a catalyst for economic transformation. Renewable energy and low-carbon systems improve regional adaptability, reduce vulnerabilities, and promote sustainable development, while these benefits depend on the effective mobilization of GI.

The results offer practical implications for policymakers, regional authorities, financial institutions, businesses, and universities. Renewable energy policies should be integrated with green financing and supportive regulations, while regional stakeholders should foster sustainable industries, clean technologies, innovation, and university–industry–government collaboration.

Appendix 1. Measurement items.

Green Energy Transition
GET1 – Adoption of renewable energy technologies
GET2 – Improvement of energy efficiency practices
GET3 – Reduction of dependence on fossil energy sources
GET4 – Implementation of low-carbon energy strategies
Green Innovation Capability
GIC1 – Development of environmentally friendly technologies
GIC2 – Ability to implement green process innovations
GIC3 – Capacity to create sustainable products and services
GIC4 – Integration of environmental knowledge into innovation processes
Green Investment
GI1 – Allocation of financial resources to green projects
GI2 – Investment in renewable energy infrastructure
GI3 – Availability of green financing mechanisms
GI4 – Long-term commitment to sustainable investment activities
Regional Economic Resilience
RER1 – Ability of the region to adapt to economic changes
RER2 – Capacity to recover from economic and environmental shocks
RER3 – Diversification of regional economic activities
RER4 – Creation of sustainable employment opportunities

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ПЕРЕХОД К ЗЕЛЁНОЙ ЭНЕРГЕТИКЕ И УСТОЙЧИВОСТЬ РЕГИОНАЛЬНОЙ ЭКОНОМИКИ

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Резюме. В условиях, когда регионы всё чаще сталкиваются с экологическими проблемами, угрозами энергетической безопасности и давлением, связанным с экономической трансформацией, изучение вклада перехода к зелёной энергетике в устойчивое и стабильное региональное развитие становится важным направлением научных исследований. Цель исследования заключается в изучении влияния перехода к зелёной энергетике на региональную экономическую устойчивость посредством анализа посреднической роли зелёных инвестиций и их воздействия на потенциал зелёных инноваций. Для оценки

предполагаемых взаимосвязей применён метод моделирования структурными уравнениями (Structural Equation Modeling – SEM) на основе данных опроса 364 специалистов, представляющих энергетические отрасли, промышленные организации, государственные учреждения, университеты и организации, связанные с устойчивым развитием в Азербайджане. Результаты показывают, что переход к зелёной энергетике оказывает статистически значимое положительное влияние как на региональную экономическую устойчивость, так и на потенциал зелёных инноваций. Полученные результаты также подтверждают, что зелёные инвестиции частично опосредуют взаимосвязь между переходом к зелёной энергетике и региональной экономической устойчивостью, указывая на важную роль финансовых механизмов в преобразовании инициатив в области возобновляемой энергетики в результаты устойчивого регионального развития. Исследование вносит вклад в научную литературу по вопросам перехода к устойчивому развитию, демонстрируя, что успешная зелёная трансформация зависит не только от внедрения возобновляемых источников энергии, но и от инвестиционного потенциала и развития инноваций. Полученные результаты свидетельствуют о том, что разработчикам государственной политики и региональным заинтересованным сторонам следует интегрировать стратегии развития зелёной энергетики с инвестиционными механизмами для повышения долгосрочной адаптивности регионов и обеспечения устойчивого экономического развития.

Ключевые слова: *внедрение возобновляемых источников энергии, устойчивое развитие, низкоуглеродная трансформация, зелёные инвестиции, экологические инновации*

YAŞIL ENERJİYƏ KEÇİD VƏ REGİONLARIN İQTİSADİ DAYANIQLIĞI

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Xülasə. Regionların ekoloji problemlər, enerji təhlükəsizliyi ilə bağlı narahatlıqlar və iqtisadi transformasiya təzyiqləri ilə getdikcə daha çox üzləşdiyi şəraitdə yaşıl enerjiyə keçidin dayanıqlı və davamlı regional inkişafa necə töhfə verdiyinin öyrənilməsi mühüm tədqiqat istiqamətinə çevrilmişdir. Tədqiqatın məqsədi yaşıl investisiyaların vasitəçi rolunu və yaşıl innovasiya potensialına təsirini təhlil etməklə yaşıl enerjiyə keçidin regional iqtisadi dayanıqlığa təsirini araşdırmaqdır. Azərbaycanda enerji sektorlarını, sənaye təşkilatlarını, dövlət müəssisələrini, universitetləri və dayanıqlı inkişafla əlaqəli təşkilatları təmsil edən 364 mütəxəssisdən toplanmış sorğu məlumatları əsasında irəli sürülən əlaqələrin qiymətləndirilməsi üçün struktur tənliklərin modelləşdirilməsi (Structural Equation Modeling – SEM) metodundan istifadə edilmişdir. Nəticələr göstərir ki, yaşıl enerjiyə keçid həm regional iqtisadi dayanıqlığa, həm də yaşıl innovasiya potensialına statistik baxımdan əhəmiyyətli müsbət təsir göstərir. Əldə edilən nəticələr, həmçinin yaşıl investisiyaların yaşıl enerjiyə keçidlə regional iqtisadi dayanıqlıq arasındakı əlaqədə qismən vasitəçi rol oynadığını təsdiqləyir. Bu isə bərpa olunan enerji təşəbbüslərinin dayanıqlı regional inkişaf nəticələrinə çevrilməsində maliyyə mexanizmlərinin mühüm əhəmiyyət daşıdığını göstərir. Tədqiqat uğurlu yaşıl transformasiyanın yalnız bərpa olunan enerji mənbələrinin tətbiqindən deyil, həm də investisiya imkanlarından və innovasiyaların inkişafından asılı olduğunu nümayiş etdirməklə dayanıqlılığa keçid üzrə elmi ədəbiyyata töhfə verir. Əldə edilən nəticələr göstərir ki, siyasətçilər və regional maraqlı tərəflər uzunmüddətli regional uyğunlaşma qabiliyyətini və dayanıqlı iqtisadi inkişafı gücləndirmək üçün yaşıl enerji strategiyalarını investisiya mexanizmləri ilə inteqrasiya etməlidirlər.

Açar sözlər: *bərpa olunan enerji mənbələrinin tətbiqi, davamlı inkişaf, aşağı karbonlu transformasiya, yaşıl investisiyalar, ekoloji innovasiyalar*

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INVESTMENT MECHANISMS FOR GREEN ENERGY DEVELOPMENT AND STRENGTHENING THE ECONOMIC RESILIENCE OF AZERBAIJAN'S REGIONS

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Summary. This study examines technical and economic approaches to managing ecological restructuring of production in Azerbaijan within the framework of sustainable regional development. An integrated economic-geographical approach is applied, considering natural resources, production structures, environmental pressures, investment, technological modernization, and environmental monitoring. System-structural, mathematical-statistical, GIS-based, and monitoring methods are used to assess the relationship between industrial development and environmental protection. The findings highlight the importance of efficient resource use, modernization of production technologies, closed-cycle and low-waste systems, emission reduction, and specialized treatment facilities. Particular attention is given to industrial and environmental conditions in the Absheron Peninsula, Baku, Sumgayit, and other production areas. The analysis indicates that technological modernization and water-reuse systems can reduce resource consumption and environmental pressure while improving production efficiency. The study concludes that effective ecological restructuring requires an integrated management framework combining technological innovation, resource efficiency, pollution prevention, environmental investment, scientifically based monitoring, and territorial planning.

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1. Introduction

Renewable-energy deployment requires substantial upfront capital, long repayment periods, grid access and credible revenue arrangements. Financing conditions and risk allocation therefore strongly influence project implementation and electricity costs. International evidence shows that green finance and financial-market development can support renewable-energy investment, while policy stability and institutional quality remain important determinants of effectiveness (Al Mamun et al., 2022; Alharbi et al., 2023; Anton & Afloarei Nucu, 2020).

Green bonds and public-private partnerships (PPPs) address different financing needs. Green bonds channel debt proceeds towards eligible environmental activities and require transparent use of proceeds, reporting and external review (Flammer, 2021; Zerbib, 2019). PPPs and independent power producer (IPP) arrangements combine private capital and expertise with public regulation, grid access and long-term power-purchase agreements, with effective risk allocation being essential to project performance (Taghizadeh-Hesary & Yoshino, 2020).

Renewable-energy investment may also support regional resilience through spatial and technological diversification, reduced fuel dependence, grid reinforcement and demand for local services. However, these channels should not be equated with observed changes in regional economic resilience, which requires direct evidence on variables such as employment, regional output and post-shock recovery (Boschma, 2015; Martin & Sunley, 2015). Accordingly, this study evaluates only measurable project-level resilience-relevant channels.

Azerbaijan provides an important case because hydrocarbons remain central to its energy economy despite substantial solar and wind resources (IEA, 2023; IRENA, 2019; World Bank Group, 2023). Garadagh Solar became operational in 2023 and Khizi-Absheron Wind in January 2026, while Bilasuvar and Neftchala add 760 MW of planned solar capacity supported by EBRD, ADB and AIIB financing (Asian Development Bank,

2024; Asian Infrastructure Investment Bank, 2024; European Bank for Reconstruction and Development, 2024a, 2024b, 2024c; President of the Republic of Azerbaijan, 2023, 2026).

The Sustainable Finance Roadmap for 2023–2026 and Azerbaijan's Green Taxonomy strengthen the institutional framework for green finance (Central Bank of the Republic of Azerbaijan, 2023, 2024). At the international level, the ICMA Green Bond Principles establish requirements for use of proceeds, project evaluation and selection, management of proceeds and reporting, complemented by external review and the Climate Bonds Standard (Climate Bonds Initiative, 2025; ICMA, 2025, 2026a). Building on previous research on Azerbaijan's renewable-energy potential (Mustafayev et al., 2022; Vidadili et al., 2017), this study evaluates project costs and output, PPP and multilateral financing, green-bond readiness, diversification and sensitivity to financing rates, cost overruns and output shortfalls.

2. Materials and methods

2.1. Research design and data

The study uses a multi-source observational design with a data cutoff of 30 June 2026. Generation projects were included when capacity was at least 200 MW and public records reported location, technology, total cost and annual output. Four projects met these criteria. The sample is purposive and disclosure-based rather than statistically representative of all renewable-energy investment in Azerbaijan. The Azerbaijan Scaling-Up Renewable Energy Project (AZURE) was assessed separately because it finances transmission rather than generation.

Government communications, project-company disclosures and multilateral development-bank documents were prioritised. When environmental estimates differed, project-company values were applied consistently because they reported generation and avoided emissions on the same basis. Values for plants under construction are documented ex ante expectations rather than audited outcomes; no missing regional employment, income or supplier-spending observations were imputed. The project-level dataset, including location, technology, installed capacity, investment cost, expected annual generation, avoided CO_2 emissions, and operational status, is presented in Table 1. The analytical framework linking financing arrangements, project-level indicators, risk factors, and potential regional resilience channels is illustrated in Fig. 1.

Table 1

Project-level dataset used in the analysis

Project	Location	Technology	Capacity (MW)	Cost (USD m)	Annual generation (GWh)	Avoided CO_2 (kt/year)	Status
Garadagh Solar PV	Garadagh, Baku	Solar PV	230	262	500	200	Operational
Khizi-Absheron Wind	Khizi and Absheron	Wind	240	340	1000	400	Operational
Bilasuvar Solar PV	Bilasuvar	Solar PV	445	383	961	393	Under construction
Neftchala (Banka) Solar PV	Neftchala	Solar PV	315	283	686	280	Under construction

Note. Bilasuvar and Neftchala values are ex ante estimates. The Khizi-Absheron avoided-emissions value conservatively represents an official estimate of more than 400 kt/year. Capacity, generation and emissions values were cross-checked against project-owner disclosures (Masdar, n.d.-a, n.d.-b, n.d.-c).

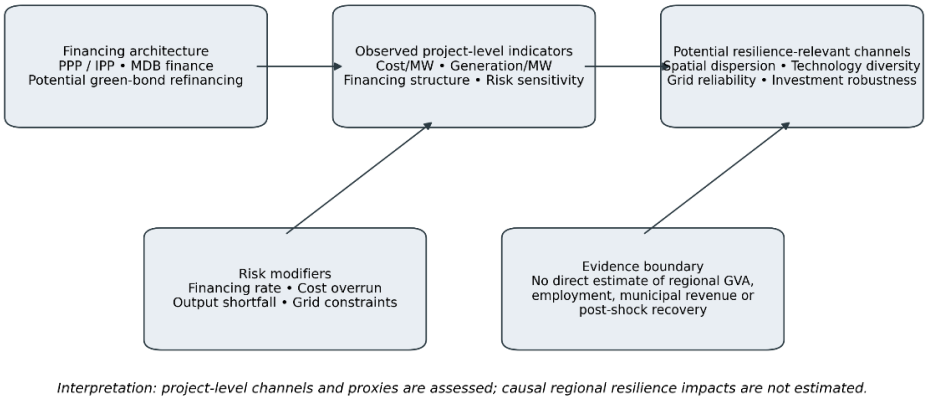


Fig. 1. Analytical framework linking financing variables to project-level indicators and potential regional resilience channels. Regional resilience itself is not estimated as an outcome.

2.2. Indicator construction

Capital intensity and expected generation yield were calculated as:

$$CI_i = \frac{I_i}{C_i}$$

$$EGY_i = \frac{G_i}{C_i}$$

where I_i is investment in USD million, C_i is capacity in MW and G_i is expected annual generation in GWh. Avoided-emissions intensity uses the same denominator.

Portfolio concentration was measured with the Herfindahl-Hirschman Index and its diversification complement:

$$HHI = \sum_{i=1}^{n} s_i^2, \qquad DIV = 1 - HHI$$

where s_i is the capacity share of a location or technology.

No project-level labelled green-bond proceeds were identified. A standards-aligned Green Bond Readiness Index (S-GBRI) was therefore constructed as a documentary pre-issuance screen. The seven criteria are mapped to the ICMA Green Bond Principles (GBP), the 2026 ICMA external-review and impact-reporting guidance, the Azerbaijan Green Taxonomy and, as a consistency check, the Climate Bonds Standard v4.3 (Climate Bonds Initiative, 2025; ICMA, 2025, 2026a, 2026b).

$$S\text{–}GBRI_i = \sum_{j=1}^{7} w_j s_{ij}, \quad s_{ij} \in \{0, 0.5, 1\}, \quad \sum_{j=1}^{7} w_j = 1$$

For each criterion, the documentary score equals 0 when no public evidence was identified, 0.5 when evidence was partial or not bond-specific, and 1 when the criterion was fully evidenced. The weighting is standards-based rather than an equal seven-way split: the four GBP core components jointly receive 0.80 (0.20 each), while external review receives 0.20 as a separate key-recommendation pillar. Where a core component contains two operational criteria, its 0.20 weight is divided equally. The index is a documentary readiness screen, not a credit rating, certification or validated predictor of issuance success; no arbitrary high/medium/low thresholds are imposed.

Table 2

Standards-aligned criteria and weights for the S-GBRI

Criterion	Standards basis	Weight	Documentary coding focus
Eligible green use of proceeds	GBP: Use of Proceeds; Azerbaijan Green Taxonomy	0.10	Renewable activity is taxonomy-consistent and eligible for green financing.
Identifiable project / asset pool	GBP: Use of Proceeds	0.10	Assets and financing need can be clearly identified and ring-fenced conceptually.
Project evaluation and selection process	GBP: Project Evaluation and Selection	0.20	Public evidence of environmental objectives, eligibility screening and material risk assessment.
Management and tracking of proceeds	GBP: Management of Proceeds	0.20	Bond-specific account, sub-account or equivalent internal tracking mechanism.
Allocation reporting framework	GBP: Reporting	0.10	Commitment and mechanism to report allocation of proceeds until full allocation.
Impact-reporting readiness	GBP: Reporting; ICMA 2026 impact framework	0.10	Comparable quantitative indicators, methods and assumptions for energy and GHG impacts.
External review	GBP key recommendation; ICMA 2026 External Reviews	0.20	Independent pre-issuance review/certification and appropriate post-issuance verification plan.

Note. The four ICMA GBP core components receive 0.20 each; Use of Proceeds and Reporting are each divided into two 0.10 subcriteria. External review receives 0.20 because it is a distinct ICMA key recommendation and a central integrity safeguard. The weights are normative and transparent rather than empirically estimated.

Multilateral mobilisation was measured as disclosed MDB finance divided by published project cost. Grid-enabling leverage was calculated as:

$$PLR = \frac{I_{private}}{L_{public}}$$

2.3. Operationalisation of resilience-relevant channels

Regional resilience is operationalised only at the channel/proxy level, not as an outcome variable. Four observable dimensions are used: (i) location diversification (DIV(L)) as a proxy for exposure to single-node concentration; (ii) technology diversification (DIV(T)) as a proxy for correlated technology/resource concentration; (iii) AZURE private-investment leverage (PLR(AZURE)) as a proxy for the enabling role of transmission investment; and (iv) CRC sensitivity to financing-rate, cost-overrun and output shocks as a measure of project-finance vulnerability. These indicators describe conditions that may support or constrain resilience, but they do not measure regional income stability, employment recovery, firm survival or other direct economic-resilience outcomes. Accordingly, the empirical language below is limited to observed project-level results and plausible resilience-relevant channels.

2.4. Financing-risk scenarios

For a 20-year recovery period, the capital recovery factor and capital-recovery component were calculated as:

$$CRF(r,n) = \frac{r(1+r)^n}{(1+r)^n - 1}$$

$$CRC = \frac{I \times CRF(r,n) \times 10^6}{G \times 10^3}$$

Scenarios use financing rates of 6%, 8% and 10%, plus 10% and 20% cost overruns and a 10% generation shortfall. These assumptions are sensitivity tests, not observed weighted average costs of capital. Because operating expenditure, taxes, degradation and curtailment are excluded, CRC is not a complete levelised cost of electricity.

3. Results

3.1. Portfolio scale and efficiency

Within the four-project sample, total capacity is 1,230 MW and disclosed investment is USD 1.268 billion. Expected full-operation output is at least 3.147 TWh annually, with avoided emissions of at least 1.273 million tonnes of CO_2. Solar accounts for 990 MW (80.5%) and wind for 240 MW. At the cutoff date, 470 MW was operational and 760 MW was under construction; the latter values are therefore ex ante project expectations rather than realised performance.

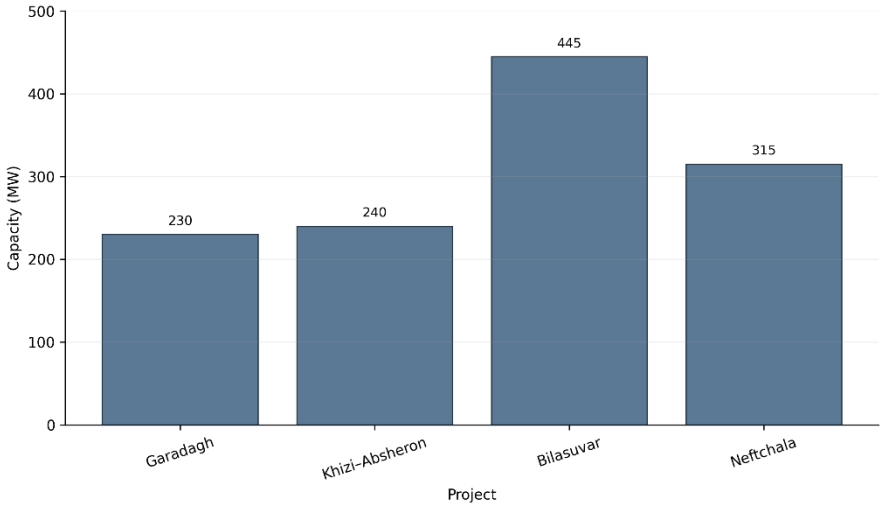


Fig. 2. Installed or planned capacity of the four renewable-energy projects in the disclosure-based sample

As shown in Fig. 2, Bilasuvar Solar PV has the largest capacity among the four projects (445 MW), followed by Neftchala Solar PV (315 MW), Khizi-Absheron Wind (240 MW), and Garadagh Solar PV (230 MW).

Weighted capital intensity is USD 1.031 million/MW. Bilasuvar has the lowest disclosed capital intensity; Khizi-Absheron has the highest cost per MW but the strongest generation yield. Consequently, at an 8% financing rate, the wind project has the lowest capital-recovery component per MWh. The calculated capital intensity, generation yield, avoided CO_2 intensity, and capital-recovery components for the analyzed projects are summarized in Table 3.

Table 3

Derived project indicators

Project	Capital intensity (USD m/MW)	Generation yield (GWh/MW)	Avoided CO_2 intensity (kt/MW)	CRC at 8% (USD/MWh)
Garadagh Solar PV	1.139	2.174	0.870	53.4
Khizi-Absheron Wind	1.417	4.167	1.667	34.6
Bilasuvar Solar PV	0.861	2.160	0.883	40.6
Neftchala (Banka) Solar PV	0.898	2.178	0.889	42.0
Portfolio weighted value	1.031	2.559	1.035	41.0

3.2. Diversification and financing structure

Location concentration is HHI(L) = 0.270, giving DIV(L) = 0.730; the analysed capacity is therefore distributed across several project nodes. Technology concentration is higher (HHI(T) = 0.686; DIV(T) = 0.314) because solar dominates capacity. These are concentration metrics, not direct measures of regional economic resilience. Spatial dispersion may reduce single-location concentration, while technology concentration increases the potential value of wind, storage, flexible demand and transmission reinforcement. PPP/IPP structures are the principal delivery model. Garadagh combines foreign investment, a PPA and a grid agreement. Khizi-Absheron received a USD 197.1 million EBRD-arranged syndicated loan, about 58.0% of reported cost (European Bank for Reconstruction and Development, 2023). EBRD, ADB and AIIB commitments for Bilasuvar and Neftchala total approximately USD 481 million, or 72.2% of their combined USD 666 million cost. In this sample, multilateral finance provides long tenor, due diligence and risk sharing at substantial scale. AZURE illustrates the complementary role of public grid investment. A USD 173.5 million World Bank loan is expected to unlock USD 384 million of private renewable investment (World Bank, 2025):

$$PLR_{AZURE} = \frac{384}{173.5} = 2.21$$

Table 4

Financing arrangements and resilience-relevant channels

Project/ programme	Principal financing structure	Quantitative financing evidence	Potential resilience-relevant channel
Garadagh Solar	Foreign-invested PPP/IPP with PPA and grid agreement	USD 262 m project cost	Operational capacity, gas savings and investment demonstration
Khizi-Absheron Wind	BOO company with syndicated debt and PPA	USD 197.1 m loan; about 58.0% of cost	Technology diversification and high output across two districts
Bilasuvar-Neftchala Solar	Sponsor equity plus EBRD, ADB and AIIB finance	About USD 481 m; 72.2% of cost	Regional capital formation and infrastructure demand
AZURE	Sovereign grid investment enabling private generation	USD 173.5 m loan; USD 384 m mobilisation	Grid reliability and lower connection and curtailment risks

As summarized in Table 4, the analyzed projects rely on different financing arrangements, including public-private partnerships, syndicated loans, and multilateral financing, which may support renewable-energy deployment through investment mobilization, technological diversification, and grid development.

3.3. Green-bond readiness and risk sensitivity

The standards-aligned scoring produces the same preliminary documentary profile for the four projects on the public evidence reviewed. Green eligibility and asset identification are fully evidenced (1.0 each). Project evaluation and selection receives a partial score (0.5) because environmental and MDB due-diligence documentation exists, but no issuer-level green-bond framework defining a formal bond selection process was identified. Impact-reporting readiness also receives 0.5 because generation and avoided-CO_2 metrics are publicly available, but several values are ex ante and no bond-specific impact-reporting commitment exists. Management of proceeds, allocation reporting and external review receive 0 because no labelled green-bond framework or issuance was identified. With the Table 2 weights:

$$S\text{–}GBRI = 0.35$$

The S-GBRI value of 0.35 is not assigned to a high, medium or low category because no validated threshold exists. It indicates partial pre-issuance documentary readiness: the underlying assets are identifiable and environmentally eligible, but the issuer-level architecture required for a credible labelled bond—proceeds tracking, allocation reporting and independent external review—has not yet been evidenced. The result therefore supports only a cautious proposition that the assets could become candidates for future refinancing or aggregation after those requirements are established.

Increasing the assumed financing rate from 6% to 10% raises the portfolio CRC from USD 35.1/MWh to USD 47.3/MWh, a 34.7% increase without any engineering change. The sensitivity of the aggregate portfolio's capital-recovery component to alternative financing-rate assumptions is presented in Table 5. The increase in the portfolio's capital-recovery component under financing-rate scenarios of 6%, 8%, and 10% is illustrated in Fig. 3.

Table 5

Financing-rate sensitivity of the aggregate portfolio

Financing rate	Capital recovery factor	Annualised capital cost (USD m)	Capital-recovery component (USD/MWh)
6%	0.0872	110.6	35.1
8%	0.1019	129.1	41.0
10%	0.1175	148.9	47.3

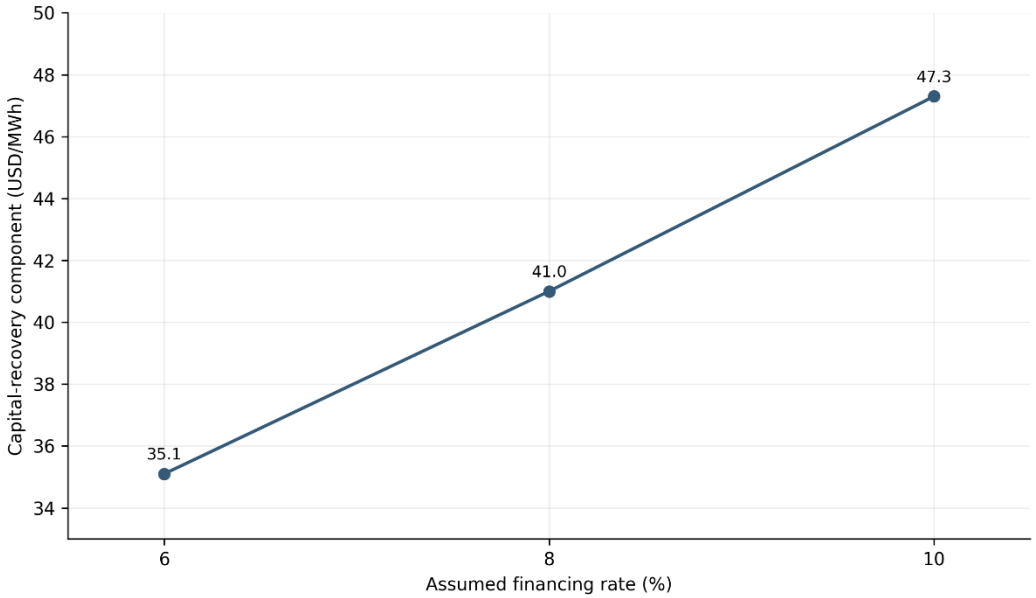


Fig. 3. Sensitivity of portfolio capital-recovery cost to assumed financing rates (scenario analysis; the rates are not observed WACC)

A 10% cost overrun adds USD 126.8 million and a 20% overrun adds USD 253.6 million. A 10% generation shortfall removes 314.7 GWh of annual output and at least 127.3 kt of expected CO_2 savings. Project value therefore depends on financing cost, construction discipline and realised performance, not capacity announcements alone.

4. Discussion

Within the selected projects, Azerbaijan's utility-scale renewable expansion relies primarily on PPP/IPP arrangements and multilateral project finance rather than domestic labelled green bonds. PPAs and dedicated project companies provide revenue predictability, while multilateral financing contributes long-term capital, due diligence and risk sharing. The Bilasuvar–Neftchala financing structure and the Khizi-Absheron syndicated facility demonstrate the role of these mechanisms in mobilising investment without placing the full financing burden on the public sector.

The results identify several resilience-relevant channels but do not establish a causal effect on regional economic resilience. Spatial diversification is relatively strong **(**DIV(L) = 0.730**),** whereas technology diversification remains limited **(**DIV(T) = 0.314**)** because solar accounts for 80.5% of the analysed capacity. This concentration highlights the potential importance of wind, storage, flexible demand and transmission reinforcement. The AZURE programme further demonstrates the enabling role of grid investment in supporting private renewable generation.

Financing conditions are also important for project economics. Increasing the assumed financing rate from 6% to 10% raises the portfolio CRC from USD 35.1/MWh to USD 47.3/MWh**,** while cost overruns and generation shortfalls further weaken project performance. Effective risk allocation, predictable regulation, bankable PPAs and adequate grid infrastructure are therefore important components of renewable-energy financing.

Green bonds could complement existing financing through refinancing or portfolio aggregation; however, the S-GBRI score of 0.35 shows that eligible renewable assets alone are insufficient. A credible labelled green-bond structure would additionally require an issuer-level Green Bond Framework, proceeds tracking, allocation and impact reporting, and independent external review in line with ICMA principles (ICMA, 2025, 2026a, 2026b).

These findings should be interpreted within the study's limitations. The analysis covers only four large, disclosure-rich projects; Bilasuvar and Neftchala data are ex ante; detailed tariffs and debt terms are unavailable; and consistent regional employment, output and post-shock recovery data are absent. Consequently, the study identifies project-level resilience channels rather than causal regional-resilience effects**.** Future research should compare expected and realised project performance and incorporate direct regional economic indicators.

5. Conclusion

The four-project portfolio comprises 1,230 MW of renewable capacity, USD 1.268 billion of disclosed investment and at least 3.147 TWh of expected annual generation. The results show that PPP/IPP arrangements and multilateral co-financing are the principal financing mechanisms in the analysed projects. Multilateral commitments finance approximately **72.2%** of the combined Bilasuvar–Neftchala project cost, while the AZURE programme is expected to mobilise USD 2.21 of private renewable investment per dollar of public lending**.**

The analysis also reveals relatively strong spatial diversification **(**DIV(L) = 0.730**)** but limited technology diversification **(**DIV(T) = 0.314**),** alongside substantial sensitivity to financing conditions and project-performance risks. The S-GBRI score of 0.35 indicates that the projects contain eligible and identifiable green assets but currently lack key bond-specific mechanisms, particularly proceeds management, allocation reporting and external review.

Overall, Azerbaijan's current utility-scale renewable financing model is driven primarily by PPP/IPP and multilateral finance**,** while green bonds represent a potential complementary financing instrument if the required institutional and reporting architecture is established. These conclusions are limited to the analysed project sample; broader claims regarding regional economic resilience require direct regional outcome data.

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ИНВЕСТИЦИОННЫЕ МЕХАНИЗМЫ РАЗВИТИЯ ЗЕЛЁНОЙ ЭНЕРГЕТИКИ И УКРЕПЛЕНИЯ ЭКОНОМИЧЕСКОЙ УСТОЙЧИВОСТИ РЕГИОНОВ АЗЕРБАЙДЖАНА

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Резюме. В исследовании рассматриваются технические и экономические подходы к управлению экологической реструктуризацией производства в Азербайджане в контексте устойчивого регионального развития. Применяется комплексный экономико-географический подход, учитывающий природные ресурсы, производственные структуры, экологические нагрузки, инвестиции, технологическую модернизацию и экологический мониторинг. Для оценки взаимосвязи между промышленным развитием и охраной окружающей среды используются системно-структурные, математико-статистические методы, методы на основе географических информационных систем (ГИС) и экологического мониторинга. Результаты подчёркивают важность рационального использования ресурсов, модернизации производственных технологий, внедрения систем замкнутого цикла и малоотходного производства, сокращения вредных выбросов и создания специализированных очистных сооружений. Особое внимание уделяется промышленным и экологическим условиям Апшеронского полуострова, Баку, Сумгаита и других производственных территорий. Анализ показывает, что технологическая модернизация и системы повторного использования воды способны снижать потребление ресурсов и антропогенную нагрузку на окружающую среду, одновременно повышая эффективность производства. По результатам исследования установлено, что эффективная экологическая реструктуризация требует внедрения комплексной системы управления, объединяющей технологические инновации, ресурсную эффективность, предотвращение загрязнения, экологические инвестиции, научно обоснованный мониторинг и территориальное планирование.

Ключевые слова: *зелёные облигации, государственно-частное партнёрство, финансирование возобновляемой энергетики, каналы укрепления устойчивости, инвестиционный риск*

AZƏRBAYCAN REGİONLARINDA YAŞIL ENERJİNİN İNKİŞAFI VƏ İQTİSADİ DAYANIQLIĞIN GÜCLƏNDİRİLMƏSİNİN İNVESTİSİYA MEXANİZMLƏRİ

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Xülasə. Tədqiqatda dayanıqlı regional inkişaf çərçivəsində Azərbaycanda istehsalın ekoloji restrukturizasiyasının idarə edilməsinə texniki və iqtisadi yanaşmalar araşdırılır. Təbii resurslar, istehsal strukturları, ekoloji təzyiqlər, investisiyalar, texnoloji modernləşmə və ekoloji monitorinq nəzərə alınmaqla kompleks iqtisadi-coğrafi yanaşma tətbiq edilmişdir. Sənayenin inkişafı ilə ətraf mühitin mühafizəsi arasındakı əlaqənin qiymətləndirilməsi üçün sistem-struktur, riyazi-statistik, coğrafi informasiya sistemlərinə (CİS) əsaslanan və monitorinq metodlarından istifadə olunmuşdur. Nəticələr resurslardan səmərəli istifadənin, istehsal texnologiyalarının modernləşdirilməsinin, qapalı dövriyyəli və az tullantılı sistemlərin tətbiqinin, zərərli emissiyaların azaldılmasının və ixtisaslaşdırılmış təmizləyici qurğuların yaradılmasının əhəmiyyətini göstərir. Abşeron yarımadasında, Bakı, Sumqayıt və digər istehsal ərazilərində sənaye və ekoloji şəraitə xüsusi diqqət yetirilmişdir. Təhlil göstərir ki, texnoloji modernləşmə və suyun təkrar istifadəsi sistemləri istehsalın səmərəliliyini artırmaqla yanaşı, resurs istehlakını və ətraf mühitə antropogen təzyiqi azalda bilər. Tədqiqatın nəticələrinə əsasən, səmərəli ekoloji restrukturizasiya texnoloji innovasiyaları, resurs səmərəliliyini, çirklənmənin qarşısının alınmasını, ekoloji investisiyaları, elmi əsaslandırılmış monitorinqi və ərazi planlaşdırılmasını birləşdirən kompleks idarəetmə sisteminin tətbiqini tələb edir.

Açar sözlər: *yaşıl istiqrazlar, dövlət–özəl tərəfdaşlığı, bərpa olunan enerjinin maliyyələşdirilməsi, dayanıqlığın gücləndirilməsi kanalları, investisiya riski*

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IMPROVING THE MANAGEMENT OF ECOLOGICAL MODERNIZATION OF PRODUCTION IN AZERBAIJAN: A TECHNICAL AND ECONOMIC APPROACH

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Keywords: *ecological restructuring of production, sustainable development, natural resource management, environmental investment, treatment facilities, Azerbaijan*

Summary. This study examines the technical and economic approaches to the effective management of ecological restructuring of production in the regions of Azerbaijan within the framework of sustainable regional development. The research applies an integrated economic-geographical approach and considers natural resource potential, production structures, environmental pressures, capital investment, technological modernization, and environmental monitoring. System-structural, mathematical-statistical, geographic information system (GIS), and monitoring-based methods are used to assess the relationship between production development and environmental protection. The results indicate that ecological restructuring requires the economical and comprehensive use of natural resources, modernization of production technologies, expansion of closed-cycle and low-waste systems, reduction of harmful emissions, and development of specialized treatment facilities. Particular attention is given to industrial and environmental conditions in the Absheron Peninsula, Baku, Sumgayit, and other production areas of Azerbaijan. The analysis demonstrates that technological modernization and water-reuse systems can reduce resource consumption and environmental pressure while supporting production efficiency. The study also emphasizes the importance of environmental investment and scientifically based monitoring for effective regional management. It concludes that ecological restructuring should integrate technological innovation, resource efficiency, pollution prevention, environmental investment, and territorial planning within a unified management framework.

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1. Introduction

The ecological restructuring of production has become an important component of sustainable regional development as economic growth increasingly depends on the efficient use of natural resources and the reduction of environmental pressures. In Azerbaijan, the interaction between industrial development, resource consumption, and environmental conditions requires an integrated economic and ecological approach to production management.

Existing studies have addressed different aspects of regional development and environmental management; however, the technical and economic mechanisms linking production restructuring with sustainable regional development remain insufficiently integrated. Ecological restructuring should therefore be considered not only as an environmental measure but also as a component of technological modernization, resource management, and territorial development.

Ecological restructuring of production reflects the interaction between social production and the natural environment and encompasses a broad range of economic and technological measures affecting industry, agriculture, and other sectors (Özal, 2019). Its implementation requires a systematic approach that combines the rational use and reproduction of natural resources, pollution prevention, technological improvement, and environmental protection.

Accordingly, this study aims to identify the principal technical and economic approaches to the effective management of ecological restructuring of production in Azerbaijan, with particular attention to resource efficiency, technological modernization, environmental monitoring, treatment infrastructure, and sustainable regional development.

2. Material and method

The study examines the territorial and structural characteristics of ecological restructuring of production in Azerbaijan and the technical and economic approaches to its effective management. The analysis considers regional differences in natural resource potential, production structures, capital investment, technological infrastructure, and environmental conditions. Particular attention is given to the relationship between economic development, resource use, and environmental pressures across industrial regions of the country (Mammadov, 2014).

The methodological framework combines system-structural, mathematical-statistical, geographic information system (GIS), and environmental monitoring methods. The assessment also considers factors influencing ecological restructuring, including natural resource potential, established production patterns, the initial level of economic development, and the territorial organization of production. These methods are used to identify regional differences, evaluate economic-environmental relationships, and determine the principal technical and economic directions of ecological restructuring within the framework of sustainable regional development.

3. Problem statement and research results.

The effective management of ecological restructuring should simultaneously address social demand for natural resources, improve the efficiency of resource use, support resource reproduction, and ensure the economical use of non-renewable resources. Scientific and technological progress has expanded the scale of production and intensified its interaction with the natural environment, increasing the importance of technological modernization and environmentally oriented resource management (Mammadov, 2016).

Ecological restructuring and the reproduction of natural resources are closely interconnected. Modern production systems therefore require not only efficient resource use but also measures aimed at preventing and mitigating environmental degradation. Environmental protection should be integrated into production management because ecological restructuring cannot be effectively implemented independently of measures designed to maintain environmental quality and ecological balance.

The Jeyranbatan Reservoir illustrates this relationship. As an important source of water supply for Baku and Sumgayit, its relatively limited self-purification capacity increases its vulnerability to industrial, agricultural, and domestic pollution. Consequently, the management of production activities affecting the reservoir must be closely linked to water protection and pollution-prevention measures.

Ecological restructuring also includes measures such as wastewater and air purification, land reclamation, and the elimination of major sources of water and air pollution. These measures are closely related to the regenerative functions of natural ecosystems. For example, forest ecosystems contribute to water conservation, carbon absorption, and oxygen production, demonstrating that environmental protection and resource reproduction should be considered complementary components of ecological restructuring (Bityukova, 2017).

Industrial development has substantially altered environmental conditions in several production areas of Azerbaijan. The Absheron Peninsula provides a notable example, where long-term oil production and related industrial activities have contributed to the accumulation of petroleum waste and pollutants in soils and groundwater. These conditions demonstrate the importance of integrating pollution prevention, environmental remediation, and ecological monitoring into the restructuring of industrial production.

Effective environmental management requires scientifically based monitoring capable of identifying changes in environmental conditions and supporting timely management decisions (Ivanova, 2021). Monitoring should combine sanitary-hygienic observations related to population health with geoecological assessment of changes occurring in natural and economic systems under anthropogenic pressure. Such an integrated approach provides an information basis for evaluating environmental risks and planning ecological restructuring measures.

Monitoring activities conducted in the oil- and gas-producing areas of the Absheron Peninsula have also contributed to the development of an electronic environmental database. The database contains spatial information on land contaminated by oil and other wastes, areas affected by formation waters, and the depth and location of contamination. The integration of these data with precise geographic coordinates can support the identification of environmentally vulnerable areas and improve the management of economic and environmental problems.

Environmental protection and production development should be considered as complementary rather than competing objectives. The modernization of production requires the systematic incorporation of ecological principles into technological and managerial decisions (Nuriyev, 2017). Accordingly, ecological restructuring should encompass all major components of the production system and should be closely linked to scientific and technological progress.

In Azerbaijan, one of the principal objectives of ecological restructuring is to combine economic development with technological modernization and more efficient use of natural resources. This process involves improving production technologies, reducing resource consumption and harmful emissions, and developing specialized treatment facilities (Mammadov, 2014). The interaction between scientific and technological progress and production is illustrated in Figure 1.

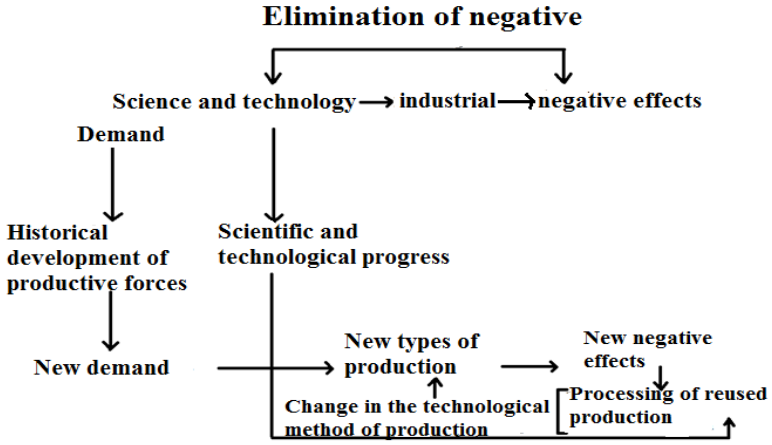


Fig. 1. Interaction between scientific and technological progress and production

The further development of ecological restructuring requires a transition from low-waste technologies to closed-cycle and, where technically feasible, waste-free production systems. Such systems promote the reuse of waste and by-products between enterprises, reduce demand for primary resources, and strengthen production linkages within territorial-industrial complexes (Mammadov, 2020). Previous industrial experience in Azerbaijan demonstrates the practical potential of this approach. For example, closed technological processes at the Sumgayit synthetic rubber plant enabled production waste to be used as a secondary resource in the manufacture of products such as sulfuric acid, alcohol, and styrene. Thus, in the former Soviet period, conditions were created in our country for the production of sulfuric acid, alcohol, and styrene from the waste of the Sumgait synthetic rubber plant in connection with the transition to a closed technological process, which ensured an additional annual increase in the efficiency of enterprises.

Analysis of the obtained data demonstrates that technological modernization has significantly reduced water consumption in industrial production. In the 1970s, the designed water consumption at Baku oil refineries reached 8 units per ton of product; by the mid-1980s, water demand had decreased approximately tenfold. Further ecological restructuring, including the expansion of water circulation and reuse systems, contributed to an additional reduction in water consumption. Closed-cycle water-use systems were also introduced at chemical enterprises in Sumgayit. As a result, water withdrawal from natural water bodies decreased by approximately 35–40%, while production increased by 25–30% (Mammadov, 2019).

These results indicate that ecological restructuring of production should be developed in two interrelated directions: (1) the rational and comprehensive use of natural resources, particularly mineral raw materials and water resources; and (2) the reduction or, where possible, elimination of negative environmental impacts associated with production processes.

Environmental investment is another important component of ecological restructuring. Although environmental protection measures do not always generate immediate economic returns, they contribute to the conservation of essential natural resources and the maintenance of environmental quality. With the development of modern production, the share of investment directed toward environmental protection has also increased internationally (Bityukova, 2017). In several industrial sectors of Western countries, environmental investment has accounted for approximately **20–25%** of total investment, particularly in metallurgy, the pulp and paper industry, oil refining, the chemical industry, and electric power generation.

In Azerbaijan, the share of environmental expenditure in capital investment and operating costs has also increased. According to the statistical data used in the study, environmental protection expenditure increased from 30.8 thousand manats in 1991 to 387 million manats in 2019 (Environment in Azerbaijan, 2020). Funds allocated to fixed capital for the efficient use of natural resources and environmental protection increased from 9.2 thousand manats in 1991 to approximately 350 million manats in recent years. Environmental expenditure has been particularly concentrated in the oil, energy, chemical, and petrochemical industries. Compared with the average expenditure across material-production sectors, the corresponding level was reported to be 2.8 times higher in the chemical and petroleum industries and 2.3 times higher in the power industry (*Regionların sosial-iqtisadi inkişafi*, 2016).

Environmental investment also varies among individual industrial sectors and production complexes. According to the estimates considered in the study, capital expenditure for environmental protection in the thermal and electric power sector amounted to 13.5 manats per 1,000 kV, while investment in water and air purification in the Ganja non-ferrous metallurgy complex accounted for approximately 6–8% of total capital expenditure. In several other processing industries, purification-related investment reached 20–25%.

One of the most important criteria for introducing new technology is its environmental performance compared with the technology previously used, particularly its ability to reduce harmful emissions per unit of production. However, the environmental efficiency of a new technological model should not be assessed independently of the regional or local conditions in which it is applied.

Accordingly, a comprehensive assessment of pollution is an important stage in evaluating both the environmental effectiveness of new equipment and the efficiency of environmental expenditure. Such an assessment makes it possible to evaluate the application of new equipment within regional territorial-production complexes over its projected service life. The expected volume of pollution associated with the introduction of new technology can be expressed as:

$$\mathbf{Q_{yt} \leq Q_{ck} \cdot X_{ts} \cdot P_{om}}$$

Here $\mathbf{Q_{yt}}$ −the expected volume of pollution when using a new technique; $\mathbf{Q_{ck}}$ - the mass of pollution resulting from the use of one technique or a single technological process per year; $\mathbf{X_{ts}}$ −the number of existing techniques used in the country's economy per year; $\mathbf{P_{om}}$- the predicted average service life of new techniques. In our country, when eliminating possible deterioration of the ecological situation of production, the following conditions should be expected. That is, when replacing an old technology with a new technology, the deterioration with the new technology should be smaller than the deterioration with the old technology $\mathbf{(Q_{new\ tec.} < Q_{old\ tec.})}$. In exceptional cases, the deterioration with the new technology may be equal to the deterioration with the old technology $\mathbf{(Q_{new\ tec.} = Q_{old\ tec.})}$.. If these requirements are not met, the existing models will need to be progressively improved.

Thus, one of the main goals of ecological restructuring of production is the creation of new technology. It should also be noted that the allocation of costs and their application is not an easy task. In this regard, it is proposed to either allocate a new model in the composition of a technological circle with a special ecological purpose, or to solve existing new models, taking a conditional share of the problem as a whole, corresponding to the urgency of ecological problems.

The determination of the absolute effectiveness of environmental protection measures, the application of ecologically reconstructed equipment and the disclosure of the sequence of capital invested in environmental protection in various sectors of the economy. All this leads to the necessity of including in economic calculations of losses or negative effective indicators, the results of economic activity.

4. Conclusion

The study demonstrates that the effective management of ecological restructuring of production in Azerbaijan requires an integrated economic and environmental approach based on the interaction between production systems and the natural environment. Such an approach should combine technological modernization, rational use of natural resources, environmental protection, and appropriate management mechanisms within regional development planning.

Ecological restructuring should not be considered an obstacle to economic development but rather an essential component of sustainable production. Its effective implementation requires the gradual introduction of environmentally efficient technologies and management systems that reduce resource consumption and negative environmental impacts while improving production efficiency. Therefore, economic and environmental considerations should be integrated into planning and investment decisions to ensure the rational use of natural resources, improve environmental quality, and support sustainable regional development in Azerbaijan.

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СОВЕРШЕНСТВОВАНИЕ УПРАВЛЕНИЯ ЭКОЛОГИЧЕСКОЙ МОДЕРНИЗАЦИЕЙ ПРОИЗВОДСТВА В АЗЕРБАЙДЖАНЕ: ТЕХНИКО-ЭКОНОМИЧЕСКИЙ ПОДХОД

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Резюме. В исследовании рассматриваются технические и экономические подходы к эффективному управлению экологической реконструкцией производства в регионах Азербайджана в рамках устойчивого регионального развития. В работе применяется комплексный экономико-географический подход и рассматриваются природно-ресурсный потенциал, производственные структуры, экологические нагрузки, капитальные вложения, технологическая модернизация и экологический мониторинг. Для оценки взаимосвязи между развитием производства и охраной окружающей среды используются системно-структурные, математико-статистические методы, географические информационные системы (ГИС) и методы, основанные на мониторинге. Результаты показывают, что экологическая реконструкция требует экономного и комплексного использования природных ресурсов, модернизации производственных технологий, расширения систем замкнутого цикла и малоотходного производства, сокращения вредных выбросов и создания специализированных очистных сооружений. Особое внимание уделяется промышленным и экологическим условиям на Апшеронском полуострове, в Баку, Сумгаите и других производственных районах Азербайджана. Анализ показывает, что технологическая модернизация и системы повторного использования воды могут снижать потребление ресурсов и экологическую нагрузку, одновременно способствуя повышению эффективности производства. В исследовании также подчёркивается значение экологических инвестиций и научно обоснованного мониторинга для эффективного регионального управления. Сделан вывод о том, что экологическая реконструкция должна объединять технологические инновации, эффективность использования ресурсов, предотвращение загрязнения, экологические инвестиции и территориальное планирование в рамках единой системы управления.

Ключевые слова: *экологическая реструктуризация производства, устойчивое развитие, управление природными ресурсами, экологические инвестиции, очистные сооружения, Азербайджан*

AZƏRBAYCANDA İSTEHSALIN EKOLOJİ MODERNLƏŞDİRİLMƏSİNİN İDARƏ EDİLMƏSİNİN TƏKMİLLƏŞDİRİLMƏSİ: TEXNİKİ-İQTİSADİ YANAŞMA

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Xülasə. Tədqiqatda dayanıqlı regional inkişaf çərçivəsində Azərbaycanın regionlarında istehsalın ekoloji yenidən qurulmasının səmərəli idarə edilməsinin texniki və iqtisadi istiqamətləri araşdırılır. Tədqiqatda kompleks iqtisadi-coğrafi yanaşma tətbiq edilir və təbii resurs potensialı, istehsal strukturları, ekoloji təzyiqlər, kapital qoyuluşları, texnoloji modernləşmə və ekoloji monitorinq nəzərdən keçirilir. İstehsalın inkişafı ilə ətraf mühitin mühafizəsi arasındakı əlaqənin qiymətləndirilməsi üçün sistem-struktur, riyazi-statistik, coğrafi informasiya sistemləri (CİS) və monitorinqə əsaslanan metodlardan istifadə edilir. Nəticələr göstərir ki, ekoloji yenidənqurma təbii resurslardan qənaətli və kompleks istifadəni, istehsal texnologiyalarının modernləşdirilməsini, qapalı dövriyyəli və az tullantılı sistemlərin genişləndirilməsini, zərərli emissiyaların azaldılmasını və ixtisaslaşdırılmış təmizləyici qurğuların yaradılmasını tələb edir. Abşeron yarımadasında, Bakı, Sumqayıt və Azərbaycanın digər istehsal ərazilərində sənaye və ekoloji şəraitə xüsusi diqqət yetirilir. Təhlil göstərir ki, texnoloji modernləşmə və suyun təkrar istifadəsi sistemləri istehsalın səmərəliliyini dəstəkləməklə yanaşı, resurs istehlakını və ətraf mühitə təzyiqi azalda bilər. Tədqiqatda, həmçinin səmərəli regional idarəetmə üçün ekoloji investisiyaların və elmi əsaslandırılmış monitorinqin əhəmiyyəti vurğulanır. Nəticə olaraq, ekoloji yenidənqurmanın texnoloji innovasiyaları, resurs səmərəliliyini, çirklənmənin qarşısının alınmasını, ekoloji investisiyaları və ərazi planlaşdırılmasını vahid idarəetmə çərçivəsində birləşdirməli olduğu müəyyən edilir.

Açar sözlər: *istehsalın ekoloji yenidən qurulması, davamlı inkişaf, təbii resursların idarə edilməsi, ekoloji investisiyalar, təmizləyici qurğular, Azərbaycan*

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THE IMPACT OF DIGITALIZATION AND ARTIFICIAL INTELLIGENCE ON HUMAN CAPITAL TAKING INTO ACCOUNT MODERN TECHNOLOGICAL TRENDS

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Summary. This study examines the impact of digitalization and artificial intelligence (AI) on organizational human capital and proposes an approach for assessing the effectiveness of its development. Based on a critical analysis of domestic and international research, human capital is considered through knowledge, skills, experience, motivation, and health, while its effectiveness is evaluated using productivity, innovation, employee satisfaction, and organizational adaptability. The study identifies digitalization and AI as major factors transforming employee competencies, labor-market requirements, work organization, and human capital management. Particular attention is given to automation, digital skills, flexible employment, staff training, and the changing role of employees in technology-intensive environments. An integrated assessment approach is proposed that incorporates weighted indicators and allows organizations to adapt their evaluation criteria to industry characteristics, organizational size, and strategic objectives. The study also proposes formulas for assessing human capital efficiency and its development over time, including the influence of risk factors. The findings emphasize the importance of continuous investment in employee competencies and organizational adaptability under ongoing digital transformation.

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Introduction

Human capital is generally understood as a combination of knowledge, skills, experience, and health that contributes to economic and organizational development. Schultz (1961) emphasized investment in human capital as an important factor in economic development, while Becker (1964) highlighted education and professional training as key determinants of human capital formation. These approaches established human capital as a strategic resource essential for long-term economic development.

Subsequent research expanded this concept by incorporating social and technological factors. Heckman (2011) emphasized the importance of human capital development, whereas Davenport (2018) highlighted the transformative role of artificial intelligence and digital technologies. Recent studies have also examined the relationship between human capital and organizational competitiveness (Brzaković et al., 2023), flexible working arrangements (Alqasa & Noor, 2022), organizational performance (Austin-Egole et al., 2022), and employee performance (Orishede & Ndudi, 2020).

Domestic research similarly considers human capital through knowledge, practical skills, and motivation (Bondarenko, 2006) and recognizes its importance for organizational competitiveness (Gromova, 2014). More recent studies emphasize the influence of digitalization, information technologies, and employee competencies on human capital development (Kondrashov et al., 2017; Malakhov & Smyslyaeva, 2022; Podverbnyh et al., 2024). Despite differences in emphasis, these approaches identify knowledge and skills as fundamental components of human capital. Accordingly, this study examines the influence of digitalization and artificial intelligence on organizational human capital and proposes an approach for evaluating the effectiveness of its development under modern technological conditions.

Results

Modern literature distinguishes different types of human capital according to alienability, individual or corporate characteristics, national affiliation, and the distinction between general and specific capital (Mineeva & Neganova, 2009; Salutova, n.d.). The continuing expansion of the concept also suggests the emergence of new interpretations and forms of human capital (Drozdov, 2013; Kapelyushnikov & Lukyanova, 2010).

In this study, an organization's human capital is defined as a set of employee characteristics—including knowledge, skills, practical experience, motivation, and health—used to achieve strategic goals and perform current organizational tasks. Its structure may include intellectual capital (knowledge, skills, and creativity), social capital (interaction and cooperation), emotional capital (motivation and loyalty), and physical capital (health and working capacity).

The practical application of the human capital concept requires its operationalization through measurable indicators. Its assessment should therefore consider the value, efficiency, and dynamics of its components. Depending on the objectives and available information, organizations may apply cost, income, or market approaches. The cost approach considers expenditures on recruitment, training, and professional development; the income approach evaluates the economic returns generated by human capital; and the market approach relies on comparisons with similar assets. Combining different approaches may provide a more comprehensive assessment, while regular evaluation is necessary because human capital changes over time.

The efficiency of an organization's human capital development can be understood as the relationship between the achievement of strategic objectives and the resources invested in developing and utilizing employee knowledge, skills, and experience. Its assessment may be based on four principal indicators: labor productivity, employee innovation, employee satisfaction, and organizational adaptability.

Effective human capital management contributes to organizational competitiveness and sustainable development. It requires continuous investment in employee development, favorable working conditions, effective interaction between management and staff, and opportunities to improve and apply professional competencies. Assessment should also consider qualification levels, work quality, staff turnover, and the return on investment (ROI) in employee training. In particular, a positive training ROI indicates that the financial benefits associated with staff development exceed the corresponding costs. These indicators collectively enable organizations to identify weaknesses and determine priorities for further human capital development.

To assess the effectiveness of an organization's human capital development, five main stages are proposed: (1) identifying its components; (2) estimating the cost of each component; (3) determining the total or weighted average cost of human capital; (4) identifying and analyzing existing problems; and (5) developing measures to optimize its structure.

Among the factors affecting human capital, digitalization and artificial intelligence (AI) have become increasingly important. Digitalization introduces technologies such as process automation, big data, and cloud computing, thereby increasing demand for digital literacy and analytical skills. AI further transforms the labor

market by automating routine tasks, supporting data analysis and process management, and creating new professional requirements.

These transformations are particularly evident in the financial, retail, transport and logistics, and industrial sectors. AI enables automation of data processing, risk analysis, and customer service in finance; personalization, demand forecasting, and supply-chain optimization in retail; and the development of intelligent management and autonomous technologies in transport and logistics.

In industry, digitalization and AI promote automation, robotics, and data-driven optimization, increasing demand for specialists in data analysis, machine learning, software development, and cybersecurity. Similar transformations are occurring in socially significant sectors, particularly healthcare and education, while routine and repetitive tasks are increasingly automated or redesigned.

In Russia, however, the effective adoption of digitalization and AI is constrained by three major challenges: digital inequality, a shortage of qualified specialists, and insufficient investment in human capital and technological development. Uneven access to digital infrastructure, particularly in rural, mountainous, and remote areas, limits the adoption of advanced technologies. At the same time, shortages of AI and IT specialists restrict innovation and technological competitiveness. Insufficient investment in research and development further limits the creation of domestic AI solutions and increases dependence on external technologies.

To realize the potential of digitalization and AI in Russia, coordinated measures are required to expand digital infrastructure, stimulate investment, support research and innovation, and strengthen the regulatory framework. Economic incentives, including targeted grants, subsidies, and tax measures, can encourage organizations to invest in digital technologies and AI solutions. At the same time, broader access to digital infrastructure and expanded education and professional training are essential for developing the required competencies.

The study identifies three principal effects of digitalization and AI on organizational human capital. First, technological transformation increases qualification requirements and demand for digital literacy, data analysis, adaptability, and non-routine problem-solving skills, requiring continuous employee training and retraining. Second, AI automates routine tasks and allows employees to focus on creative and strategic activities while supporting recruitment, performance assessment, and other human resource management processes. Third, digital technologies facilitate flexible and remote employment, expanding access to talent while increasing the importance of self-organization, communication, and time-management skills.

To assess the effectiveness of human capital in the time period t1, the following formula can be used:

$$\mathrm{EHCt1} = \frac{(\mathrm{PD}+\mathrm{IN}+\mathrm{ES})*\mathrm{OA}}{\mathrm{Ac}}, \quad (1)$$

where EHCt1 is the efficiency of the human capital of an organization in the time period t1; PD is productivity; IN is the set of innovations; ES is employee satisfaction; OA is the organization's adaptability to environmental conditions; Ac is aggregate cost.

To clarify the calculation, weights can be introduced into formula 1 depending on the significance of the indicator. In this case, formula 1 will be as follows:

$$\mathrm{EHCt1} = \frac{(\mathrm{W}_1 * \mathrm{PD} + \mathrm{W}_2 * \mathrm{IN} + \mathrm{W}_3 * \mathrm{ES}) * (\mathrm{W}_4 * \mathrm{OA})}{\mathrm{Ac}}, \quad (2)$$

where W1-W4 are the corresponding weights characterizing the significance of the components ($0<W<1$).

The need to consider weights for each component based on industry, size and strategic goals is critical. In this regard, it would be useful to develop a framework within which organizations could adjust the weighting factors according to their specific context. For example, a knowledge-intensive organization may place greater emphasis on innovation than a trading company focused on operational efficiency.

Each component of the formula requires detailed disclosure, including its essence, measures and methods for determining values.

For example, productivity reflects the ability of employees and the organization as a whole to achieve set goals with minimal time and resource costs. In the context of using digitalization and AI, productivity is related to the automation of routine processes, the use of AI to analyze data and optimize work processes.

Various indicators can serve as measuring instruments of productivity:

1. Output per employee of the organization (volume of products or services per unit of time).
2. Speed of task execution (time spent on performing specific operations).

3. Resource utilization factor (the ratio of actually used resources to planned ones).

Methods for determining productivity values may include: analysis of KPIs (key performance indicators) of employees, automated time tracking systems, comparison of indicators before and after the implementation of digital solutions, etc.

Innovation is an important component of the formula for determining the effectiveness of an organization's human capital development. Innovation is the ability of an organization to create and implement new ideas, technologies, products or processes that improve competitiveness and efficiency. In modern conditions, innovation is often connected with digitalization, the use of AI, and other advanced technologies.

The following indicators can be used to measure innovation:

1. The number of implemented innovative projects over a certain period.
2. The share of new products or services in total sales.
3. Investment level of R&D (research and development).

The following methods can be used to determine the values of these indicators: conducting internal audits of innovation activity, analyzing the company's patent activity, assessing the market share occupied by new products, and others.

Satisfaction is one of the difficult to define components of the formula for the effectiveness of an organization's human capital development.

Satisfaction reflects the level of employee satisfaction with working conditions, corporate culture, opportunities for professional growth and the implementation of digital technologies and AI. High satisfaction helps to reduce staff turnover and increase staff involvement in solving the organization's development problems.

A number of relevant indicators can be used to measure the level of satisfaction:

1. Employee satisfaction index.
2. Rate of employee turnover.
3. Results of employee surveys and questionnaires.

Methods for determining the values of these indicators include conducting regular employee surveys, analyzing feedback on employer platforms, and assessing engagement through monitoring systems.

To assess the effectiveness of human capital development in the time period t1 and t2, one can use the calculation according to the formula:

$$\mathrm{EDHC}(t1, t2) = \mathrm{EHC}(t2) - \mathrm{EHC}(t1) \tag{3}$$

where EDHC (t1, t2) is the efficiency of development (growth) of human capital for periods of time t1 and t2; EHC(t1) and EHC(t2) are the efficiency of the organization's human capital in periods of time t1 and t2, respectively.

Formula 3, considering the heterogeneity of the risk impact at the stages of human capital development, can also be modified to the following form:

$$\begin{aligned}\mathrm{EDHC}(t1, t2, t3) = [\mathrm{EHC}(t2) - \mathrm{EHC}(t1) * \mathrm{R}(t2, t1)] - \\ -[\mathrm{EHC}(t3) - \mathrm{EHC}(t2) * \mathrm{R}(t3, t2)]\end{aligned} \tag{4}$$

where EDHC(t1,t2,t3) is the efficiency of development of human capital for periods 1, 2 and 3; R(t1,t2) is the share of the result accounting losses due to the influence of risk in the period from 1 to 2 (0<R>1); R(t2,t3) is the share of the result considering losses caused by the influence of risk in the period from 2 to 3 (0<R>1).

Calculations according to formulas 1 and 4 allow us to obtain general assessments of the effectiveness of an organization's human capital for the compared periods of time and determine its trends. In addition, it is possible to identify and analyze the impact of individual components of an organization's human capital to optimize them.

If necessary, formulas can be contextualized, for example, by expanding the number of indicators used in them (organizational culture, cooperation, etc.)

It should be considered the possibility of the discussion how the weighting of each component in formulas 1 and 2 (productivity, innovation, or employee satisfaction) may vary depending on the industry, size of the organization, or specific strategic goals. This will allow for a more accurate interpretation and detailed disclosure of the influence of factors on the effectiveness of human capital, which will contribute to the development of correct conclusions and sound management decisions.

Conclusion

1. The human capital of the organization is the most important characteristic of the state of the staff involved in the implementation of strategic goals and solving current tasks of the activity.

2. Digitalization and AI have a significant impact on human capital development, changing skill requirements and transforming the labor market.

3. To improve the efficiency of human capital development, organizations need to implement modern technologies, invest in employee training and adaptability to changing conditions.

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ВЛИЯНИЕ ЦИФРОВИЗАЦИИ И ИСКУССТВЕННОГО ИНТЕЛЛЕКТА НА РАЗВИТИЕ ЧЕЛОВЕЧЕСКОГО КАПИТАЛА С УЧЁТОМ СОВРЕМЕННЫХ ТЕХНОЛОГИЧЕСКИХ ТЕНДЕНЦИЙ

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Резюме. В исследовании рассматривается влияние цифровизации и искусственного интеллекта (ИИ) на человеческий капитал организаций и предлагается подход к оценке эффективности его развития. На основе критического анализа отечественных и зарубежных исследований человеческий капитал рассматривается через знания, навыки, опыт, мотивацию и здоровье, а его эффективность оценивается с использованием показателей производительности, инновационной деятельности, удовлетворённости сотрудников и организационной адаптивности. В исследовании цифровизация и искусственный интеллект определяются как основные факторы, трансформирующие компетенции работников, требования рынка труда, организацию труда и управление человеческим капиталом. Особое внимание уделяется автоматизации, цифровым навыкам, гибкой занятости, обучению персонала и изменяющейся роли работников в технологически интенсивной среде. Предлагается комплексный подход к оценке, включающий взвешенные показатели и позволяющий организациям адаптировать критерии оценки к отраслевым особенностям, размеру организации и стратегическим целям. В исследовании также предлагаются формулы для оценки эффективности человеческого капитала и динамики его развития с течением времени, включая влияние факторов риска. Полученные результаты подчёркивают важность непрерывных инвестиций в компетенции сотрудников и организационную адаптивность в условиях продолжающейся цифровой трансформации.

Ключевые слова: *человеческий капитал, цифровизация, искусственный интеллект, эффективность, компетенции, рынок труда*

MÜASİR TEXNOLOJİ MEYİLLƏR NƏZƏRƏ ALINMAQLA RƏQƏMSALLAŞMANIN VƏ SÜNİ İNTELLEKTİN İNSAN KAPİTALINA TƏSİRİ

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Xülasə. Tədqiqatda rəqəmsallaşmanın və süni intellektin (Sİ) təşkilatların insan kapitalına təsiri araşdırılır və onun inkişafının səmərəliliyinin qiymətləndirilməsi üçün yanaşma təklif olunur. Yerli və beynəlxalq tədqiqatların tənqidi təhlili əsasında insan kapitalı

bilik, bacarıq, təcrübə, motivasiya və sağlamlıq baxımından nəzərdən keçirilir, onun səmərəliliyi isə məhsuldarlıq, innovasiya, işçilərin məmnunluğu və təşkilati adaptasiya qabiliyyəti göstəriciləri əsasında qiymətləndirilir. Tədqiqatda rəqəmsallaşma və süni intellekt işçilərin kompetensiyalarını, əmək bazarının tələblərini, əməyin təşkilini və insan kapitalının idarə edilməsini dəyişdirən əsas amillər kimi müəyyən edilir. Avtomatlaşdırmaya, rəqəmsal bacarıqlara, çevik məşğulluğa, kadr hazırlığına və texnologiya tutumlu mühitdə işçilərin dəyişən roluna xüsusi diqqət yetirilir. Çəkili göstəriciləri özündə birləşdirən və təşkilatlara qiymətləndirmə meyarlarını sahə xüsusiyyətlərinə, təşkilatın ölçüsünə və strateji məqsədlərinə uyğunlaşdırmağa imkan verən kompleks qiymətləndirmə yanaşması təklif olunur. Tədqiqatda, həmçinin risk amillərinin təsiri nəzərə alınmaqla insan kapitalının səmərəliliyinin və onun zaman üzrə inkişafının qiymətləndirilməsi üçün düsturlar təklif edilir. Əldə edilən nəticələr davam edən rəqəmsal transformasiya şəraitində işçilərin kompetensiyalarına və təşkilati adaptasiya qabiliyyətinə davamlı investisiya qoyuluşunun əhəmiyyətini vurğulayır.

Açar sözlər: *insan kapitalı, rəqəmsallaşma, süni intellekt, səmərəlilik, səriştələr, əmək bazarı*

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ECOLOGICAL TRANSFORMATION OF AZERBAIJAN'S REGIONS: A LINGUISTIC ANALYSIS OF STATE STRATEGIES AND PROGRAMS

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Summary. Climate-policy documents do more than report environmental conditions: they select problems, assign responsibility, and construct preferred futures. This study examines how green transition and regional resilience are linguistically framed in three English-language documents central to Azerbaijan's climate-development agenda: the Updated Nationally Determined Contribution (NDC 2.0, 2023), Azerbaijan's NDC 3.0 (2025), and the World Bank Country Climate and Development Report (CCDR, 2023). A corpus-assisted ecolinguistic design was applied to a 70,440-token corpus. Four lexical frames - risk and vulnerability, adaptation and resilience, green transition, and participation and inclusion - were measured through normalized frequency per 10,000 tokens. Three modality categories - obligation and necessity, commitment and futurity, and possibility and capacity - were also examined. The distribution of frame tokens was tested using chi-square and Cramér's V. Green-transition vocabulary dominated all documents, but its salience increased from 92.40 in NDC 2.0 to 182.33 in NDC 3.0. The CCDR foregrounded risk and vulnerability (76.36) and adaptation and resilience (44.66), whereas NDC 3.0 recorded the strongest participation and inclusion score (60.91) and the highest commitment and futurity score (155.18). Frame distributions differed significantly, chi-square = 143.23, df = 6, $p < .001$; $V = .186$. The findings indicate a shift in national discourse toward integrated decarbonization, implementation commitments, and inclusive governance, while the international diagnostic genre emphasizes exposure, uncertainty, and enabling capacity. The study recommends clearer, more participatory, and locally meaningful climate communication.

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1. Introduction

Climate change is simultaneously a physical process, a policy challenge, and a communicative problem. Scientific assessments and policy documents do not merely transmit neutral information; through lexical selection, grammatical agency, modality, and narrative structure, they define what counts as a problem, who is expected to act, and which futures appear desirable or unavoidable. Framing theory describes this selective organization of reality as the foregrounding of particular problem definitions, causes, evaluations, and remedies (Entman, 1993). Ecolinguistics extends this concern by asking whether recurring linguistic patterns support or weaken ecologically sustainable relations among people, institutions, and the living world (Alexander & Stibbe, 2014; Fill & Penz, 2018; Stibbe, 2021). Recent climate assessments likewise underline the need to connect mitigation, adaptation, development, and social resilience within coherent policy narratives (Intergovernmental Panel on Climate Change [IPCC], 2023).

Climate discourse is especially sensitive to framing because it must connect abstract time scales and technical evidence with everyday decisions. Terms such as risk, resilience, transition, and green growth are not

interchangeable labels; they activate different assumptions about urgency, responsibility, uncertainty, and social participation. Research on climate communication has therefore examined metaphors, narratives, voices, and modal expressions that shape public and institutional understandings (Fløttum & Gjerstad, 2017; Nerlich et al., 2010). A risk-centered text can strengthen preparedness but may also construct communities primarily as vulnerable recipients. A transition-centered text can mobilize investment while obscuring distributional consequences when citizens and local actors remain linguistically backgrounded.

Corpus-assisted discourse analysis provides a useful bridge between close reading and reproducible quantitative evidence. Frequency patterns identify recurrent lexical priorities, while qualitative interpretation connects those patterns to institutional purpose and genre. Baker et al. (2008) show that corpus methods can test whether intuitively identified discourses are systematic across a text collection, and Mautner (2009) emphasizes their value for critical discourse research. For environmental policy, this combination is useful because official reports are long, highly structured, and lexically repetitive; normalized counts permit comparison without assuming that documents of different lengths have identical communicative functions.

Azerbaijan offers a relevant case because its climate agenda must address both exposure to climatic hazards and an economic transition shaped by the energy sector. The Updated Nationally Determined Contribution issued in 2023 established a renewed national commitment framework, while NDC 3.0 expanded sectoral pathways, implementation language, and social dimensions in 2025 (Republic of Azerbaijan, 2023, 2025). The World Bank's Country Climate and Development Report (CCDR) approached the same national context through a diagnostic development lens, linking climate shocks, decarbonization, and economic resilience (World Bank, 2023). These documents are influential, yet their linguistic differences have received little systematic attention.

This study addresses that gap through three questions: (1) Which environmental and social frames are most salient in the three documents? (2) How do obligation, commitment, and possibility differ across national pledge and international diagnostic genres? (3) What does the comparison reveal about the evolution of Azerbaijan's climate-policy discourse between NDC 2.0 and NDC 3.0? The objective is not to evaluate the technical adequacy of the policies, but to identify the linguistic architecture through which transition, risk, resilience, and participation are made prominent.

2. Materials and methods

The study used a small, purpose-built English-language policy corpus consisting of three publicly available documents. The corpus was selected to support both a diachronic comparison of national commitments and an institutional comparison between national and international policy genres. Table 1 summarizes the dataset. The final analytical corpus contained 70,440 alphabetic tokens after preprocessing.

Table 1

Composition and analytical role of the policy corpus

Document	Institutional genre	Year	Tokens	Analytical role
NDC 2.0	National climate pledge/update	2023	6,818	Baseline for diachronic national comparison
NDC 3.0	Expanded national climate commitment	2025	25,777	Current national framing and implementation discourse
World Bank CCDR	International diagnostic report	2023	37,845	Institutional and genre comparison

Source: Author's corpus compiled from the official English-language documents

PDF text was extracted from the official English versions. Soft hyphens and common ligatures were normalized; repeated page headers, disclosure notices, and document-title strings were removed; all text was converted to lowercase; and alphabetic tokens were identified, with hyphenated compounds retained as single units. Numbers were excluded because the study focused on lexical framing rather than numerical target analysis. Tables and headings remained in the corpus when they contained meaningful lexical material because they form part of each document's communicative design. A reproducible scripted workflow was used for tokenization, dictionary matching, normalization, and statistical calculation.

Four semantic frames were operationalized through transparent dictionaries developed from ecolinguistic literature and iterative corpus inspection. The risk and vulnerability frame included risk, vulnerability, hazard,

exposure, loss, damage, and shock. The adaptation and resilience frame included adaptation, resilience, resilient, preparedness, and recovery. The green-transition frame included transition, decarbonization, renewable, low-carbon, green, clean, net-zero, mitigation, efficiency, and electrification. The participation and inclusion frame included community, stakeholder, participation, citizen, public, local, women, youth, inclusive, equity, and justice. Inflectional variants were counted separately and aggregated within each frame.

Because the documents differ considerably in length, frame salience was expressed as normalized frequency per 10,000 tokens. In Equation (1), f_td is the frequency of term or category t in document d, and N_d is the total number of tokens in that document.

$$\mathrm{NF_{td}} = \frac{\mathrm{f_{td}}}{\mathrm{N_d}} \times 10{,}000 \tag{1}$$

Modality was analyzed through three functional categories. Obligation and necessity included must, should, need, required, and necessary. Commitment and futurity included will, shall, aim, commitment, target, and plan. Possibility and capacity included can, could, may, potential, opportunity, enable, and capacity. These categories indicate whether a document primarily directs action, pledges future action, or constructs pathways as feasible and conditional. They are lexical indicators rather than complete grammatical annotations; for example, the analysis does not distinguish every epistemic and deontic use of may or should.

A 3 × 4 chi-square test compared the distribution of raw lexical-frame tokens across the three documents. Equation (2) summarizes the test, where O_{ij} and E_{ij} are observed and expected counts. Cramér's V, shown in Equation (3), was used as an effect-size measure. Because dictionary counts can include polysemous words such as public and green, the results were interpreted as document-level indicators of discursive salience rather than exhaustive semantic classifications.

$$\chi^2 = \Sigma \frac{(\mathrm{O_{ij}} - \mathrm{E_{ij}})^2}{\mathrm{E_{ij}}} \tag{2}$$

$$\mathrm{V} = \sqrt{\frac{\chi^2}{\mathrm{N} \times \min(\mathrm{r}-1, \mathrm{c}-1)}} \tag{3}$$

3. Results

Table 2 shows that green-transition vocabulary was the dominant frame in every document. Its normalized frequency nearly doubled between NDC 2.0 and NDC 3.0, increasing from 92.40 to 182.33 occurrences per 10,000 tokens. The increase was associated with expanded use of decarbonization, efficiency, renewable, mitigation, transition, and electrification. The CCDR also displayed strong transition salience (165.94), while risk and adaptation language accounted for a larger share of its frame profile.

Table 2

Normalized lexical-frame frequencies per 10,000 tokens

Document	Risk and vulnerability	Adaptation and resilience	Green transition	Participation and inclusion
NDC 2.0 (2023)	13.20	13.20	92.40	32.27
NDC 3.0 (2025)	19.40	27.93	182.33	60.91
World Bank CCDR (2023)	76.36	44.66	165.94	32.77

Source: Author's calculations. Values are occurrences per 10,000 alphabetic tokens

The World Bank report recorded 76.36 risk-and-vulnerability items per 10,000 tokens, compared with 19.40 in NDC 3.0 and 13.20 in NDC 2.0. It also had the highest adaptation-and-resilience score (44.66). NDC 3.0 differed from NDC 2.0 in two additional respects: its adaptation score more than doubled, and its participation-and-inclusion score rose from 32.27 to 60.91.

The distribution of lexical frames differed significantly across the three documents, $\chi^2(6) = 143.23$, $p < .001$, with a modest Cramér's V of .186. Standardized residuals indicated that the CCDR contained more risk vocabulary than expected, whereas NDC 3.0 contained more green-transition and participation vocabulary than expected. The statistical association does not establish causal influence.

Modality patterns in Table 3 further distinguished the texts. NDC 3.0 had the highest commitment-and-futurity frequency (155.18), reflecting extensive use of will, targets, plans, aims, and commitments. Its commitment-to-possibility ratio was 3.17, compared with 1.85 in NDC 2.0 and 0.94 in the CCDR. The international report recorded the highest possibility-and-capacity frequency (75.84), including can, could, potential, opportunity, and capacity. Obligation-and-necessity frequencies were comparatively moderate in all three documents.

Table 3

Modality frequencies and discursive-orientation ratios

Document	Obligation	Pledge	Possibility	P:R	C:P
NDC 2.0 (2023)	36.67	92.40	49.87	2.44	1.85
NDC 3.0 (2025)	27.93	155.18	48.88	3.14	3.17
World Bank CCDR (2023)	38.05	71.34	75.84	0.43	0.94

Note. Frequencies are per 10,000 tokens. Obligation = obligation/necessity; Pledge = commitment/futurity; Possibility = possibility/capacity; P:R = participation-to-risk ratio; C:P = commitment-to-possibility ratio.

Figure 1 combines the participation-to-risk and commitment-to-possibility ratios. NDC 3.0 occupies the upper-right position because participation language exceeds risk language by a factor of 3.14 and commitment language exceeds possibility language by a factor of 3.17. NDC 2.0 shows a similar but less pronounced pledge orientation. The CCDR appears in the lower-left area, with a participation-to-risk ratio of 0.43 and a commitment-to-possibility ratio below one. The visualization summarizes contrasting communicative orientations and does not rank document quality.

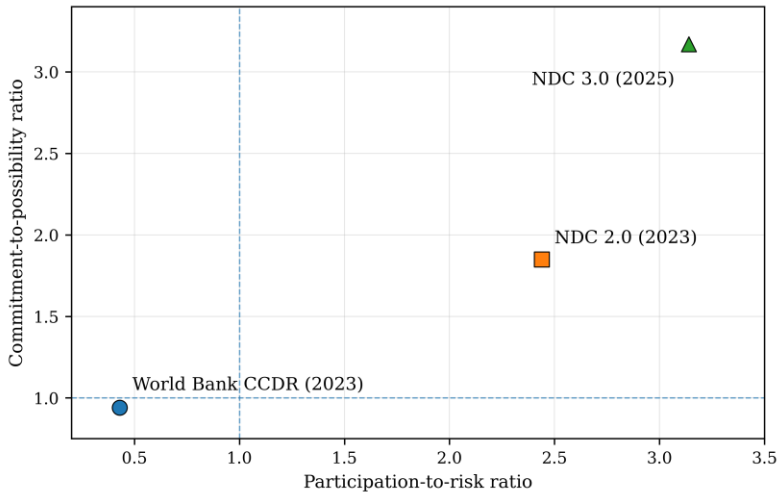


Fig. 1. Discursive orientation of the analyzed documents
Source: Author's calculations based on the normalized lexical frequencies

4. Discussion

The results demonstrate that a shared topic does not produce a single climate-policy discourse. All three documents privilege green-transition vocabulary, yet they organize it around different institutional purposes. The NDCs function as sovereign commitment documents, so their language presents targets, planned measures, and future implementation as nationally owned. The CCDR functions as an external diagnostic and investment-oriented assessment, so it foregrounds vulnerability, trade-offs, uncertainty, and the capacity required to manage change. This genre contrast helps explain why the CCDR uses more risk and possibility language, whereas NDC 3.0 uses more commitment language.

The diachronic difference between the national documents is particularly important. NDC 2.0 already emphasized renewable energy and green development, but NDC 3.0 develops a more integrated decarbonization vocabulary and gives greater lexical space to resilience, stakeholders, youth, communities, and inclusion. From an ecolinguistic perspective, this shift is constructive because it broadens the imagined community of climate action. Environmental policy is represented not only as a technical process of emissions reduction but

also as a social process involving institutions and groups. This pattern is consistent with the view that climate narratives become more actionable when they identify agents and pathways rather than presenting change as an abstract condition (Fløttum & Gjerstad, 2017).

Lexical inclusion, however, does not automatically equal substantive agency. Words such as public and local may refer to public finance, public transport, or local infrastructure rather than to citizens acting as decision-makers. Likewise, frequent nouns such as transition, decarbonization, and implementation can nominalize processes and conceal who performs them. A fuller grammatical analysis would determine whether communities appear as active subjects, affected objects, or beneficiaries. Stibbe's (2021) concept of the 'stories we live by' is relevant here: a policy may mention people frequently while still constructing expertise, investment, and technology as the principal agents of change.

The modality findings also have practical significance. The high commitment ratio in NDC 3.0 can strengthen accountability by making intended action visible. Yet repeated will-statements may sound formulaic unless they are accompanied by clearly named institutions, timelines, and verification mechanisms. Conversely, the CCDR's possibility-oriented language can encourage flexible planning, but excessive reliance on can, could, and potential may weaken perceived urgency. Effective climate communication should connect three linguistic moves: define the risk in locally intelligible terms, identify the responsible actor, and specify the feasible action. This risk-actor-action sequence can reduce both alarmism and vague optimism.

For bilingual and multilingual communication in Azerbaijan, terminology management is also essential. English expressions such as resilience, just transition, climate-proofing, and adaptive capacity do not always have a single, widely stabilized Azerbaijani equivalent. Parallel glossaries should preserve technical precision while avoiding literal translations that are inaccessible to non-specialists. Executive summaries can use short sentences, active voice, and concrete actor labels such as municipalities, energy regulators, farmers, schools, and neighborhood organizations. Consultation materials should distinguish information provision from actual participation by using verbs that show what stakeholders can decide, co-design, monitor, or evaluate.

The study has several limitations. It examines only three English-language documents and uses dictionary-based counts. Document length, genre, and production processes differ, and some lexical items are polysemous. The statistical test evaluates the distribution of selected frame words rather than the entire discourse. Metaphor, negation, syntactic agency, visual framing, and Azerbaijani-language versions were outside the present scope. Future research should build a parallel Azerbaijani-English corpus, use concordance coding and dependency parsing, and compare policy texts with media coverage, municipal documents, and stakeholder interviews. These extensions would show whether inclusive vocabulary is reproduced consistently across levels of governance.

5. Conclusion

This corpus-assisted ecolinguistic study identified clear differences in the framing of Azerbaijan's climate-development agenda. Green-transition vocabulary dominated the three documents, but NDC 3.0 displayed the strongest integration of decarbonization, commitment, and participation language. The World Bank CCDR foregrounded risks, exposure, adaptation, and enabling capacity, reflecting its diagnostic and scenario-oriented function. NDC 2.0 occupied an earlier, more compact pledge profile, while NDC 3.0 constructed a broader future of sectoral transformation and inclusive implementation.

The research questions are answered in three ways. First, transition is the shared master frame, but risk and adaptation are much more salient in the international report. Second, national commitment discourse relies heavily on futurity, whereas the CCDR gives more space to possibility and capacity. Third, the movement from NDC 2.0 to NDC 3.0 suggests a discursive expansion from target-centered green development toward a more integrated narrative of decarbonization, resilience, and stakeholder involvement.

For policy communication, technical ambition should be accompanied by explicit social agency. Documents should name responsible actors, connect risks to concrete actions, stabilize bilingual terminology, and clarify how communities participate in implementation and monitoring. Such language can support regional resilience by making climate policy not only technically credible but also understandable, accountable, and socially shared.

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ЭКОЛОГИЧЕСКАЯ ТРАНСФОРМАЦИЯ РЕГИОНОВ АЗЕРБАЙДЖАНА: ЛИНГВИСТИЧЕСКИЙ АНАЛИЗ ГОСУДАРСТВЕННЫХ СТРАТЕГИЙ И ПРОГРАММ

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Резюме. Документы климатической политики не только отражают состояние окружающей среды, но и определяют круг проблем, распределяют ответственность и формируют предпочтительные представления о будущем. В исследовании рассматривается, каким образом зелёный переход и региональная устойчивость получают лингвистическое фреймирование в трёх англоязычных документах, занимающих центральное место в климатической повестке и повестке развития Азербайджана: Обновлённом национально определяемом вкладе (NDC 2.0, 2023), документе Азербайджана NDC 3.0 (2025) и Докладе Всемирного банка о климате и развитии страны (CCDR, 2023). К корпусу объёмом 70 440 токенов применён корпусно-ориентированный эколингвистический подход. Четыре лексических фрейма — риск и уязвимость, адаптация и устойчивость, зелёный переход, участие и инклюзивность — оценивались на основе нормализованной частоты употребления на 10 000 токенов. Также были исследованы три категории модальности: обязательство и необходимость, принятие обязательств и ориентация на будущее, возможность и потенциал. Распределение токенов по фреймам проверялось с использованием критерия хи-квадрат и коэффициента V Крамера. Лексика зелёного перехода преобладала во всех документах, однако её выраженность увеличилась с 92,40 в NDC 2.0 до 182,33 в NDC 3.0. В документе CCDR на первый план выдвигались риск и уязвимость (76,36), а также адаптация и устойчивость (44,66), тогда как в NDC 3.0 зафиксированы наиболее высокие показатели участия и инклюзивности (60,91), а также принятия обязательств и ориентации на будущее (155,18). Распределения фреймов статистически значимо различались ($\chi^2 = 143{,}23$; число степеней свободы = 6; $p < 0{,}001$; $V = 0{,}186$). Полученные результаты указывают на смещение национального дискурса в сторону комплексной декарбонизации, обязательств по реализации намеченных мер и инклюзивного управления, тогда как международный диагностический жанр акцентирует внимание на подверженности рискам, неопределённости и формировании необходимых возможностей. В исследовании рекомендуется более ясная, основанная на широком участии и учитывающая местный контекст коммуникация по вопросам изменения климата.

Ключевые слова: *климатическая коммуникация, институциональная модальность, лексическая значимость, включение заинтересованных сторон, устойчивое развитие*

AZƏRBAYCAN REGİONLARININ EKOLOJİ TRANSFORMASİYASI: DÖVLƏT STRATEGİYALARI VƏ PROQRAMLARININ LİNQVİSTİK TƏHLİLİ

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Xülasə. İqlim siyasətinə dair sənədlər yalnız ətraf mühitin vəziyyəti haqqında məlumat verməklə kifayətlənmir, həm də problemləri seçir, məsuliyyəti müəyyənləşdirir və üstünlük verilən gələcək inkişaf istiqamətlərini formalaşdırır. Tədqiqatda Azərbaycanın iqlim və inkişaf gündəliyində mühüm yer tutan üç ingilisdilli sənəddə yaşıl keçid və regional dayanıqlığın linqvistik baxımdan necə çərçivələndirildiyi araşdırılır: Yenilənmiş Milli Səviyyədə Müəyyən Edilmiş Töhfə (NDC 2.0, 2023), Azərbaycanın NDC 3.0 sənədi (2025) və Dünya Bankının Ölkə üzrə İqlim və İnkişaf Hesabatı (CCDR, 2023). 70 440 tokendən ibarət korpusa korpus əsaslı ekolinqvistik yanaşma tətbiq edilmişdir. Dörd leksik çərçivə – risk və həssaslıq, adaptasiya və dayanıqlıq, yaşıl keçid, iştirak və inklüzivlik – hər 10 000 tokenə düşən normallaşdırılmış tezlik əsasında ölçülmüşdür. Həmçinin üç modallıq kateqoriyası – öhdəlik və zərurət, öhdəlik götürmə və gələcəyə yönəlmə, imkan və potensial – araşdırılmışdır. Çərçivələrə aid tokenlərin paylanması xi-kvadrat testi və Kramerin V əmsalı vasitəsilə yoxlanılmışdır. Yaşıl keçidlə bağlı leksika bütün sənədlərdə üstünlük təşkil etmiş, lakin onun ifadəlilik səviyyəsi NDC 2.0 sənədindəki 92,40 göstəricisindən NDC 3.0 sənədində 182,33-ə yüksəlmişdir. CCDR sənədində risk və həssaslıq (76,36), eləcə də adaptasiya və dayanıqlıq (44,66) ön plana çıxmış, NDC 3.0 sənədində isə iştirak və inklüzivlik (60,91), həmçinin öhdəlik götürmə və gələcəyə yönəlmə (155,18) üzrə ən yüksək göstəricilər qeydə alınmışdır. Çərçivələrin paylanması arasında statistik baxımdan əhəmiyyətli fərqlər müəyyən edilmişdir ($\chi^2 = 143,23$; sərbəstlik dərəcəsi = 6; $p < 0,001$; $V = 0,186$). Nəticələr milli diskursda inteqrasiya olunmuş dekarbonizasiyaya, icra öhdəliklərinə və inklüziv idarəetməyə doğru keçidin baş verdiyini, beynəlxalq diaqnostik sənəd janrında isə risklərə məruz qalma, qeyri-müəyyənlik və imkanların yaradılmasına xüsusi diqqət yetirildiyini göstərir. Tədqiqatda iqlim məsələləri üzrə daha aydın, iştirakçılığa əsaslanan və yerli şərait baxımından mənalı kommunikasiyanın qurulması tövsiyə olunur.

Açar sözlər: *iqlim kommunikasiyası, institusional modallıq, leksik önəçıxma, maraqlı tərəflərin prosesə cəlb edilməsi, dayanıqlı inkişaf*

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PROMOTING ENVIRONMENTAL CITIZENSHIP FOR REGIONAL SUSTAINABLE DEVELOPMENT

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Keywords: *sustainable production practices, digital environmental transparency, corporate environmental responsibility, environmental citizenship behavior, regional sustainable development*

Summary. As environmental sustainability and regional development become increasingly interconnected, understanding the organizational factors that promote environmentally responsible behavior has become an important research priority. This study aims to examine the effects of sustainable production practices and digital environmental transparency on environmental citizenship behavior while investigating the moderating role of corporate environmental responsibility. Using survey data collected from 425 respondents involved in the production and consumption of environmentally sustainable products across Azerbaijan, Structural Equation Modeling was employed to test the proposed relationships. The results indicate that both sustainable production practices and digital environmental transparency have significant positive effects on environmental citizenship behavior. The findings further reveal that corporate environmental responsibility positively moderates the relationship between digital environmental transparency and environmental citizenship behavior, suggesting that transparent environmental communication is more effective when supported by genuine environmental responsibility. The study contributes to the sustainability literature by demonstrating that environmentally responsible production, transparent environmental disclosure, and corporate environmental responsibility jointly promote environmental citizenship behavior and support regional sustainable development. These findings provide practical implications for policymakers and business managers seeking to strengthen environmental governance, encourage stakeholder participation, and foster long-term regional sustainability through more effective corporate sustainability strategies and collaborative environmental initiatives across sectors.

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Introduction

Environmental sustainability has become a global priority in response to climate change, environmental degradation, and the growing demand for sustainable regional development. Organizations are increasingly adopting sustainable production practices, improving environmental transparency through digital technologies, and strengthening corporate environmental responsibility to support sustainable development objectives. These initiatives are recognized not only as environmental management tools but also as strategic approaches that encourage environmentally responsible behavior among employees and stakeholders (Aguinis & Glavas, 2012; Lyon, & Montgomery, 2015; Zeynalova, 2019; Yusubov, 2024).

Environmental citizenship behavior (ECB) refers to voluntary environmental actions that contribute to environmental protection beyond formal organizational responsibilities (Boiral & Paillé, 2012). In this context, sustainable production practices and digital environmental transparency can promote ECB by increasing environmental awareness, stakeholder trust, and participation in sustainability initiatives. This issue is particularly important for regions pursuing sustainable development through responsible production systems, transparent environmental governance, and stronger collaboration between organizations and society (Paillé et al., 2013; Schnackenberg & Tomlinson, 2016).

Despite the growing body of research on environmental management and corporate sustainability, important research gaps remain. Existing studies have primarily examined sustainable production, environmental disclosure, and corporate social responsibility independently (Rosati & Faria, 2019; Rupp et al., 2016), while

limited attention has been given to environmental citizenship behavior and the moderating role of corporate environmental responsibility in the relationship between digital environmental transparency and environmental citizenship behavior.

Therefore, this study aims to examine the effects of sustainable production practices and digital environmental transparency on environmental citizenship behavior and investigate the moderating role of corporate environmental responsibility. The proposed framework contributes to explaining how responsible production, transparent environmental communication, and corporate environmental responsibility jointly promote environmental citizenship and support regional sustainable development.

2. Literature review and hypotheses development

2.1. Sustainable production practices and environmental citizenship behavior

Sustainable production practices (SPP) have become a fundamental component of corporate sustainability strategies, enabling organizations to reduce environmental impacts through efficient resource utilization, waste minimization, pollution prevention, and environmentally responsible production processes. Beyond improving environmental performance, these practices contribute to developing an organizational culture that encourages employees and stakeholders to engage in voluntary environmental activities (Fianko et al., 2021). As regions increasingly pursue sustainable development, environmentally responsible production systems are expected to promote environmental awareness and environmentally responsible behavior.

Environmental citizenship behavior (ECB) refers to voluntary actions that individuals undertake to support environmental protection beyond their formal job responsibilities (Zheng, 2025). Such behaviors include resource conservation, recycling, participation in environmental initiatives, and encouraging sustainable practices within organizations. Previous studies suggest that organizations implementing environmental management and sustainable production practices create favorable conditions for strengthening employees' environmental commitment and citizenship behavior (Daily et al., 2009). Similarly, Bissing-Olson et al. (2013) demonstrate that positive workplace conditions and pro-environmental attitudes significantly encourage employees' environmental behavior.

Although previous research has extensively examined the relationship between environmental management practices and organizational environmental performance, relatively limited attention has been given to the direct contribution of sustainable production practices to environmental citizenship behavior within the context of regional sustainable development. Sustainable production not only improves operational sustainability but also encourages environmentally responsible behavior that contributes to broader regional sustainability goals.

Accordingly, the following hypothesis is proposed:

H1. Sustainable production practices have a positive effect on environmental citizenship behavior.

2.2. Digital environmental transparency and environmental citizenship behavior

Digital environmental transparency (DET) has become an essential component of corporate sustainability by enabling organizations to disclose environmental information through digital platforms, sustainability reports, and online communication channels. Greater transparency improves stakeholders' access to environmental information, enhances organizational accountability, and strengthens trust in corporate environmental initiatives (Schnackenberg & Tomlinson, 2016). As digital technologies continue to reshape sustainability communication, transparent environmental disclosure has become an important mechanism for promoting environmentally responsible behavior.

Environmental citizenship behavior (ECB) can be encouraged when employees and stakeholders perceive organizations as open and accountable regarding their environmental performance. Transparent environmental disclosure increases environmental awareness, reduces information asymmetry, and motivates individuals to participate in environmental protection activities (Hahn & Kühnen, 2013). Conversely, misleading or incomplete environmental information may reduce stakeholder confidence and weaken environmental engagement (Delmas & Burbano, 2011). Recent studies also indicate that digital transformation enhances environmental communication and stakeholder participation, thereby supporting corporate sustainability objectives (Li & Zhao, 2024; Huynh & Nguyen, 2025).

Although previous studies have investigated sustainability reporting and environmental disclosure, limited attention has been given to the direct influence of digital environmental transparency on environmental citizenship behavior. Improving digital transparency may strengthen environmentally responsible behavior by increasing trust, stakeholder engagement, and participation in organizational sustainability initiatives.

Accordingly, the following hypothesis is proposed:

H2. Digital environmental transparency has a positive effect on environmental citizenship behavior.

2.3. The moderating role of corporate environmental responsibility

Corporate environmental responsibility (CER) reflects an organization's commitment to integrating environmental protection into its business strategy, operational activities, and stakeholder relationships. Organizations with strong environmental responsibility not only implement sustainable environmental practices but also communicate their environmental commitments more credibly, thereby strengthening stakeholder trust and engagement (Aguinis & Glavas, 2012). Consequently, CER is considered an important organizational capability that enhances the effectiveness of sustainability initiatives.

Digital environmental transparency provides stakeholders with accessible and reliable environmental information, encouraging environmentally responsible attitudes and behaviors. However, the effectiveness of transparent environmental disclosure depends on whether stakeholders perceive the organization's environmental commitment as genuine. Previous studies indicate that corporate environmental responsibility increases the credibility of sustainability communication and positively influences employees' and stakeholders' responses to environmental initiatives (Du et al., 2010; Glavas & Kelley, 2014). Similarly, Farooq et al. (2014) argue that responsible corporate practices strengthen organizational commitment through greater stakeholder trust, while Koh et al. (2023) demonstrate that high-quality CSR disclosure enhances stakeholder engagement.

Despite growing research on environmental disclosure and corporate responsibility, limited studies have examined the moderating role of corporate environmental responsibility in the relationship between digital environmental transparency and environmental citizenship behavior. Organizations with stronger environmental responsibility are more likely to convert transparent environmental communication into greater environmental participation and voluntary environmental behavior.

Accordingly, the following hypothesis is proposed:

H3. Corporate environmental responsibility positively moderates the relationship between digital environmental transparency and environmental citizenship behavior.

3. Materials and methods

Data were collected through a structured questionnaire based on validated measurement scales for sustainable production practices (SPP), digital environmental transparency (DET), corporate environmental responsibility (CER), and environmental citizenship behavior (ECB). Sustainable production practices refer to firms' implementation of environmentally responsible production processes, digital environmental transparency reflects the extent to which firms openly disclose environmental information through digital platforms, corporate environmental responsibility represents firms' commitment to integrating environmental responsibility into their business activities, and environmental citizenship behavior captures individuals' voluntary actions that contribute to environmental sustainability. The survey was conducted in Azerbaijan between June and October 2025 using a purposive sampling approach targeting individuals involved in the production and consumption of environmentally sustainable products.

All items were measured using a five-point Likert scale ranging from 1 ("strongly disagree") to 5 ("strongly agree"). After data screening, 425 valid questionnaires were retained for analysis. As shown in Table 1, respondents aged 26–35 years constituted the largest age group (35.3%), followed by those aged 36–45 years (30.1%). Male respondents accounted for 56.0% of the sample, while females represented 44.0%. Among the occupational groups, organic food producers formed the largest category (25.6%). Regarding purchasing behavior, 50.8% of respondents reported that they frequently purchase eco-friendly products.

The data were analyzed using SPSS 26 and AMOS 26. Reliability was assessed using Cronbach's alpha (α) and composite reliability, while confirmatory factor analysis was employed to examine convergent and discriminant validity using standardized factor loadings, average variance extracted, the Fornell–Larcker criterion, and the heterotrait–monotrait ratio. The overall model fit was evaluated using χ^2/df, CFI, TLI, RMSEA, and SRMR. Finally, structural equation modeling was performed to test the proposed hypotheses, and statistical significance was determined at $p < 0.05$.

4. Results

The results of the structural model examining the relationships among sustainable production practices (SPP), digital environmental transparency (DET), corporate environmental responsibility (CER), and environmental citizenship behavior (ECB) are presented in Figure 1. The structural model presents the estimated standardized path coefficients for the proposed direct relationships together with the moderating effect of corporate environmental responsibility.

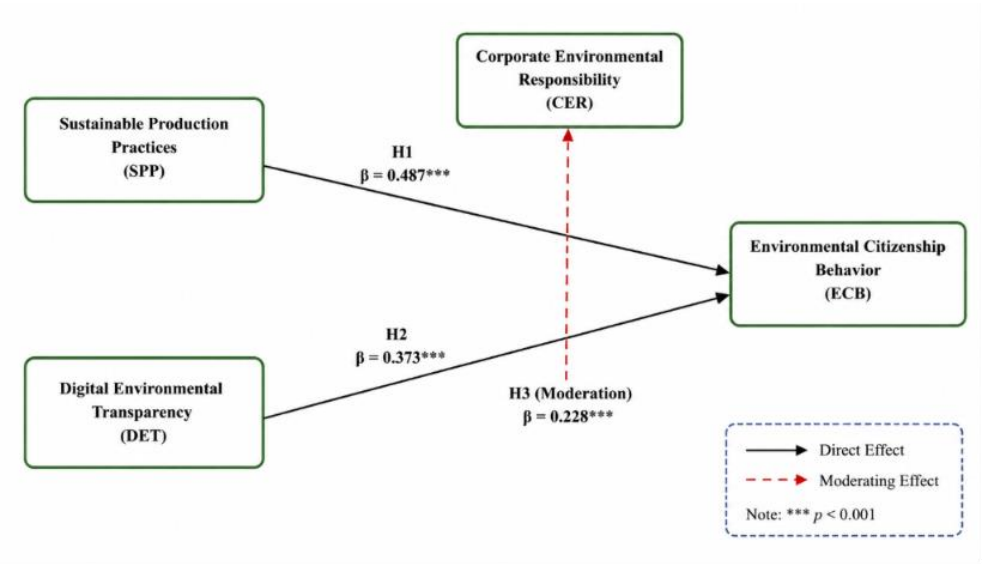


Fig. 1. Structural model results

The detailed results of the structural relationships are presented in Table 1. The findings indicate that all estimated structural paths are positive and statistically significant.

Table 1

Results of the structural relationships

Path Relationship	Path Coefficient (β)	S.E.	C.R.	Hypothesis Result
SPP → ECB	0.487	0.075	6.493	H1 Supported
DET → ECB	0.373	0.066	5.652	H2 Supported
DET × CER → ECB	0.250	0.058	4.310	H3 Supported

The results indicate that sustainable production practices have a significant positive effect on environmental citizenship behavior ($\beta = 0.487$, $p < 0.001$), supporting H1. This finding suggests that environmentally sustainable production systems encourage employees and stakeholders to engage in voluntary environmental activities beyond their formal responsibilities.

Digital environmental transparency also has a significant positive effect on environmental citizenship behavior ($\beta = 0.373$, $p < 0.001$), supporting H2. This result indicates that transparent digital disclosure of environmental information strengthens environmental awareness, stakeholder trust, and participation in sustainability initiatives.

The explanatory power of the structural model was evaluated using the coefficient of determination. Sustainable production practices, digital environmental transparency, and the interaction between digital environmental transparency and corporate environmental responsibility jointly explain 55% of the variance in environmental citizenship behavior ($R^2 = 0.55$), indicating satisfactory explanatory power.

To further assess the moderating role of corporate environmental responsibility, a moderation analysis was conducted. The results are presented in Table 2.

Table 2

Moderation analysis results

Effect Type	Path	Standardized Effect (β)	S.E.	95% Bootstrap CI
Interaction effect	DET × CER → ECB	0.228	0.063	[0.101, 0.329]

The moderation analysis confirms that corporate environmental responsibility significantly moderates the relationship between digital environmental transparency and environmental citizenship behavior. The interaction effect is positive and statistically significant ($\beta = 0.228$, $p < 0.001$), while the 95% bootstrap confidence interval [0.101, 0.329] does not include zero. This finding indicates that the positive effect of

digital environmental transparency on environmental citizenship behavior becomes stronger when corporate environmental responsibility is higher. Therefore, H3 is supported.

5. Discussion

5.1. Advancing environmental citizenship through sustainable production practices

The findings demonstrate that sustainable production practices have a significant positive effect on environmental citizenship behavior (H1), indicating that environmentally responsible production systems play an important role in encouraging voluntary environmental actions among employees and stakeholders. This suggests that sustainability-oriented production extends beyond improving operational efficiency and contributes to the development of an organizational culture that values environmental responsibility.

From a theoretical perspective, the results support the view that sustainable production practices create an environment in which individuals become more willing to engage in environmentally responsible behavior beyond their formal responsibilities. By integrating resource efficiency, waste reduction, and environmentally friendly production processes into daily operations, organizations foster stronger environmental awareness and commitment. Consequently, environmental citizenship behavior becomes a natural outcome of organizational sustainability efforts rather than merely an individual initiative.

These findings are consistent with previous studies emphasizing the importance of environmental management practices in promoting pro-environmental behavior. However, the present study extends the existing literature by demonstrating that sustainable production practices also contribute to broader regional sustainable development through their influence on environmental citizenship behavior. Therefore, organizations investing in sustainable production are likely to generate not only environmental and operational benefits but also stronger stakeholder engagement in sustainability initiatives.

5.2. The influence of digital environmental transparency on environmental citizenship behavior

The findings reveal that digital environmental transparency has a significant positive effect on environmental citizenship behavior (H2). This indicates that transparent disclosure of environmental information through digital platforms enhances stakeholders' environmental awareness and encourages greater participation in environmental protection activities.

From a theoretical perspective, digital environmental transparency functions as a mechanism that strengthens organizational legitimacy and stakeholder trust. When organizations openly communicate their environmental performance, sustainability initiatives, and environmental objectives, employees and external stakeholders perceive these commitments as more credible and become more willing to support environmental initiatives. In this sense, digital transparency reduces information asymmetry while creating stronger relationships between organizations and their stakeholders.

The findings are consistent with previous research highlighting the importance of transparency and sustainability reporting in promoting stakeholder engagement. Nevertheless, this study contributes to the literature by demonstrating that digital environmental transparency influences not only organizational reputation but also environmentally responsible behavior. Consequently, digital disclosure should be viewed as a strategic sustainability tool capable of fostering environmental citizenship and supporting regional sustainable development.

5.3. The boundary role of corporate environmental responsibility in environmental citizenship behavior

The moderation analysis confirms that corporate environmental responsibility strengthens the positive relationship between digital environmental transparency and environmental citizenship behavior (H3). This finding suggests that transparent environmental communication alone may not be sufficient to maximize environmental citizenship unless it is supported by genuine corporate environmental responsibility.

From a theoretical perspective, corporate environmental responsibility enhances the credibility of environmental disclosure and reinforces stakeholders' confidence in organizational sustainability commitments. When environmental transparency is accompanied by responsible environmental practices, stakeholders are more likely to perceive sustainability communication as authentic rather than symbolic. As a result, they become more willing to engage in voluntary environmental activities and support organizational sustainability goals.

The findings support stakeholder theory and corporate environmental responsibility literature, which emphasize that responsible organizational behavior enhances stakeholder trust and engagement (Aguinis & Glavas, 2012; Glavas & Kelley, 2014; Farooq et al., 2014). Unlike previous studies that primarily examined the

direct effects of corporate environmental responsibility, this research demonstrates its role as a boundary condition that amplifies the effectiveness of digital environmental transparency. Therefore, organizations seeking to promote environmental citizenship behavior should complement transparent environmental communication with genuine environmental responsibility initiatives. Together, these practices create a stronger foundation for stakeholder participation and contribute to long-term regional sustainable development.

6. Conclusion

Promoting environmental citizenship has become an essential component of regional sustainable development as organizations increasingly integrate sustainability into their production systems and corporate strategies. This study developed and tested a structural framework examining the effects of sustainable production practices (SPP) and digital environmental transparency (DET) on environmental citizenship behavior (ECB), while investigating the moderating role of corporate environmental responsibility (CER). Using structural equation modeling, the study provides empirical evidence on the mechanisms through which organizational sustainability practices contribute to environmentally responsible behavior.

The findings demonstrate that both sustainable production practices and digital environmental transparency significantly enhance environmental citizenship behavior. Organizations adopting environmentally responsible production systems and transparent environmental communication are more likely to encourage employees and stakeholders to engage in voluntary environmental actions. Furthermore, the results reveal that corporate environmental responsibility strengthens the positive relationship between digital environmental transparency and environmental citizenship behavior, highlighting the importance of combining transparent environmental disclosure with genuine environmental commitment.

The findings offer several practical implications for policymakers, business managers, and regional development stakeholders. Policymakers should encourage sustainable production through supportive environmental policies and incentives while promoting greater transparency in corporate environmental reporting. Organizations should integrate sustainable production practices with effective digital communication strategies and strengthen their environmental responsibility to increase stakeholder trust and participation. By fostering environmental citizenship behavior, these efforts can contribute to stronger environmental governance, sustainable business practices, and long-term regional sustainable development.

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ФОРМИРОВАНИЕ ЭКОЛОГИЧЕСКОЙ ГРАЖДАНСТВЕННОСТИ КАК ФАКТОРА УСТОЙЧИВОГО РАЗВИТИЯ РЕГИОНОВ

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Резюме. В условиях усиливающейся взаимосвязи между экологической устойчивостью и региональным развитием изучение организационных факторов, способствующих экологически ответственному поведению, становится важным направлением научных исследований. Цель исследования заключается в оценке влияния практик устойчивого производства и цифровой экологической прозрачности на экологическое гражданское поведение с одновременным изучением модерирующей роли корпоративной экологической ответственности. Для проверки предполагаемых взаимосвязей применён метод моделирования структурными уравнениями (Structural Equation Modeling – SEM) на основе данных опроса 425 респондентов, участвующих в производстве и потреблении экологически устойчивой продукции в Азербайджане. Результаты показывают, что как практики устойчивого производства, так и цифровая экологическая прозрачность оказывают статистически значимое положительное влияние на экологическое гражданское поведение. Полученные результаты также свидетельствуют о том, что корпоративная экологическая ответственность оказывает положительное модерирующее воздействие на взаимосвязь между цифровой экологической прозрачностью и экологическим гражданским поведением. Это указывает на то, что прозрачная экологическая коммуникация становится более эффективной, когда подкрепляется подлинной экологической ответственностью. Исследование вносит вклад в научную литературу по вопросам устойчивого развития, демонстрируя, что экологически ответственное производство, прозрачное раскрытие экологической информации и корпоративная экологическая ответственность совместно способствуют формированию экологического гражданского поведения и поддерживают устойчивое региональное развитие. Полученные результаты имеют практическое значение для разработчиков государственной политики и руководителей предприятий, стремящихся укреплять экологическое управление, стимулировать участие заинтересованных сторон и обеспечивать долгосрочную региональную устойчивость посредством более эффективных корпоративных стратегий устойчивого развития и совместных межотраслевых экологических инициатив.

Ключевые слова: *практики устойчивого производства, цифровая прозрачность экологической информации, корпоративная экологическая ответственность, экологическое гражданское поведение, устойчивое региональное развитие*

REGİONLARIN DAYANIQLI İNKİŞAFININ AMİLİ KİMİ EKOLOJİ VƏTƏNDAŞLIĞIN FORMALAŞDIRILMASI

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Xülasə. Ekoloji dayanıqlılıq və regional inkişaf arasında qarşılıqlı əlaqələrin getdikcə gücləndiyi şəraitdə ekoloji məsuliyyətli davranışı təşviq edən təşkilati amillərin öyrənilməsi mühüm tədqiqat istiqamətinə çevrilmişdir. Tədqiqatın məqsədi korporativ ekoloji məsuliyyətin moderator rolunu araşdırmaqla dayanıqlı istehsal təcrübələrinin və rəqəmsal ekoloji şəffaflığın ekoloji vətəndaşlıq davranışına təsirlərini qiymətləndirməkdir. Azərbaycanda ekoloji cəhətdən dayanıqlı məhsulların istehsalı və istehlakında iştirak edən 425 respondentdən toplanmış sorğu məlumatları əsasında irəli sürülən əlaqələrin yoxlanılması üçün struktur tənliklərin modelləşdirilməsi (Structural Equation Modeling – SEM) metodundan istifadə edilmişdir. Nəticələr göstərir ki, həm dayanıqlı istehsal təcrübələri, həm də rəqəmsal ekoloji şəffaflıq ekoloji vətəndaşlıq davranışına statistik baxımdan əhəmiyyətli müsbət təsir göstərir. Əldə edilən nəticələr, həmçinin korporativ ekoloji məsuliyyətin rəqəmsal ekoloji şəffaflıqla ekoloji vətəndaşlıq davranışı arasındakı əlaqəyə müsbət moderator təsir göstərdiyini aşkar edir. Bu isə şəffaf ekoloji kommunikasiyanın həqiqi ekoloji məsuliyyətlə dəstəkləndiyi hallarda daha səmərəli olduğunu göstərir. Tədqiqat ekoloji məsuliyyətli istehsalın, ekoloji məlumatların şəffaf şəkildə açıqlanmasının və korporativ ekoloji məsuliyyətin birlikdə ekoloji vətəndaşlıq davranışını təşviq etdiyini və dayanıqlı regional inkişafı dəstəklədiyini nümayiş etdirməklə dayanıqlı inkişaf sahəsində elmi ədəbiyyata töhfə verir. Əldə edilən nəticələr ekoloji idarəetməni gücləndirməyə, maraqlı tərəflərin iştirakını təşviq etməyə və daha səmərəli korporativ dayanıqlılıq strategiyaları və sektorlararası birgə ekoloji təşəbbüslər vasitəsilə uzunmüddətli regional dayanıqlılığı təmin etməyə çalışan siyasətçilər və biznes rəhbərləri üçün praktiki əhəmiyyət daşıyır.

Açar sözlər: *dayanıqlı istehsal təcrübələri, ekoloji məlumatların rəqəmsal şəffaflığı, korporativ ekoloji məsuliyyət, ekoloji vətəndaşlıq davranışı, regionların dayanıqlı inkişafı.*

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SUSTAINABLE FOUNDATIONS FOR THE DEVELOPMENT OF REGIONAL TOURISM IN AZERBAIJAN

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Keywords: *regional tourism, tourism demand, ecotourism, cultural tourism, outdoor tourism, SPSS and Chi-Square analysis, regression analysis*

Summary. This study examines the contribution of tourism to sustainable regional development in Azerbaijan by integrating survey-monitoring results with official statistical indicators. Tourism demand, recreational preferences, overnight stays, accommodation activity, and regional tourism dynamics were analyzed using comparative statistical methods, SPSS, Chi-Square testing, correlation, and regression analysis. The analysis covers the principal tourism-oriented economic regions of Azerbaijan and evaluates differences in demand for nature-based recreation, wellness, ecotourism, outdoor activities, and cultural heritage tourism. The results indicate particularly strong demand for nature-based recreation and demonstrate substantial regional differences in tourism activity. Guba-Khachmaz recorded the highest growth in overnight stays, while Shaki-Zagatala and Ganja-Dashkasan also showed significant positive dynamics. Regression models produced high goodness-of-fit values across the analyzed regions ($R^2 = 0.964–0.990$; $p < 0.05$), supporting a positive relationship between tourism activity and regional economic development. The findings also show that nature-based recreation, ecotourism, wellness, and outdoor tourism have considerable potential to generate additional regional value. Sustainable tourism policies should therefore combine destination development, local-resource use, infrastructure improvement, community participation, and diversified tourism products to strengthen regional economic resilience.

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1. Introduction

Tourism is an important driver of regional economic and social development through employment creation, local income generation, entrepreneurship, and the formation of added value. Its effects are particularly significant in rural and peripheral regions, where tourism can diversify economic activity and support the use of local natural and cultural resources. Regional tourism development can also stimulate investment in accommodation, transport, services, and other related sectors (Economic Forum, 2021; Walas et al., 2025).

In Azerbaijan, tourism has increasingly been considered within sustainable and regional development strategies. The development of tourism destinations can strengthen local economies, improve community welfare, create new professional opportunities, and increase the economic value of regional resources. Investment and effective resource use are therefore important for maintaining the sector's long-term contribution to regional development (Imrani et al., 2025).

However, evaluating this contribution requires more than general tourism statistics. Combining official indicators with survey-monitoring data makes it possible to compare actual tourism flows with visitor preferences and identify regional differences in demand. Accordingly, this study aims to assess the role of tourism in the sustainable development of Azerbaijan's regions by integrating official statistical data with survey results and SPSS-based statistical analysis.

2. Research materials and methods

This study combines official tourism statistics with survey-monitoring data to assess regional differences in tourism demand and their relationship with sustainable regional development in Azerbaijan. The analysis covers the Shaki-Zagatala, Mountainous Shirvan, Guba-Khachmaz, Lankaran-Astara, Ganja-Dashkasan, Karabakh, and Eastern Zangezur economic regions. Official indicators include tourist flows, overnight stays, accommodation activity, and regional tourism dynamics, while survey data are used to examine preferences for different forms of recreation and tourism.

2.1. Literature review

Previous studies demonstrate that regional tourism can contribute to economic growth, employment, infrastructure development, destination competitiveness, and community income, although its effects vary spatially and depend on governance, human capital, accessibility, and resource use (Motsa et al., 2021; Astanakulov & Goyipnazarov, 2023; Li et al., 2024). Research on Azerbaijan similarly emphasizes the importance of tourism-recreation zoning, natural tourism resources, ecotourism, and destination development for regional economies (Imrani & Veliyeva, 2021; Dargahov et al., 2023, 2024; Imrani et al., 2024).

Sustainable tourism research increasingly links regional development with circular resource use, community participation, infrastructure, digitalization, and environmental responsibility (Baggio & Cooper, 2011; Einarsson & Sorin, 2020; UNWTO, 2021). These approaches indicate that tourism should be assessed not only through visitor numbers but also through its relationship with regional demand, local resources, economic activity, and sustainability.

2.2. Methodology

The methodological framework combines survey monitoring, comparative analysis, Chi-Square testing, correlation analysis, and regression modelling to assess the relationship between tourism demand and regional development. Survey data were processed in SPSS to compare observed and expected frequencies of tourism preferences, while official statistical indicators were used to evaluate regional differences and temporal changes in tourism activity.

Regression analysis was applied to examine changes in overnight stays across the selected economic regions. The B coefficient, constant (A), coefficient of determination (R^2), and p-value were used to assess the direction, explanatory power, and statistical significance of the models. Survey results were then compared with official regional statistics to identify relationships between tourism preferences, tourism activity, and regional development. The use of integrated survey and statistical approaches is consistent with established methods in sustainable tourism research (Einarsson & Sorin, 2020; UNWTO, 2021; Kaurav et al., 2021).

3. Research results

Tourism is one of the most dynamic sectors of the global economy. According to the World Travel and Tourism Council (WTTC), the tourism industry had fully recovered by the end of 2024, accounting for 10.4% of global GDP. Azerbaijan also experienced rapid post-pandemic recovery, reaching 83% of its pre-pandemic tourism level by 2024 (Travel Market Report, 2024). Before the pandemic, tourism accounted for approximately 3.5–4.5% of Azerbaijan's GDP, while its current contribution is about 3.0%, with particularly visible effects on regional economic activity and household income (ARSTA ASSC, 2025).

The value generated by tourism services in Azerbaijan increased from USD 845 million in 2022 to USD 1.2 billion in 2024, although this remained below the level recorded in neighboring Georgia (USD 4.6 billion). Despite increased investment and national tourism-development initiatives, the sector's full economic potential has not yet been reflected in GDP, while WTTC projections indicate further growth over the next five years. Sustainable tourism development therefore requires integrated strategies, investment, transparency, community participation, and the transformation of local resources into tourism products capable of generating regional added value (UNWTO, 2017). At the same time, technological and socio-economic innovations in tourism products, services, organizational structures, business models, and circular-economy solutions can strengthen competitiveness and regional economic benefits (Innovation in Tourism, 2017).

To evaluate tourism's contribution to regional development in Azerbaijan, official statistical indicators were integrated with survey-monitoring results and analyzed using SPSS. The analysis covers Shaki-Zagatala, Mountainous Shirvan, Guba-Khachmaz, Lankaran-Astara, Ganja-Dashkasan, Karabakh, and Eastern Zangezur and considers tourist flows, accommodation capacity, overnight stays, recreational preferences, and regional tourism dynamics. These indicators were used to compare tourism demand and assess differences in tourism activity and its potential contribution to regional added value. A total of 1,058 respondents participated in the survey-monitoring, and SPSS analysis was used to determine tourism demand based on variable and fixed frequencies. Among the participants, 650 were male and 450 were female. The

questionnaire focused primarily on demand for different recreational activities and their potential contribution to additional value creation in the regions.

In the SPSS analysis of leisure categories, the respondents were grouped by preferences for passive and active recreation. The Chi-Square analysis in SPSS was used to assess frequency distributions according to the variables. The calculated expected frequencies were 264.5 for passive recreation and 163.5 for active recreation. Thus, if the expected frequency were equal for each category: $\frac{1058}{4} = 264.5$.

This formula illustrates the expected frequency distribution for the passive recreation category. The comparison between observed and expected frequencies across the main recreational categories is presented in Fig. 1.

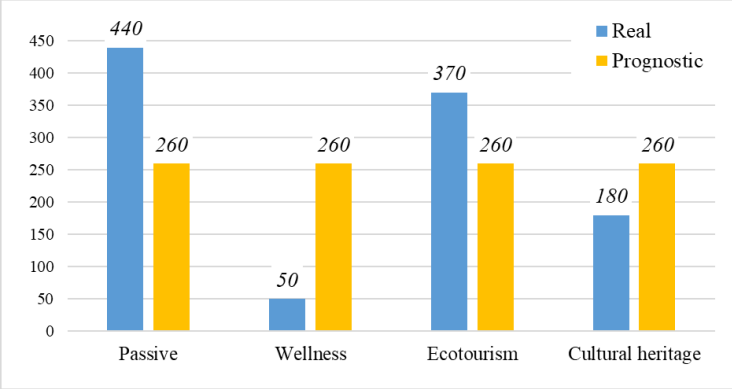


Fig. 1. Comparison of the real and prognostic amounts

The SPSS analysis of tourist demand for different types of tourism activities across regions allows for a comparative assessment between actual and expected figures. The results indicate that the predominance of passive recreation in natural areas has made traditional tourism destinations the primary choice among travelers. In particular, the notable difference between actual and expected figures in health tourism reflects the official statistical data on the number of users of health tourism services in the country.

Specifically, the number of both domestic and international tourists utilizing health tourism services in Azerbaijan stands at approximately 200,000 people, with a significant portion – around 73,500 individuals – receiving services at Naftalan's therapeutic and wellness facilities (ARSTA. ASSC, 2025). Additionally, visitors frequent other wellness resorts under the TABIA Group, such as Galaalty, Lankaran Springs, Yengija Thermal Spa, and Duzdagh Sanatorium. Health tourism services are also offered through traditional social referral systems in sanatoriums operated under the Trade Union Confederation, primarily in Baku and the Absheron Peninsula. The SPSS analysis reveals that the presence of real health tourism offers in the country has the potential to increase both domestic and international tourist numbers and generate added economic value for the regions.

The SPSS analysis of ecological and outdoor tourism activities shows a relatively small difference between actual and expected figures. In the post-pandemic period, the growing demand for outdoor leisure and nature-based recreation has led to the expansion of ecological and outdoor tourism activities and the establishment of new tourism routes across the regions.

The increasing number of visitors to national parks, along with the provision of services along hiking trails, has positioned ecological tourism as an emerging trend. Currently, the number of users of national parks exceeds 350,000 people and continues to grow steadily. In parallel, the offering of tourism routes covering natural areas, route marking, the growing number of companies offering mountain sports, hiking, and other outdoor tourism activities, and the services provided at major resorts such as Shahdagh and Tufandagh reflect the dynamic development of this sector. The growth of ecological and outdoor tourism in Azerbaijan, alongside the diversification of agro-tourism and open-air tourism products, has notably contributed to the creation of additional value within the regions (Dargahov, 2023).

In determining the demand for cultural and historical heritage tourism, the difference between actual and expected visitor numbers remains minimal. While cultural heritage is not the primary motivation for most regional tourists, in recent years, the formation of eco-cultural and ethno-cultural destinations and the increasing number of visitors to the nine cultural heritage reserves under the State Tourism Agency (STA) have contributed to steady growth in this sector.

Notable examples include the villages of Basgal, Lahij, and Khinalig as eco-cultural destinations, and the historic center of Shaki as a cultural heritage destination. According to official data, the number of participants in cultural tourism activities has reached approximately 800,000 people, with 667,000 of them visiting the nine cultural heritage reserves managed by the STA (ARSTA. ASSC, 2025). The analysis of survey-monitoring results confirms that the share of cultural heritage within tourism demand continues to rise, directly linked to the emergence of newly established eco-cultural and ethno-cultural destinations and centers. Moreover, in the inbound tourism market, cultural and historical heritage remains a key attraction, with visitors showing a preference for Baku's historical architecture, Shaki's historic center, Gobustan National Historical and Cultural Reserve, and the ethnocultural villages of Basgal, Lahij, and Khinalig.

The increase in regional tourism demand has directly influenced the growth in the number of overnight stays. Statistical analysis shows that the number of overnight stays has increased most significantly in the Guba-Khachmaz and Shaki-Zagatala economic regions. The annual dynamics of overnight stays across the selected economic regions during 2021–2024 are presented in Table 1.

Table 1

The Results of SPSS regression analysis for economic regions **(**ARSTA. ASSC, 2025)

Regions	2021	2022	2023	2024
Mountainous Shirvan	34,9	56,6	63,7	82,4
Shaki-Zagatala	188,2	220,5	223,4	284,7
Ganja-Dashkesan	64,1	115,2	194,6	203,5
Karabakh	13,7	33,5	46,1	57,2
Guba-Khachmaz	398,7	491,1	609,8	752,3
Lankaran-Astara	112,0	130,0	162,5	182,1

The correlation analysis between the dynamics of overnight stays and the results of survey-monitoring data confirms that regression coefficients indicate growth patterns in both fixed and variable parameters, complementing the monitoring results of tourism demand in these regions. The regression coefficients, constants, coefficients of determination (R^2), and statistical significance levels for the selected economic regions are summarized in Table 2.

Table 2

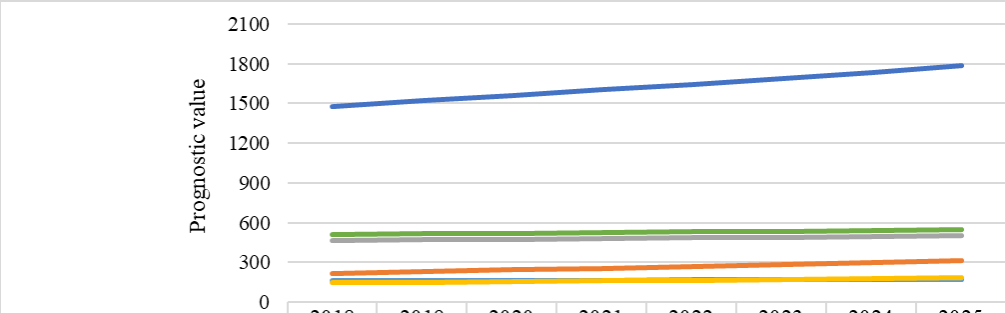
SPSS Regression Analysis Results for Economic Regions

Regions	B (coefficient)	A (constant)	R^2	P
Mountainous Shirvan	15,96	-32027,5	0,987	0,006
Shaki-Zagatala	21,83	-43833,5	0,964	0,017
Ganja-Dashkesan	46,55	-93555,5	0,979	0,010
Karabakh	14,53	-29099,8	0,989	0,005
Guba-Khachmaz	118,0	-236676,5	0,990	0,005
Lankaran-Astara	23,4	-46689,8	0,989	0,005

The regression analysis results indicate that the B coefficient shows a positive relationship between the annual increase in overnight stays and the generation of added value within the regions. For example, in the Guba-Khachmaz economic region, an increase of 118,000 overnight stays corresponds to a positive correlation coefficient when compared with expected figures based on survey-monitoring results. Additionally, the model fit indicators (R^2) for the economic regions were found to be very high, ranging from 0.98 to 0.99. Statistical analyses confirmed, with p-values < 0.05, that the variables contribute to additional economic value and support prospects for sustainable development.

Based on the linear trend graph of overnight stays, the Guba-Khachmaz economic region displays a clear advantage over other regions. Although the Karabakh and Mountainous Shirvan economic regions currently have lower starting figures, they demonstrate consistent upward trends, indicating potential for added value in the future. Furthermore, the sharp increase observed in the Ganja-Dashkasan economic region is directly linked to the growing tourism demand in this area.

In assessing tourist preferences, variable factors correspond to the type of recreation selected, while constant factors reflect the dynamics of respondent opinions. The analysis reveals that natural areas constitute most overall tourist flows, evidenced by statistical data showing increased numbers of visitors to nearby and medium-distance tourism destinations. Accordingly, the dynamic rise in overnight stays in Guba, Gusar, Gabala, Shamakhi, and Ismayilli districts is associated with the predominance of nature-based recreation, ecotourism, and outdoor tourism activities. The linear trends in tourism activity across the selected economic regions for the period 2018–2025 are illustrated in Fig. 2. The distribution of respondents' tourism preferences, including nature-based recreation, coastal areas, cultural heritage, wellness tourism, and other activities, is presented in Table 3.



	2018	2019	2020	2021	2022	2023	2024	2025
Mountainous Shirvan	159,00	161,00	163,03	165,08	167,15	169,25	171,38	173,54
Shaki-Zagatala	218,00	230,00	242,66	256,02	270,11	284,98	300,67	317,22
Ganja-Dashkesan	465,00	470,00	475,05	480,16	485,32	490,54	495,82	501,15
Karabakh	145,00	150,00	155,17	160,52	166,06	171,78	177,71	183,84
Guba-Khachmaz	1480,00	1520,00	1561,08	1603,27	1646,60	1691,11	1736,81	1783,75
Lankaran-Astara	510,00	515,00	520,05	525,15	530,30	535,50	540,74	546,05

Fig. 2. Linear trend graph for regions (2018–2025)

Table 3

SPSS Coefficients Based on Tourist Interests

Tourist intersts	Amount	Percentage (%)	Coefficient
Nature areas	470	42,6	0,426
Coastal areas and lakes	135	12,2	0,122
Historical and cultural heritage	136	12,3	0,123
Wellness	242	21,9	0,219
Others	121	11,0	0,110
Total	1104	100	1,0

4. Conclusion

The evaluation of the tourism sector's impact on regional development in Azerbaijan, based on the correlation between official statistical data and survey-monitoring assessments, reveals that the demand for nature-based recreation, health tourism, ecological, and outdoor tourism activities has notably increased. This growth has, in turn, contributed to the rise in visitor numbers to traditional tourism destinations and facilitated the creation of additional economic value within the regions.

According to the results of SPSS analyses and regression modeling, the analysis of both fixed and variable factors by location or region showed statistical significance at the $p < 0.05$ level, indicating that these factors contribute to additional economic value. Moreover, the R^2 values obtained from the SPSS regression models demonstrated a high level of model fit across economic regions and existing tourism destinations, ranging between 0.98 and 0.99.

Furthermore, the direct proportionality between the survey-monitoring results and the dynamics of tourism activity confirms that expanding nature-based recreation, ecological, and outdoor tourism activities in destination management strategies will stimulate the development of complementary programs and projects. This finding highlights the importance of integrating these tourism types into regional tourism policies and investment priorities to ensure sustainable economic growth and increased added value in Azerbaijan's regions.

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УСТОЙЧИВЫЕ ОСНОВЫ РАЗВИТИЯ РЕГИОНАЛЬНОГО ТУРИЗМА В АЗЕРБАЙДЖАНЕ

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Резюме. В исследовании рассматривается вклад туризма в устойчивое региональное развитие Азербайджана посредством объединения результатов опросов и мониторинга с официальными статистическими показателями. Туристский спрос, рекреационные предпочтения, количество ночёвок, деятельность средств размещения и региональная динамика туризма анализировались с использованием сравнительных статистических методов, программы SPSS, критерия хи-квадрат, корреляционного и регрессионного анализа. Анализ охватывает основные экономические районы Азербайджана, ориентированные на развитие туризма, и оценивает различия в спросе на отдых на природе, оздоровительный туризм, экотуризм, активный отдых на открытом воздухе и культурно-познавательный туризм. Результаты свидетельствуют об особенно высоком спросе на отдых на природе и демонстрируют существенные региональные различия в туристской деятельности. Наибольший рост количества ночёвок зафиксирован в Губа-Хачмазском экономическом районе, тогда как в Шеки-Загатальском и Гянджа-Дашкесанском экономических районах также наблюдалась значительная положительная динамика. Регрессионные модели продемонстрировали высокие показатели качества аппроксимации по анализируемым регионам (R^2 = 0,964–0,990; $p < 0,05$), подтверждающие положительную взаимосвязь между туристской деятельностью и региональным экономическим развитием. Полученные результаты также показывают, что отдых на природе, экотуризм, оздоровительный туризм и туризм, связанный с активным отдыхом на открытом воздухе, обладают значительным потенциалом создания дополнительной региональной стоимости. Следовательно, политика устойчивого развития туризма должна объединять развитие туристских дестинаций, использование местных ресурсов, совершенствование инфраструктуры, участие местных сообществ и диверсификацию туристских продуктов для укрепления региональной экономической устойчивости.

Ключевые слова: *региональный туризм, туристический спрос, экотуризм, культурный туризм, активный туризм, анализ с использованием SPSS и критерия хи-квадрат, регрессионный анализ*

AZƏRBAYCANDA REGİONAL TURİZMİN İNKİŞAFININ DAYANIQLI ƏSASLARI

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Xülasə. Tədqiqatda sorğu-monitorinq nəticələri rəsmi statistik göstəricilərlə birləşdirilməklə turizmin Azərbaycanda dayanıqlı regional inkişafa töhfəsi araşdırılır. Turizm tələbatı, rekreasiya üstünlükləri, gecələmələrin sayı, yerləşdirmə müəssisələrinin fəaliyyəti və regional turizm dinamikası müqayisəli statistik metodlar, SPSS proqramı, xi-kvadrat testi, korrelyasiya və reqressiya təhlili vasitəsilə araşdırılmışdır. Təhlil Azərbaycanın turizm yönümlü əsas iqtisadi rayonlarını əhatə edir və təbiət əsaslı istirahətə, sağlamlıq turizminə, ekoturizmə, açıq hava fəaliyyətlərinə və mədəni irs turizminə olan tələbatdakı fərqləri qiymətləndirir. Nəticələr təbiət əsaslı istirahətə xüsusilə yüksək tələbatın olduğunu göstərir və turizm fəaliyyətində əhəmiyyətli regional fərqləri ortaya qoyur. Gecələmələrin sayında ən yüksək artım Quba-Xaçmaz iqtisadi rayonunda qeydə alınmış, Şəki-Zaqatala və Gəncə-Daşkəsən iqtisadi rayonlarında da əhəmiyyətli müsbət dinamika müşahidə edilmişdir. Reqressiya modelləri təhlil edilən regionlar üzrə yüksək uyğunluq göstəriciləri nümayiş etdirmişdir (R^2 = 0,964–0,990; $p < 0,05$). Bu nəticələr turizm fəaliyyəti ilə regional iqtisadi inkişaf arasında müsbət əlaqənin mövcudluğunu dəstəkləyir. Əldə edilən nəticələr, həmçinin təbiət əsaslı istirahətin, ekoturizmin, sağlamlıq turizminin və açıq hava turizminin əlavə regional dəyər yaratmaq baxımından əhəmiyyətli potensiala malik olduğunu göstərir. Buna görə də dayanıqlı turizm siyasəti regional iqtisadi dayanıqlığın gücləndirilməsi məqsədilə turizm destinasiyalarının inkişafını, yerli resurslardan istifadəni, infrastrukturun təkmilləşdirilməsini, yerli icmaların iştirakını və turizm məhsullarının şaxələndirilməsini birləşdirməlidir.

Açar sözlər: *regional turizm, turizm tələbi, ekoturizm, mədəni turizm, açıq havada turizm, SPSS və xi-kvadrat təhlili, reqressiya təhlili*

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COMPETITIVENESS AND ATTRACTIVENESS OF TOURISM REGIONS: A SYSTEMATIC REVIEW OF INTERNATIONAL STUDIES

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Keywords: *tourism competitiveness, destination attractiveness, systematic literature review, composite indicators, tourism performance*

Summary. Tourism competitiveness and destination attractiveness are central to how countries position themselves in the global travel market, yet research on both has grown quickly and unevenly. This article reviews 109 Scopus-indexed documents published between 2003 and 2026, combining a quantitative profile of the literature with a thematic synthesis. The corpus expands sharply after 2015 and is markedly unbalanced: measurement and frameworks (33.0 per cent) and determinants (32.1 per cent) dominate, analytical methods account for 24.8 per cent, and demand-side perception research for only 10.1 per cent. The Travel and Tourism Competitiveness Index remains the default benchmark, but its equal weighting, data demands and uneven predictive validity have pushed the field toward alternative and hybrid measures. No technique dominates: data envelopment analysis, TOPSIS, PLS path modelling and game-theoretic weighting compensate for one another's weaknesses. Infrastructure, information and communication technology readiness and environmental quality are the most stable determinants, with effects conditioned by income level. An illustration matching the 2024 Travel & Tourism Development Index with UN Tourism data for twenty-one leading destinations finds moderate correlation with arrivals ($r = 0.59$) but stronger correlation with receipts ($r = 0.72$): measured competitiveness tracks the value of tourism more closely than its volume.

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Introduction

Few sectors reveal a country's development choices as plainly as tourism: whether visitors arrive and return depends on roads and airports, hotels and health services, digital networks, and the natural and cultural assets that draw people. These ingredients are unevenly distributed and slow to change, so the useful question is rarely how a destination performs in one year, but how it performs against its peers over time.

Two constructs organise this research. Competitiveness describes a destination's capacity to deliver value that outperforms rivals without eroding the resource base supporting it (Dwyer & Kim, 2003; Enright & Newton, 2004); attractiveness describes the pull it exerts on prospective visitors, shaped by perceived resources, image and the match between what a place offers and what segments want (Formica & Uysal, 2006). The space between them, where destinations are attractive yet uncompetitive or competitive yet under-visited, has driven much of the empirical work (Cracolici & Nijkamp, 2009), and panel designs expose what rankings conceal: the drivers of competitiveness do not carry equal weight everywhere (Hanafiah & Ali, 2024; Magrini & Grassini, 2019). Reviewing 109 Scopus-indexed documents published between 2003 and 2026, this article asks how the field has grown, how the constructs are measured, which methods and determinants recur, and whether measured competitiveness tracks realised performance.

2. Theoretical background

The conceptual scaffolding of the field was built in the early 2000s. The models of Ritchie and Crouch, of Dwyer and Kim, and of Heath share a layered logic in which resources sit beneath supporting factors and

management, which interact with demand conditions and the wider environment (Azzopardi & Nash, 2017). Dwyer and Kim (2003) paired determinants with indicators that later work could operationalise, and Enright and Newton (2004) pushed toward quantification through managers' ratings.

Attractiveness enters from the demand side. Formica and Uysal (2006) framed it as the relationship between what a destination supplies and what visitors seek, so a well-endowed place can still fail to attract if its offer misaligns with market preferences. Cracolici and Nijkamp (2009) showed for southern Italy that the two constructs, though correlated, respond to different levers, evident potential coexisting with weak rankings. The distinction matters for measurement: indices built only on supply-side data capture one construct better than the other, which is why several authors argue for frameworks keeping both in view (Mior Shariffuddin et al., 2023).

3. Materials and methods

The article follows a systematic quantitative review design, quantifying the structure of a fast-growing literature and synthesising work too heterogeneous for meta-analytic pooling (Mior Shariffuddin et al., 2023). The literature was identified through Scopus, combining "tourism competitiveness" and "destination attractiveness" with "cross-country", "panel", "composite indicator" and "index", complemented by backward citation tracking. Documents were eligible if published in English between 2003 and 2026 and addressing the measurement of the two constructs, comparative or panel methodology, or determinants in multi-country settings; firm-level studies were excluded. The corpus comprises 109 documents, the earliest Dwyer and Kim (2003), each coded to one primary theme by principal contribution: measurement and frameworks, analytical methods, determinants, or demand-side perceptions.

A deliberately simple empirical illustration complements the synthesis. Competitiveness is proxied by the overall score of the Travel & Tourism Development Index (TTDI) 2024, successor to the TTCI (World Economic Forum, 2024), and performance by international arrivals and receipts in 2023 (UN Tourism, 2024). Of the thirty top-ranked economies, comparable arrivals were unavailable for nine, leaving twenty-one that received some 679 million arrivals, about half the world total. The methods are correlations and bivariate regressions of log performance on the score; no causal claim is made.

4. Results

4.1. The Research landscape

The corpus documents a field that barely existed at the turn of the century and grew in two waves (Figure 1): a climb after 2015, with the diffusion of composite-indicator critique and of DEA- and PLS-based techniques, and a surge from 2023, in post-pandemic recovery and the move from the TTCI to its successor. Almost three quarters of it (73.4 per cent) appeared in 2016 or later. Publication is dispersed across 82 outlets, while thematic attention is similarly uneven, with measurement, frameworks, and determinants dominating the corpus and demand-side perception research declining to just one of the 44 publications produced during 2021–2026 (Table 1).

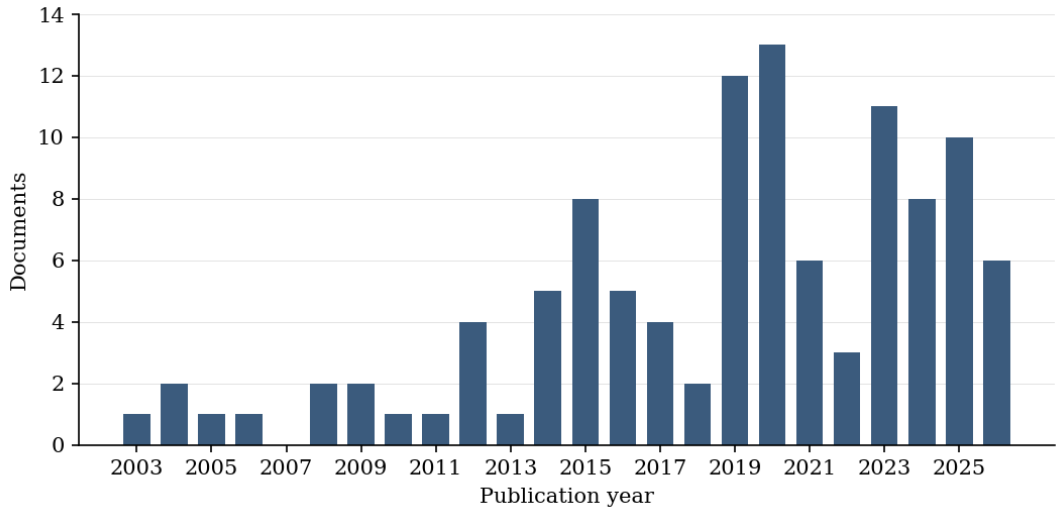


Fig. 1. Annual distribution of the reviewed documents, 2003-2026 (n = 109).

Table 1

Thematic distribution of the reviewed documents (n = 109)

Primary theme	Documents	Share of corpus (%)
Measurement and frameworks	36	33.0
Determinants	35	32.1
Analytical methods	27	24.8
Demand-side perceptions	11	10.1
Total	109	100.0

Source: Authors' elaboration based on the reviewed corpus

4.2. Measuring competitiveness: The TTCI and its limitations

Measurement begins with the Travel and Tourism Competitiveness Index, which groups roughly ninety variables into fourteen pillars spanning infrastructure, cultural and natural resources, information and communication technology (ICT) readiness, environmental sustainability, health, human resources and price (Martinez et al., 2019). Three criticisms recur. Aggregation: combining variables measured in different units, some duplicating information, can distort the composite (Martinez et al., 2019). Weighting: pillars are treated as equally important, yet rankings shift sharply under alternative schemes, most in the tiers where policy attention concentrates (Gómez-Vega & Picazo-Tadeo, 2019). Predictive validity, the most damaging, is contested: Hiyab et al. (2023) found the index's power over African arrivals weak and in places negative, and Hanafiah and Zulkifly (2019) found the competitiveness-performance link more conditional than its design implies, while Hanafiah and Ali (2024) showed that it tracks performance more reliably in low-income countries, where basic conditions still bind, than in high-income ones, whose rankings are stable but loosely tied to outcomes. None of this retires the index, but it explains why researchers treat it as a point of departure rather than a verdict.

4.3. Alternative measurement and comparative methods

Alternatives have moved along two lines: reducing the data burden and improving weighting. Principal component analysis builds composites from fewer variables while retaining most of the underlying variation, which matters for the many countries where full index data are unavailable (Pérez León et al., 2022); data envelopment analysis (DEA) derives weights endogenously, scoring destinations against an efficiency frontier rather than imposing weights from outside (Omrani et al., 2020); and multi-criteria and participatory schemes make the weighting step explicit and more sensitive to context.

Each comparative instrument has a characteristic blind spot. DEA suits multiple inputs and outputs with no agreed price for combining them, but with many indicators it loses discrimination and can leave relevant dimensions unweighted (Gómez-Vega & Picazo-Tadeo, 2019), while TOPSIS, ranking destinations by distance from ideal and anti-ideal profiles, is intuitive but wholly dependent on externally supplied weights - a complementarity explaining the appeal of hybrid DEA-TOPSIS designs (Lin et al., 2023). Partial least squares path modelling is the workhorse for questions of structure and evolution, accommodating formative constructs, small samples and multicollinearity (Magrini & Grassini, 2019), while game-theoretic weighting curbs the zero-weight objection and systemic models locate leverage points for policy. No method dominates; the choice should follow the research question and the data.

4.4. Determinants of competitiveness and attractiveness

A consistent set of determinants surfaces, though their relative weight shifts with income level. Infrastructure is the most reliable predictor: transport, accommodation and health services drive arrivals and repeat visitation, and longitudinal analyses spanning a decade or more confirm that these effects persist rather than fade (Magrini & Grassini, 2019), while core natural and cultural resources furnish the enduring appeal that infrastructure then makes accessible. Digital readiness has moved from a peripheral concern to a central one, strengthening competitiveness through information flow, reservation and payment systems and communication with visitors, but its gains are distributional: ICT amplifies the tourism-growth relationship only where the enabling infrastructure and skills are present (Jayaraman & Makun, 2020).

Environmental factors simultaneously attract visitors and support long-term viability, with their effects on tourism demand and competitiveness shaped by sustainability indicators, environmental regulation, green policies, governance quality, institutional and human-resource conditions, stakeholder cooperation (Enright &

Newton, 2004), and transport-related environmental externalities associated with growing economic and trade activity (Gachayev et al., 2026).

4.5. Demand-side dynamics

Travellers' perceptions convert competitive conditions into visits, satisfaction and return, yet this is the part of the field that panel studies integrate least well. Andrades-Caldito et al. (2014) showed for Andalusia that visitors' assessments of infrastructure and service quality shape satisfaction, length of stay and spending, outcomes supply-side indices predict only indirectly, while motivations condition how visitors read competitiveness, so the same attributes register differently across segments (Ban et al., 2025). A destination competes not on its attributes as measured, but on how they are perceived. More recently, digital information environments have added another layer to this demand-side mechanism, as the credibility of online reviews and tourists' cognitive processing of social-media information can shape sustainable tourism choices (Eminov et al., 2026).

4.6. Empirical illustration: Competitiveness scores and tourism performance

Table 2 presents the dataset. The twenty-one economies span the top of the 2024 ranking, from the United States (5.24) to Cyprus (4.37), mean 4.75 (SD 0.28), while performance varies far more widely: arrivals from 3.9 to 100.0 million (mean 32.3 million) and receipts from US$3.2 to US$189.1 billion (mean US$42.7 billion). Nineteen are high-income economies, mirroring the index's upper tier.

Table 2

Competitiveness scores and tourism performance of the sampled economies (n = 21)

Economy	TTDI 2024 score	Arrivals 2023 (million)	Receipts 2023 (US$ billion)
United States	5.24	66.48	189.1
Spain	5.18	85.17	92.2
Japan	5.09	25.07	38.6
France	5.07	100.00	71.2
Australia	5.00	7.19	46.1
Germany	5.00	34.80	37.4
United Kingdom	4.96	37.22	73.4
Italy	4.90	57.25	55.9
Canada	4.81	18.34	38.5
Portugal	4.78	26.54	27.4
Korea, Rep.	4.74	11.03	15.3
Austria	4.65	30.91	24.7
Netherlands	4.64	20.30	20.7
United Arab Emirates	4.62	28.15	51.9
Sweden	4.57	7.53	9.9
Greece	4.52	32.74	22.3
Ireland	4.44	6.30	7.5
Brazil	4.41	5.91	6.9
Poland	4.40	18.99	15.0
Türkiye	4.39	55.16	49.5
Cyprus	4.37	3.85	3.2

Sources: World Economic Forum (2024); UN Tourism (2024)

The association is positive and significant on every metric, but its strength depends on which side of performance is examined (Table 3). The score correlates moderately with arrivals and markedly more strongly with receipts, and the bivariate regressions tell the same story: a one-point higher score implies 1.91 log-points more arrivals but explains only a third of their variation, whereas for receipts the coefficient is 2.74 and the explained share rises to 0.62. A 0.1-point advantage thus implies roughly 21 per cent more arrivals but about 32 per cent higher receipts (Figure 2).

Table 3

Association between the TTDI 2024 score and tourism performance (n = 21)

Statistic	log arrivals 2023	log receipts 2023
Pearson r	0.59 (p = 0.005)	0.72 (p < 0.001)
Spearman rho	0.56 (p = 0.009)	0.75 (p < 0.001)
OLS slope on TTDI score	1.91	2.74
t-statistic	3.08 (p = 0.006)	5.60 (p < 0.001)
R^2	0.33	0.62
Implied effect of +0.1 score	+21%	+32%

Note: bivariate OLS of the natural logarithm of each performance measure on the overall TTDI score.

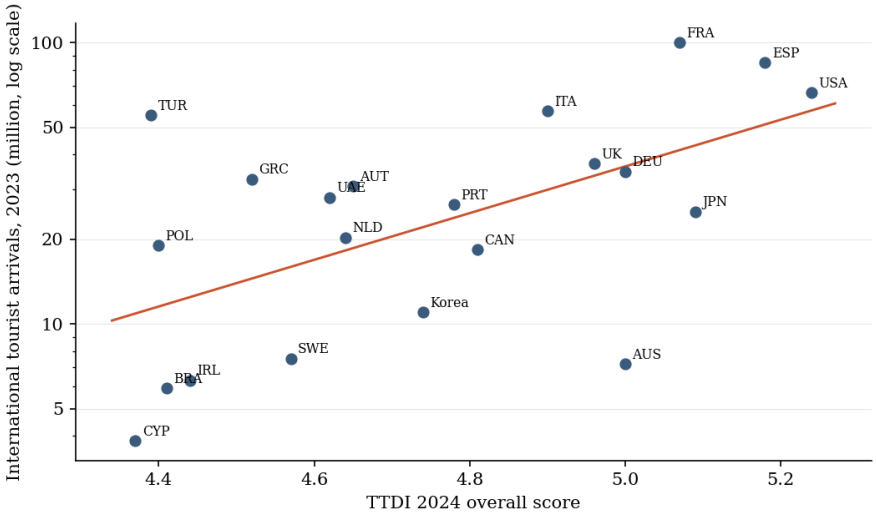


Fig. 2. TTDI 2024 score and international tourist arrivals, 2023 (n = 21; fitted line from the regression of log arrivals on the score).

Türkiye's low score despite high arrivals and Australia's higher score despite fewer visitors but substantial receipts suggest that the index better captures tourism value creation than visitor volume, helping reconcile mixed evidence on its predictive validity (Hiyab et al., 2023).

5. Discussion

The measurement debate is inherently theoretical because weighting choices reflect competing definitions of competitiveness, making transparent and stress-tested index construction essential (Gómez-Vega & Picazo-Tadeo, 2019). Competitiveness is also development-dependent: infrastructure and connectivity remain critical in lower-income destinations, while advanced economies increasingly rely on experience quality, sustainability, and digital capabilities (Hanafiah & Ali, 2024; Jayaraman & Makun, 2020), although existing frameworks still underrepresent demand-side mechanisms linking competitiveness to visits and loyalty (Andrades-Caldito et al., 2014; Ban et al., 2025).

Future research should integrate supply- and demand-side measures (Mior Shariffuddin et al., 2023), develop dynamic and predictive indices, examine environmental–digital interactions, and employ transparent hybrid approaches (Lin et al., 2023). These conclusions remain limited by English-language Scopus coverage, single-author coding, the absence of statistical pooling, and a cross-sectional illustration that indicates association rather than causation.

6. Conclusions

Infrastructure, ICT readiness and environmental quality are the most stable drivers of destination competitiveness, though their force depends on a country's level of development. The TTCI remains the common reference, but its aggregation, equal weighting and uneven predictive power have pushed researchers toward alternative measures and toward methods that compensate for one another's limits. The demand side still waits to be written into competitiveness models, even though perceptions and motivations are what turn competitive potential into performance. The agenda therefore calls for frameworks holding supply and demand together, indices that are dynamic rather than fixed, and a practice plural in its tools and transparent about its assumptions.

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КОНКУРЕНТОСПОСОБНОСТЬ И ПРИВЛЕКАТЕЛЬНОСТЬ ТУРИСТИЧЕСКИХ РЕГИОНОВ: СИСТЕМАТИЧЕСКИЙ ОБЗОР МЕЖДУНАРОДНЫХ ИССЛЕДОВАНИЙ

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Резюме. Конкурентоспособность туризма и привлекательность туристских дестинаций являются ключевыми факторами позиционирования стран на мировом туристском рынке. Вместе с тем научные исследования по обоим направлениям развивались быстрыми и неравномерными темпами. В статье рассматриваются 109 документов, индексируемых в базе данных Scopus и опубликованных в период с 2003 по 2026 год, с объединением количественной характеристики научной литературы и тематического синтеза. Исследовательский корпус резко расширился после 2015 года и характеризуется выраженной структурной несбалансированностью:

исследования, посвящённые измерению и концептуальным основам (33,0%), а также определяющим факторам (32,1%), занимают доминирующее положение; на аналитические методы приходится 24,8%, тогда как на исследования восприятия со стороны спроса — лишь 10,1%. Индекс конкурентоспособности путешествий и туризма остаётся основным сравнительным ориентиром. Однако использование равных весов показателей, высокие требования к данным и неоднородная прогностическая валидность данного индекса способствовали переходу к альтернативным и гибридным методам оценки. Ни один метод не занимает доминирующего положения: анализ среды функционирования (DEA), TOPSIS, моделирование путей методом частичных наименьших квадратов (PLS) и взвешивание на основе теории игр взаимно компенсируют недостатки друг друга. Инфраструктура, уровень готовности к использованию информационно-коммуникационных технологий и качество окружающей среды выступают наиболее устойчивыми определяющими факторами, влияние которых зависит от уровня доходов. Иллюстративный анализ, основанный на сопоставлении Индекса развития путешествий и туризма за 2024 год с данными ООН Туризм по 21 ведущей туристской дестинации, выявил умеренную корреляцию с количеством туристских прибытий (r = 0,59) и более сильную корреляцию с доходами от туризма (r = 0,72). Это свидетельствует о том, что измеряемая конкурентоспособность в большей степени связана с экономической ценностью туризма, чем с его объёмом.

Ключевые слова: *конкурентоспособность туризма, привлекательность туристических дестинаций, систематический обзор литературы, комплексные показатели, результативность туризма*

TURİZM REGİONLARININ RƏQABƏTQABİLİYYƏTLİLİYİ VƏ CƏLBEDİCİLİYİ: BEYNƏLXALQ TƏDQİQATLARIN SİSTEMATİK İCMALI

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Xülasə. Turizmin rəqabətqabiliyyətliliyi və turizm destinasiyalarının cəlbediciliyi ölkələrin qlobal turizm bazarında mövqelərini müəyyənləşdirməsində əsas amillərdir. Bununla belə, hər iki istiqamət üzrə elmi tədqiqatlar sürətlə və qeyri-bərabər şəkildə inkişaf etmişdir. Məqalədə 2003–2026-cı illər ərzində dərc edilmiş və Scopus bazasında indeksləşdirilmiş 109 sənəd nəzərdən keçirilmiş, elmi ədəbiyyatın kəmiyyət xarakteristikası tematik sintezlə birləşdirilmişdir. Tədqiqat korpusu 2015-ci ildən sonra kəskin şəkildə genişlənmiş və nəzərəçarpacaq dərəcədə qeyri-bərabər struktur nümayiş etdirmişdir: ölçmə və konseptual çərçivələr (33,0%) və müəyyənedici amillər (32,1%) üstünlük təşkil etmiş, analitik metodların payı 24,8%, tələb tərəfinin qavrayışına dair tədqiqatların payı isə cəmi 10,1% olmuşdur. Səyahət və Turizmin Rəqabətqabiliyyətliliyi İndeksi əsas müqayisə meyarı olaraq qalır. Lakin bu indeksdə göstəricilərə bərabər çəki verilməsi, məlumatlara yüksək tələbat və proqnozlaşdırma etibarlılığının qeyri-bərabər olması tədqiqat sahəsini alternativ və hibrid qiymətləndirmə üsullarına yönəltmişdir. Heç bir metod üstün mövqe tutmur: verilənlərin əhatə təhlili (DEA), TOPSIS, qismən ən kiçik kvadratlar əsasında yol modelləşdirilməsi (PLS) və oyun nəzəriyyəsinə əsaslanan çəkiləndirmə metodları bir-birinin zəif tərəflərini kompensasiya edir. İnfrastruktur, informasiya və kommunikasiya texnologiyalarına hazırlıq səviyyəsi və ətraf mühitin keyfiyyəti ən sabit müəyyənedici amillərdir və onların təsiri gəlir səviyyəsindən asılı olaraq dəyişir. 2024-cü il Səyahət və Turizmin İnkişafı İndeksinin 21 aparıcı turizm destinasiyası üzrə BMT Turizminin məlumatları ilə uyğunlaşdırılması əsasında aparılan nümunəvi təhlil turist gəlişlərinin sayı ilə orta səviyyəli korrelyasiya (r = 0,59), turizm gəlirləri ilə isə daha güclü korrelyasiya (r = 0,72) aşkar etmişdir. Bu, ölçülən rəqabətqabiliyyətliliyin turizmin həcmindən daha çox onun yaratdığı iqtisadi dəyərlə əlaqəli olduğunu göstərir.

Açar sözlər: *turizmin rəqabət qabiliyyəti, turizm destinasiyalarının cəlbediciliyi, ədəbiyyatın sistematik icmalı, kompleks göstəricilər, turizm fəaliyyətinin nəticələri*

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THE RELATIONSHIP BETWEEN TOURISM DEMAND AND HOTEL BUSINESS REVENUES: A CASE STUDY OF MINGACHEVIR

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Keywords: *tourism demand, hotel revenues, domestic tourism, foreign tourism, ARDL, FMOLS, Mingachevir*

Summary. As a multifaceted economic activity, tourism plays a crucial role in regional development by increasing income levels, stimulating investment, and generating employment through strong multiplier effects across related sectors. In this context, the hotel industry constitutes a central element of local tourism economies, as hotel revenues are directly influenced by tourism demand. This study examines the relationship between tourism demand and hotel revenues in Mingachevir, Azerbaijan, with a particular focus on the comparative effects of domestic and foreign overnight stays. Annual data from official statistical sources are analyzed using the Autoregressive Distributed Lag (ARDL) approach and Fully Modified Ordinary Least Squares (FMOLS) estimation techniques. The ARDL bounds test indicates a statistically significant long-run cointegration relationship among hotel revenues, domestic overnight stays, and foreign overnight stays. The error correction term is negative and significant, confirming convergence toward long-run equilibrium. FMOLS results show that both domestic and foreign tourism positively affect hotel revenues; however, domestic tourism has a substantially stronger impact. Specifically, a 1% increase in domestic overnight stays leads to an approximate 2.98% rise in hotel revenues, compared to 0.50% for foreign overnight stays. These findings underscore the dominant role of domestic tourism in shaping hotel performance and provide policy-relevant implications for regional tourism development and revenue optimization strategies.

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1. Introduction

Tourism supports regional development through employment, business activity, and multiplier effects across construction, agriculture, trade, and services (Motsa et al., 2021; Bassil et al., 2023), while growing visitor flows can stimulate investment in transport, utilities, digital infrastructure, accommodation, and recreation, consistent with Butler's Tourism Area Life Cycle (Corbos et al., 2024; Butler, 2024). Hotels are central to these linkages because visitor expenditure extends beyond accommodation to complementary services and local suppliers (Garcia-Delgado et al., 2020; Solmaz, 2024), although revenues remain sensitive to seasonality and visitor composition (Cosmin and Nistoreanu, 2021).

Tourism demand directly influences hotel occupancy and RevPAR (Ismail et al., 2002; Lee et al., 2019), while stronger demand can support higher ADR (Hikmawati and Ramdhani, 2024), with financial effects varying across visitor segments (Le et al., 2026). Demand itself responds to income, prices, and exchange rates (Martins, Gan, & Ferreira-Lopes, 2017), and long-run relationships are well established through cointegration approaches (Song, Romilly, & Liu, 2000). Nevertheless, hotel-specific demand research remains relatively limited (Wu, Song, & Shen, 2017), despite advances in econometric specification (Dogru, Bulut, & Sirakaya-Turk, 2021; Song, Qiu, & Park, 2023) and evidence linking hotel performance to consumer confidence, tourism flows, occupancy, ADR, inflation, wages, and energy costs (Chen et al., 2019; Chu, 2025), alongside broader links between tourism-led growth and demand elasticity (Stauvermann & Kumar, 2017).

Recent research has expanded toward data-driven forecasting (Kaya et al., 2022), technology and sustainability (Sampaio, Sebastião, & Farinha, 2024), and digital tools that can stimulate tourism demand and revenues (Hao, Ouyang, & Yao, 2026). COVID-19 further highlighted the importance of pricing, revenue management, resilience, and regional recovery (Agbola, Dogru, & Gunter, 2020; Denizci Guillet & Chu, 2021; Boto-García & Mayor, 2022; Singh & Corsun, 2023), while accommodation infrastructure remains important for regional tourism development (Matyakubov, Allonazarov, & Farudz, 2026). Yet medium-sized destinations remain understudied, making Mingachevir—with its natural and cultural tourism resources (ATB, 2026) and nine hotel-type establishments—a relevant setting for examining how visitor flows translate into hotel revenues.

2. Data and methodology

This study examines the relationship between tourism demand and hotel revenues in Mingachevir using annual data from the World Bank (WB, 2026) and the State Statistical Committee of the Republic of Azerbaijan (SSCRA, 2026). Figure 1 indicates that hospitality growth has been driven mainly by steadily increasing domestic overnight stays, while foreign demand is more volatile, underscoring the importance of domestic tourism for hotel revenue stability.

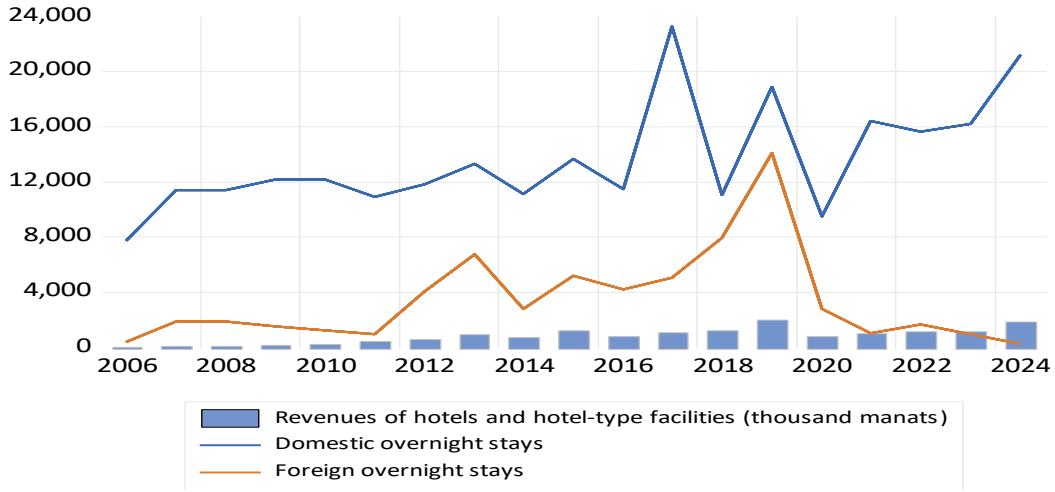


Fig. 1. Time-Series Evolution of Tourism Demand and Hotel Revenues in Mingachevir

Hotel revenue (LREV) and domestic (LDOM) and foreign (LFORE) overnight stays were log-transformed, allowing coefficient interpretation as elasticities. Table 1 indicates approximate normality and greater stability of domestic tourism, reinforcing its dominant role in Mingachevir's hotel demand.

Table 1

Descriptive Statistics of the Variables

Statistic	LREV	LFORE	LDOM
Mean	6.360	7.681	9.484
Median	6.71	7.526	9.409
Maximum	7.618	9.553	10.054
Minimum	4.166	5.552	8.954
Std. Dev.	1.038	1.03	0.276
Skewness	-0.87	-0.25	0.431
Kurtosis	2.433	2.596	2.777
Jarque-Bera	2.680	0.34	0.628
Probability	0.261	0.842	0.730

The Augmented Dickey–Fuller (ADF) test was applied to determine the variables' integration orders and confirm the absence of I(2) series. Given the potential mixture of I(0) and I(1) variables, the ARDL bounds-

testing approach of Pesaran, Shin, and Smith (2001) was then used to assess long-run cointegration. The unrestricted error correction representation of the ARDL model is specified as follows:

$$\Delta LREV_t = \alpha_0 + \sum_{\{i=1\}}^{\{p\}} \beta_{\Delta LREV_{\{t-i\}}} + \sum_{\{j=0\}}^{\{q_1\}} \gamma_{\Delta LDOM_{\{t-j\}}} + \sum_{\{k=0\}}^{\{q_2\}} \theta_{\Delta LFORE_{\{t-k\}}} + \phi_1 LREV_{\{t-1\}} + \phi_2 LDOM_{\{t-1\}} + \phi_3 LFORE_{\{t-1\}} + \varepsilon_t \quad (1)$$

To obtain robust long-run estimates while addressing issues of endogeneity and serial correlation in cointegrated systems, the Fully Modified Ordinary Least Squares (FMOLS) estimator developed by Phillips and Hansen (1990) was applied. The FMOLS estimator can be expressed as:

$$\hat{\beta}_{FMOLS} = \left(\sum_{\{t=1\}}^{\{T\}} (X_t - \bar{X})^2 \right)^{-1} \sum_{\{t=1\}}^{\{T\}} (X_t - \bar{X})\left(Y_t^* - \hat{\Omega}_{21}\hat{\Omega}_{22}^{-1}\Delta X_t\right) \quad (2)$$

where Y_t denotes the bias-corrected dependent variable, while Ω_{21} and Ω_{22} represent the long-run covariance components used to correct for endogeneity and serial correlation. Following the ADF stationarity and ARDL bounds cointegration tests, FMOLS was employed to estimate robust long-run elasticities of domestic and foreign tourism demand with respect to hotel revenues in Mingachevir.

3. Results

The Augmented Dickey–Fuller (ADF) results in Table 2 show that LREV, LFORE, and LDOM are non-stationary at levels but become stationary after first differencing, confirming that all variables are integrated of order one, I(1). The absence of I(2) variables satisfies the integration-order requirement for the ARDL bounds-testing approach, while the I(1) properties of the series also support the subsequent application of FMOLS for estimating their cointegrating long-run relationship.

Table 2

Augmented Dickey–Fuller (ADF) Unit Root Test Results

Variable	Level (t-stat)	Prob.	First Difference (t-stat)	Prob.	Order of Integration
LREV	-2.290	0.185	-5.466 ***	0.000	I(1)
LFORE	-1.853	0.344	-3.941 ***	0.009	I(1)
LDOM	-1.388	0.562	-4.240 ***	0.006	I(1)

*** denotes statistical significance at the 1% level, and "Prob." indicates MacKinnon (1996) one-sided p-values.

Figure 2 reveals a positive relationship between both domestic and foreign overnight stays and hotel revenues in Mingachevir, although the stronger and more consistent association observed for domestic stays suggests that domestic tourism is the more stable contributor to revenue growth.

The ARDL bounds test results in Table 3 yield an **F-statistic of 5.4425**, exceeding the **1% upper critical bound (I(1) = 5.00)** and therefore providing strong evidence against the null hypothesis of no long-run relationship. Accordingly, **LREV, LDOM, and LFORE are cointegrated**, indicating that hotel revenues and domestic and foreign overnight stays share a stable long-run equilibrium relationship and move together systematically over time.

The error-correction term (ECT = −0.1622, $p < 0.01$) reported in Table 4 is negative and statistically significant, confirming convergence toward a stable long-run equilibrium. Its magnitude indicates that approximately 16.2% of short-run disequilibrium is corrected annually, while changes in foreign overnight stays (ΔLFORE) exert a positive but only weakly significant short-run effect on hotel revenues at the 10% level.

The Variance Inflation Factor (VIF) results presented in Table 5 indicate that multicollinearity is not a significant issue in the estimated model. All centered VIF values for the explanatory variables, including LDOM, LFORE, and their lagged terms, are well below both the conservative threshold of 5 and the conventional upper limit of 10. This confirms the absence of strong linear interdependencies among the regressors, ensuring that the estimated coefficients remain stable and are not affected by redundancy in the explanatory variables. Consequently, the individual impacts of domestic and foreign overnight stays on hotel revenues in Mingachevir can be reliably interpreted. Overall, the model satisfies the multicollinearity diagnostic requirement, thereby reinforcing the robustness and validity of the ARDL estimation results.

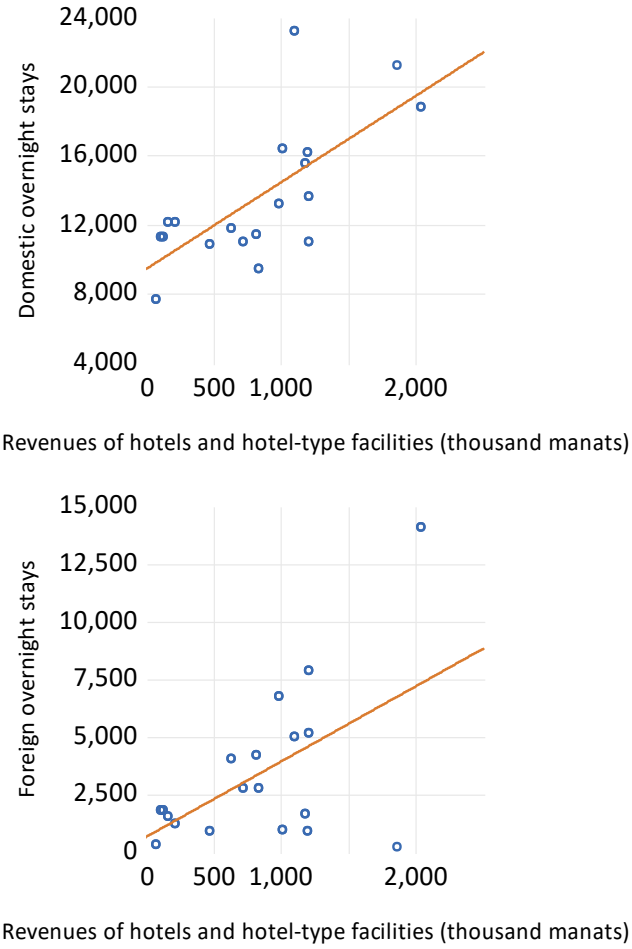


Fig. 2. Scatter plot of domestic and foreign tourism vs hotel revenues

Table 3

ARDL (1,1,0) Bounds Test Results for Cointegration

Test Statistic	Value	Significance Level	I(0) Lower Bound	I(1) Upper Bound	Decision
F-statistic	5.4425	10%	2.63	3.35	Reject H_0
		5%	3.10	3.87	Reject H_0
		2.5%	3.55	4.38	Reject H_0
		1%	4.13	5.00	Reject H_0

Note: H_0: No long-run (cointegration) relationship exists.

Table 4

Error Correction Model (ECM) Results

Variable	Coefficient	Std. Error	t-Statistic	Probability	Interpretation
D(LFORE)	0.1376	0.0706	1.9487	0.0732	Positive, weakly significant (10%)
CointEq(-1)	-0.1622	0.0313	-5.1763	0.0002	Negative, highly significant (1%)

Note: CointEq(-1) represents the error correction term (ECT), capturing the speed of adjustment toward long-run equilibrium.

Table 5

Multicollinearity Diagnostic Results (VIF)

Variable	Coefficient Variance	Uncentered VIF	Centered VIF
LREV(-1)	0.009253	89.78245	2.206698
LFORE	0.007365	107.9794	1.546178
LFORE(-1)	0.014050	206.7822	2.671581
LDOM	0.091942	1988.612	1.312321
C (Constant)	8.773253	2095.243	NA

The diagnostic results in Table 6 confirm the adequacy of the estimated ARDL model, as the Breusch–Godfrey test (p = 0.4588) indicates no evidence of serial correlation, while the Breusch–Pagan–Godfrey test (p = 0.8918) suggests homoskedastic residuals. These findings indicate that the model is free from these key residual specification problems, supporting the reliability of statistical inference regarding the effects of domestic and foreign overnight stays on hotel revenues in Mingachevir.

Table 6

Model Diagnostic Results

Test Type	Statistic	Value	p-value	Result
Breusch-Godfrey LM	Obs*R-squared	0.548896	0.4588	No Serial Correlation
Breusch-Pagan-Godfrey	Obs*R-squared	1.115703	0.8918	Homoskedasticity

The CUSUM and CUSUM of Squares results presented in Figure 3 support the structural stability of the estimated model, as the recursive statistics remain within the 5% critical boundaries throughout the sample period. This suggests no evidence of parameter instability and supports the reliability of the ARDL short- and long-run estimates for interpreting the relationship between overnight stays and hotel revenues in Mingachevir.

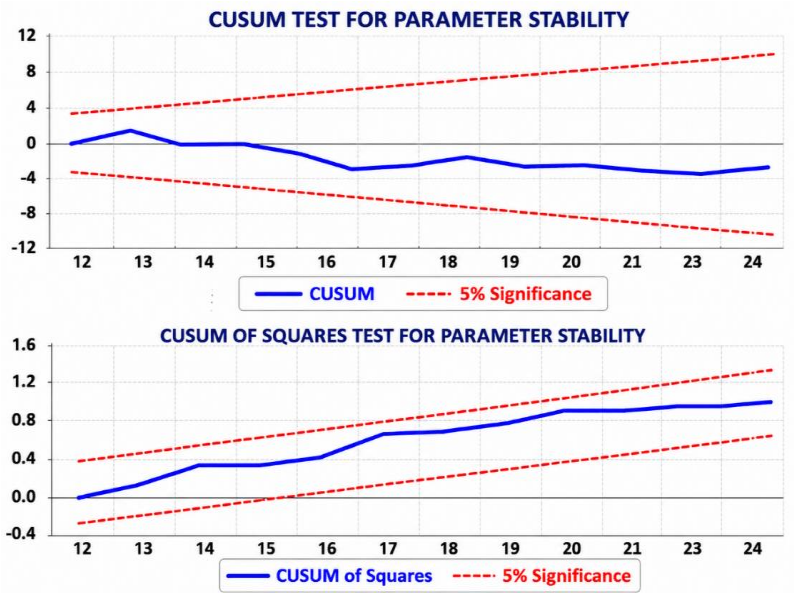


Fig. 3. Model Stability Diagnostics Using CUSUM and CUSUM of Squares Tests

The FMOLS (Fully Modified Least Squares) results reported in Table 7 indicate that both foreign and domestic overnight stays have a positive and statistically significant influence on hotel revenues in Mingachevir, at the 5% and 1% significance levels, respectively. The estimated coefficients further suggest that domestic tourism has a substantially stronger effect, as a 1% increase in LDOM leads to an approximate 2.98% increase in revenues, whereas the corresponding effect of LFORE is comparatively smaller, at around 0.50%.

Table 7

FMOLS Long-Run Cointegration Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LFORE	0.496448	0.209046	2.374825	0.0313**
LDOM	2.983698	0.801741	3.721522	0.0020***
C (Constant)	-25.73276	7.991632	-3.219963	0.0057***

Note: Statistical significance levels are indicated as follows: **p < 0.05, and ***p < 0.01.

These findings reinforce the robustness of the long-run relationship identified in the model and highlight the dominant role of domestic demand in shaping revenue dynamics. While international tourism contributes positively, the domestic segment emerges as the principal driver of financial performance in the local hospitality sector.

4. Discussion

The empirical findings confirm that tourism demand significantly influences hotel revenues in Mingachevir, supporting the established relationship between visitor demand and hotel performance (Song & Li, 2008). Although both domestic and foreign overnight stays contribute positively to revenues, domestic tourism emerges as the stronger and more statistically significant driver, consistent with the heterogeneous economic effects of different visitor segments identified by Dwyer and Forsyth (2006). Mingachevir's accessibility and its Kura River–based recreational opportunities support short-stay and seasonal domestic tourism, reflecting the importance of water-based resources for tourism demand (Hall & Page, 2014), while tourism activity in Azerbaijan remains sensitive to economic conditions and external shocks such as COVID-19 (Mayis et al., 2021).

The weaker contribution of foreign overnight stays suggests that Mingachevir may function more as a supplementary or transit destination for international visitors, with limited entertainment and experience-based services potentially restricting visitor stays and expenditure (Middleton & Clarke, 2001). Overall, strengthening year-round tourism products, extending visitor stays, and developing higher-value experiences could enhance the long-term financial performance of Mingachevir's hotel sector.

5. Conclusion

Tourism and hospitality demand is shaped by economic conditions, prices, destination characteristics, seasonality, and external shocks. The literature consistently shows that income positively influences tourism demand, while higher prices generally reduce it, supporting conventional demand theory. Cointegration-based approaches, including ARDL, Johansen, and error-correction models, further demonstrate that tourism demand and its macroeconomic determinants tend to share stable long-run relationships, although temporary short-run deviations may occur. Significant error-correction mechanisms indicate that such disequilibria gradually return to their long-run paths. Meanwhile, forecasting methods have increasingly evolved from traditional econometric techniques toward hybrid and data-driven approaches that can improve predictive performance under changing market conditions. From a policy perspective, stronger tourism data systems, resilient domestic tourism, sustainable infrastructure investment, and balanced destination development are essential. At the industry level, advanced econometric and machine-learning forecasting can support more effective pricing, capacity planning, and revenue management, thereby strengthening the tourism sector's long-term competitiveness, resilience, and financial sustainability.

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ВЗАИМОСВЯЗЬ ТУРИСТИЧЕСКОГО СПРОСА И ДОХОДОВ ГОСТИНИЧНОГО БИЗНЕСА: ИССЛЕДОВАНИЕ НА ПРИМЕРЕ МИНГЯЧЕВИРА

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Резюме. Туризм как многоаспектный вид экономической деятельности играет важную роль в региональном развитии, способствуя повышению уровня доходов, стимулированию инвестиций и созданию рабочих мест благодаря выраженным мультипликативным эффектам в смежных отраслях. В данном контексте гостиничная индустрия представляет собой ключевой элемент местной туристской экономики, поскольку доходы гостиниц непосредственно зависят от туристского спроса. В исследовании рассматривается взаимосвязь между туристским спросом и доходами гостиниц в городе Мингячевир (Азербайджан) с особым акцентом на сравнительном влиянии ночёвок внутренних и иностранных туристов. Годовые данные, полученные из официальных статистических источников, анализировались с использованием модели авторегрессии с распределёнными лагами (Autoregressive Distributed Lag – ARDL) и метода полностью модифицированных наименьших квадратов (Fully Modified Ordinary Least Squares – FMOLS). Граничный тест ARDL указывает на наличие статистически значимой долгосрочной коинтеграционной связи между доходами гостиниц, количеством ночёвок внутренних туристов и количеством ночёвок иностранных туристов. Отрицательное и статистически значимое значение коэффициента коррекции ошибок подтверждает сходимость к долгосрочному равновесию. Результаты применения метода FMOLS показывают, что как внутренний, так и международный туризм оказывают положительное влияние на доходы гостиниц, однако воздействие внутреннего туризма значительно сильнее. В частности, увеличение количества ночёвок внутренних туристов на 1% приводит к росту доходов гостиниц приблизительно на 2,98%, тогда как соответствующий показатель для ночёвок иностранных туристов составляет 0,50%. Полученные результаты подчёркивают доминирующую роль внутреннего туризма в формировании показателей деятельности гостиниц и имеют важное практическое значение для разработки политики регионального развития туризма и стратегий оптимизации доходов.

Ключевые слова: *туристический спрос, доходы гостиниц, внутренний туризм, иностранный туризм, ARDL, FMOLS, Мингячевир*

TURİZM TƏLƏBİ İLƏ MEHMANXANA BİZNESİNİN GƏLİRLƏRİ ARASINDA ƏLAQƏ: MİNGƏÇEVİR NÜMUNƏSİNDƏ TƏDQİQAT

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Xülasə. Çoxşaxəli iqtisadi fəaliyyət növü olan turizm əlaqəli sahələrdə güclü multiplikativ təsirlər yaratmaqla gəlir səviyyəsinin yüksəldilməsi, investisiyaların stimullaşdırılması və məşğulluğun təmin edilməsi vasitəsilə regional inkişafda mühüm rol oynayır. Bu kontekstdə mehmanxana sənayesi yerli turizm iqtisadiyyatının əsas tərkib hissəsini təşkil edir, çünki mehmanxana gəlirləri birbaşa turizm tələbatından asılıdır. Tədqiqatda Azərbaycanın Mingəçevir şəhərində turizm tələbatı ilə mehmanxana gəlirləri arasındakı əlaqə araşdırılır və daxili və xarici turistlərin gecələmələrinin müqayisəli təsirlərinə xüsusi diqqət yetirilir. Rəsmi statistik mənbələrdən əldə edilmiş illik məlumatlar avtoreqressiv paylanmış gecikmə (Autoregressive Distributed Lag – ARDL) modeli və tam modifikasiya olunmuş ən kiçik kvadratlar (Fully Modified Ordinary Least Squares – FMOLS) qiymətləndirmə metodları vasitəsilə təhlil edilmişdir. ARDL sərhəd testi mehmanxana gəlirləri, daxili turistlərin gecələmələri və xarici turistlərin gecələmələri arasında statistik baxımdan əhəmiyyətli uzunmüddətli kointeqrasiya əlaqəsinin mövcudluğunu göstərir. Xətaların korreksiyası əmsalının mənfi və statistik baxımdan əhəmiyyətli olması uzunmüddətli tarazlığa doğru yaxınlaşmanı təsdiqləyir. FMOLS metodunun nəticələri həm daxili, həm də xarici turizmin mehmanxana gəlirlərinə müsbət təsir göstərdiyini, lakin daxili turizmin təsirinin əhəmiyyətli dərəcədə daha güclü olduğunu göstərir. Belə ki, daxili turistlərin gecələmələrinin sayında 1% artım mehmanxana gəlirlərinin təxminən 2,98% yüksəlməsinə səbəb olduğu halda, xarici turistlərin gecələmələri üzrə müvafiq göstərici 0,50% təşkil edir. Əldə edilən nəticələr mehmanxanaların fəaliyyət göstəricilərinin formalaşmasında daxili turizmin üstün rolunu vurğulayır və regional turizmin inkişafı, eləcə də gəlirlərin optimallaşdırılması strategiyaları baxımından turizm siyasətinin formalaşdırılması üçün əhəmiyyətli nəticələr təqdim edir.

Açar sözlər: *turizm tələbi, mehmanxana gəlirləri, daxili turizm, xarici turizm, ARDL, FMOLS, Mingəçevir*

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SPATIAL ASSESSMENT OF SMART TOURISM READINESS IN POST-WAR TERRITORIES

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Keywords: *smart tourism readiness, post-war reconstruction, spatial assessment, Analytic Hierarchy Process, Karabakh, destination competitiveness*

Summary. Territories rebuilt from war are almost absent from smart tourism research, which has developed around mature cities that add digital tools to infrastructure accumulated over decades. This matters because reconstruction offers a rare chance to design a destination and its digital layer together from the ground up, yet no instrument exists to assess how ready such a place is. This study fills that gap with the Smart Tourism Readiness Index (SITRI), a five-dimension composite weighted through the Analytic Hierarchy Process (AHP) at a confirmed consistency ratio of CR = 0.018. Using a mixed secondary-data design and four-category source triangulation, the index is applied to Azerbaijan's Karabakh and East Zangezur regions across the 2020–2026 reconstruction period, scoring five destinations against documented evidence. The regional mean readiness is 3.63 on a 1–5 scale; Zangilan (4.17) and Fuzuli (4.03) reach the High band through purpose-built airports and greenfield settlement design, while heritage-anchored Shusha (3.95) leads on demand. The central finding is a sequencing signature: the mobility backbone is built first and fastest, while the traveller-facing services that turn a reachable place into a usable one are deferred behind physical construction. The study repositions readiness as a reconstruction-phase variable and offers a diagnostic transferable to other post-conflict contexts.

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1. Introduction

In the tourism literature, the reconstruction of a destroyed region is seldom treated as more than an aftermath — a repair of what was lost, whose interest fades once the crisis passes. The settlements now emerging across formerly contested territories invite a different reading. They are not being rebuilt to their earlier form, but planned from the outset around digital administration, renewable energy, and networked infrastructure, so that the language of the smart city is applied to what is, in effect, an empty map. Where there is no legacy system to work around, the analytical question shifts: the issue is no longer how quickly a place recovers, but what kind of place it is deliberately being designed to become.

Azerbaijan's Karabakh and East Zangezur regions offer an unusually legible instance of this dynamic. Following the events of 2020, the government launched one of the most capital-intensive reconstruction programmes of the past decade, directing roughly USD 10.3 billion into the two regions through the 2025 budget cycle. Three international airports were built at Fuzuli, Zangilan, and Lachin; more than 1,400 kilometres of road entered construction; and the new settlements — Aghali in Zangilan being the earliest completed example — were conceived as "smart villages" integrating renewable generation, digital public services, and networked utilities. Shusha opened to visitors in December 2023 and a wider group of destinations from July 2025, with over 500,000 predominantly domestic arrivals reported in July 2025 alone. The reconstruction thus constitutes a large, well-documented natural experiment in building a tourism geography without a legacy.

The analytical apparatus needed to evaluate these places has not kept pace. Established destination-competitiveness and smart-tourism frameworks were calibrated for cities with continuous histories of use, assuming an installed base of transport, accommodation, and services onto which digital tools are grafted, and they say little about a destination where the accommodation, the road, the airport, and the digital permit system all arrive within the same five-year span. The reconstructed territory therefore falls into a conceptual blind spot, being neither a mature destination benchmarked in the usual way nor a greenfield project unconnected to prior settlement.

This study addresses that blind spot. Its guiding proposition is that smart tourism readiness, normally reserved for mature destinations, is most consequential in reconstruction, because the design choices locked in now will define the destination for a generation. Three research questions follow: how can readiness be conceptualised and measured where physical and digital infrastructure are built concurrently (RQ1); how does it vary spatially across reconstructed destinations within a single region (RQ2); and does the pattern reveal a systematic sequencing of reconstruction that enables or constrains tourism development (RQ3)? The contribution is at once conceptual, methodological, and empirical, and the analysis finds that the region is being rebuilt "backbone-first": physical access advances rapidly, but the digital and demand layers that make a destination usable for an actual visitor lag behind, leaving the design advantage of reconstruction only partly captured.

2. Conceptual background

Smart tourism transposes smart-city thinking into the visitor economy, describing destinations that weave together digital infrastructure, real-time data, and connected services to shape the visitor experience. Its most durable insight is that the "smartness" of a destination lies not in the presence of technology but in its integration into a coherent experience layer that reduces friction for the traveller — a distinction between mere deployment and genuine integration that carries directly into the reconstruction setting, where the temptation to equate new hardware with readiness is especially strong.

Destination-competitiveness research has long treated transport and infrastructure as core determinants, yet tends to conceptualise them as physical, supply-side stock — airport capacity, road density, bed count — capturing what a destination has installed rather than how a visitor engages it. A more recent strand on digital readiness corrects this by foregrounding the traveller-facing layer of contactless payment, real-time information, and integrated permits. Both traditions, however, presuppose an existing destination, and neither was designed for a place where physical stock and digital layer are created within the same construction cycle, so that readiness becomes a matter of design sequencing rather than accumulated endowment — precisely the condition a reconstruction setting imposes.

Research on post-conflict recovery, meanwhile, has concentrated on security, resettlement, livelihoods, and physical rehabilitation, and where tourism enters it is usually as dark or memorial tourism rather than as a planned sector with its own infrastructure logic. The purpose-built-city literature adds a caution that bears directly here: technological sophistication without organic economic density produces impressive but underused environments, so that readiness measured only through installed hardware risks reproducing the error of infrastructure without users. Three gaps therefore define the space this study occupies: no measurable instrument exists for readiness in a reconstruction setting; existing indices privilege physical stock and never ask the design-sequencing question; and post-conflict territories remain outside the smart-tourism evidence base. The SITRI is built to close all three.

3. Materials and methods

3.1. Design and data

The study adopts a mixed secondary-data design combining quantitative index construction with qualitative source triangulation, a choice dictated by the object of study: primary field survey across an active, partly demined reconstruction zone would be neither safe nor representative at this stage. The reconstruction is, however, unusually well documented, and evidence was drawn from four categories that corroborate one another: official state documents (reconstruction budgets, the Great Return State Programme, tourism concepts, smart-village design); international and independent reporting used to verify official figures; operator records (airport operations, permit portals, hotel openings); and peer-reviewed literature indexed in Scopus and Web of Science. All figures were taken in their most recent form as of early 2026, with the more conservative figure retained where sources diverged, over a 2020–2026 frame that captures the full reconstruction arc.

3.2. The smart tourism readiness index

The SITRI scores a destination across five dimensions on a 1–5 ordinal scale anchored to documented conditions rather than perception. D1, physical–digital mobility infrastructure, captures air, road, and rail connectivity with its digital enablement — the backbone that makes a destination reachable at all. D2, destination-facing digital services, measures electronic permits, booking and information systems, and multilingual usability, the layer that converts reachability into usability. D3, green and sustainable integration, assesses whether renewable energy and smart utilities are embedded from the outset rather than retrofitted. D4, institutional and governance readiness, records the presence of a coordinated planning body, an approved tourism concept, and an investment mechanism. D5, heritage and demand anchoring, gauges the cultural or resettlement base that generates actual demand — the corrective against readiness without users.

3.3. AHP weighting and computation

Rather than assuming equal contribution, the dimensions were weighted through the Analytic Hierarchy Process, which derives priorities from structured pairwise comparisons on the Saaty scale. Judgements prioritised the dimensions that determine whether a reconstructed place can function as a destination at all: mobility infrastructure (D1) was judged most decisive, since in a recently inaccessible territory reachability governs everything else, followed by destination-facing services (D2). The priority vector was obtained by the eigenvalue method (Table 1), and the consistency ratio, at CR = 0.018, lies well below the 0.10 threshold, confirming coherent judgements. The composite is computed as SITRI = Σ ($d_i \times w_i$), yielding a value on the 1.0–5.0 scale, with bands set at High ≥ 4.0, Moderate-High 3.0–3.9, Moderate 2.0–2.9, and Emerging < 2.0; an equal-weighted variant was computed as a robustness check. The five destinations — Shusha, Fuzuli, Zangilan, Lachin, and Aghdam — were selected purposively as the settlements combining the most advanced physical progress with the clearest tourism intent, spanning both economic regions, both reconstruction logics (heritage restoration and greenfield construction), and the full range of access maturity from the longest-open site to the earliest.

Table 1

AHP priority weights for the five SITRI dimensions (CR = 0.018)

Dim.	Definition	AHP weight	Rank
D1	Physical–digital mobility infrastructure	0.366	1
D2	Destination-facing digital services	0.253	2
D4	Institutional and governance readiness	0.153	3
D3	Green and sustainable integration	0.141	4
D5	Heritage and demand anchoring	0.087	5

Note. $\lambda_{max} = 5.078$; *CI = 0.020; RI = 1.12; CR = 0.018 < 0.10. Source: author's computation.*

4. Reconstruction context, 2020–2026

The SITRI values are meaningful only against the material conditions from which they derive. Between 2020 and the 2025 allocation, cumulative reconstruction spending reached approximately USD 10.3 billion, compressing into a few years a scale of destination-building that would ordinarily unfold across decades. The transport programme delivered the region's defining assets — Fuzuli International Airport (operational since October 2021, the principal gateway), Zangilan International Airport (October 2022), and a third airport at Lachin — alongside more than 1,400 kilometres of road, including the Fuzuli–Shusha "Victory Road". Resettlement advanced under the Great Return programme toward a planned 140,000 returnees by end-2026, and the tourism apparatus developed in parallel: concepts were prepared for Kalbajar and Lachin, hotel capacity concentrated in Shusha, and access was formalised through the yolumuzqarabaga.az and myGov permit portals, extended to foreign passport holders from July 2025. Table 2 summarises the indicators against which readiness is scored.

Table 2

Principal reconstruction and tourism indicators, Karabakh and East Zangezur, 2020–2026.

Indicator	Value (2020–2026)
Cumulative reconstruction spending	≈ USD 10.3 bn (+ 2.35 bn for 2025)
International airports built	3 (Fuzuli 2021, Zangilan 2022, Lachin)
Roads under construction	> 1,400 km across ~15 projects
Planned resettlement by end-2026	≈ 140,000 persons (both regions)
Reported visitors, July 2025	> 500,000 (predominantly domestic)
Foreign access opened	Shusha Dec 2023; wider set July 2025

Note. Compiled by the author from official budget disclosures, State Tourism Agency concepts, and corroborating reporting.

5. Results

The scores answer a simple question: how far has each place actually travelled toward being a functioning smart tourism destination? Fuzuli and Zangilan score at the ceiling on mobility (D1 = 5), each hosting a purpose-built airport on a new corridor, and Zangilan additionally leads on green integration (D3 = 5) through the Aghali smart-village design, where renewable generation and networked utilities were embedded from the first foundation rather than retrofitted. Shusha derives its strength from the demand side: as the region's cultural centre, the longest-open destination, and the site of the most developed hotel stock, it tops heritage anchoring (D5 = 5) and destination-facing services (D2 = 4). Aghdam, the largest reconstruction site by area, remains at an earlier tourism stage and trails on the digital-service and demand dimensions. Table 3 reports the full scoring and AHP-weighted composite.

Table 3

SITRI dimension scores (1–5) and AHP-weighted composite index by destination

Destination	D1	D2	D3	D4	D5	SITRI	Level
Zangilan	5	3	5	4	3	**4.17**	High
Fuzuli	5	3	4	4	3	**4.03**	High
Shusha	4	4	3	4	5	**3.95**	Mod-High
Aghdam	4	2	3	3	2	**3.03**	Mod-High
Lachin	3	3	3	3	3	**3.00**	Mod-High

Note. Equal-weighted robustness variant preserves the ranking (Zangilan 4.00; Shusha 4.00; Fuzuli 3.80; Lachin 3.00; Aghdam 2.80). Regional mean SITRI = 3.63.

The regional mean of 3.63 — Moderate-High — conceals a clear internal gradient (RQ2): the two greenfield airport destinations occupy the High band, the heritage centre sits at the top of Moderate-High, and the two later-stage sites anchor the lower end. Readiness tracks two things at once, purpose-built mobility infrastructure and the maturity of the tourism-specific overlay. Where both coincide (Zangilan, Fuzuli) readiness peaks; where mobility is strong but the overlay thin (Aghdam) the composite falls despite heavy investment, showing that hardware alone does not translate into readiness; and Shusha inverts the logic, offsetting a modest mobility score with an unmatched demand anchor and the region's most developed service layer. Reading down the columns exposes a sequencing signature (RQ3): every destination scores at least as high on mobility as on any other dimension, and lowest on digital services or demand anchoring. The backbone is installed first and fastest while the traveller-facing layer and demand lag behind — the same reform asymmetry seen in mature emerging destinations, here compressed into a single construction cycle.

6. Discussion

Three implications follow. The first concerns the meaning of readiness. The Karabakh case makes visible a distinction the mature-destination literature can afford to blur: that between a destination which is reachable and one which is usable. Fuzuli and Zangilan are highly reachable, since an airport and a corridor settle physical access, but whether they are yet usable — offering a non-resident an integrated digital pathway from permit to arrival to on-site information — is a separate and less advanced question that the SITRI captures by keeping D1 and D2 apart.

The second concerns the design window. Since the recurring lesson of purpose-built smart cities is that infrastructure without users becomes a costly monument, the reconstruction setting appears to offer an escape: physical and digital layers can be designed together from the outset — smart by design rather than smart by retrofit. The evidence suggests this promise is real but only partly realised, for the green and utility layer is integrated by design, most clearly at Aghali, whereas the traveller-facing digital layer is deferred behind physical construction in the familiar backbone-first sequence. The window is open but not used to its full width, from which the central policy inference follows: the digital-service and demand-anchoring dimensions should advance concurrently with the mobility backbone, not after it.

The third concerns transferability, since the value of a single-region index lies less in its specific scores than in whether the instrument travels. The five SITRI dimensions are not specific to Azerbaijan but describe conditions common to any territory rebuilding a tourism geography after conflict — reachability, visitor-facing services, sustainable integration, institutional coordination, and a demand anchor — so that, applied with locally calibrated scoring, the frame could furnish a common language for the cross-case comparison the literature currently lacks.

7. Conclusion

This study asked whether smart tourism readiness can be measured in a setting the concept was never designed for — a territory rebuilt from destruction, where the destination and its digital layer arrive together — and the answer is affirmative. The AHP-weighted Smart Tourism Readiness Index yields a coherent spatial reading of the Karabakh and East Zangezur reconstruction across 2020–2026: two greenfield, airport-anchored cases in the High band, a heritage centre leading on demand, and two later-stage sites consolidating, for a regional mean of 3.63 that is advancing distinctly backbone-first.

The study's central proposition — that post-war territories hold a narrow window in which smart tourism can be engineered by design rather than retrofitted — is thus supported but qualified. In practical terms, permit, information, and booking systems should be treated as first-phase infrastructure alongside the airport and the road, and each destination's demand anchor developed deliberately rather than assumed to follow from physical completion. Two limitations bound these conclusions: the scoring rests on documentary rather than primary visitor data, carrying a risk of assessment subjectivity, and the single-region scope leaves external validity to be demonstrated. Future research should therefore validate the SITRI against survey-based visitor data as the destinations mature, calibrate the AHP weights through an expert panel, and apply the framework comparatively across post-conflict geographies, converting a single-region diagnostic into a comparative research programme on the tourism geography of reconstruction.

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ПРОСТРАНСТВЕННЫЙ АНАЛИЗ ПОТЕНЦИАЛА РАЗВИТИЯ УМНОГО ТУРИЗМА НА ПОСТКОНФЛИКТНЫХ ТЕРРИТОРИЯХ

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Резюме. Территории, восстанавливаемые после военных конфликтов, практически не представлены в исследованиях умного туризма, которые преимущественно сосредоточены на развитых городах, внедряющих цифровые технологии в инфраструктуру, формировавшуюся на протяжении десятилетий. Данная проблема имеет существенное значение, поскольку процесс восстановления предоставляет редкую возможность одновременно проектировать туристскую дестинацию и её цифровую инфраструктуру

с нуля. Вместе с тем инструмент для оценки степени готовности таких территорий до настоящего времени отсутствует. Для устранения данного пробела в исследовании предлагается Индекс готовности к умному туризму (Smart Tourism Readiness Index – SITRI), представляющий собой составной показатель из пяти измерений, веса которых определены с помощью метода анализа иерархий (Analytic Hierarchy Process – AHP) при подтверждённом коэффициенте согласованности CR = 0,018. На основе смешанного исследовательского дизайна с использованием вторичных данных и триангуляции источников по четырём категориям индекс применяется к Карабахскому и Восточно-Зангезурскому регионам Азербайджана за период восстановления 2020–2026 годов. Оценка пяти туристских дестинаций проведена на основе документально подтверждённых данных. Средний региональный показатель готовности составил 3,63 по шкале от 1 до 5. Зангилан (4,17) и Физули (4,03) достигли высокого уровня готовности благодаря специально построенным аэропортам и проектированию новых населённых пунктов с нуля, тогда как Шуша (3,95), развитие которой опирается на культурное наследие, лидирует по показателю спроса. Основным результатом исследования является выявление характерной последовательности этапов развития: базовая транспортная инфраструктура создаётся в первую очередь и наиболее быстрыми темпами, тогда как развитие услуг для туристов, превращающих транспортно доступную территорию в полноценную для посещения дестинацию, откладывается на период после завершения физического строительства. Исследование переосмысливает готовность как переменную, зависящую от этапа восстановления, и предлагает диагностический инструмент, применимый также в других постконфликтных условиях.

Ключевые слова: *готовность к умному туризму, послевоенное восстановление, пространственная оценка, метод анализа иерархий, Карабах, конкурентоспособность туристической дестинации*

MÜHARİBƏDƏN SONRAKI ƏRAZİLƏRİN AĞILLI TURİZMƏ HAZIRLIĞININ MƏKAN QİYMƏTLƏNDİRİLMƏSİ

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Xülasə. Müharibədən sonra yenidən qurulan ərazilər ağıllı turizm sahəsində aparılan tədqiqatlarda demək olar ki, nəzərə alınmır. Bu sahədəki tədqiqatlar əsasən onilliklər ərzində formalaşmış infrastruktura rəqəmsal texnologiyaların əlavə edildiyi inkişaf etmiş şəhərlər üzərində cəmləşmişdir. Bu məsələ mühüm əhəmiyyət kəsb edir, çünki yenidənqurma prosesi turizm destinasiyasını və onun rəqəmsal infrastrukturunu sıfırdan, vahid yanaşma əsasında layihələndirmək üçün nadir imkan yaradır. Bununla belə, belə ərazilərin hazırlıq səviyyəsini qiymətləndirmək üçün müvafiq alət mövcud deyil. Tədqiqatda bu boşluğu aradan qaldırmaq məqsədilə Analitik İyerarxiya Prosesi (Analytic Hierarchy Process – AHP) vasitəsilə çəkiləndirilmiş beş ölçüdən ibarət kompozit Ağıllı Turizmə Hazırlıq İndeksi (Smart Tourism Readiness Index – SITRI) təklif olunur. İndeks üzrə uyğunluq nisbəti CR = 0,018 səviyyəsində təsdiqlənmişdir. İkinci dərəcəli məlumatların istifadəsinə əsaslanan qarışıq tədqiqat dizaynı və dörd kateqoriyalı mənbə trianqulyasiyası tətbiq edilməklə indeks Azərbaycanın Qarabağ və Şərqi Zəngəzur regionlarında 2020–2026-cı illəri əhatə edən yenidənqurma dövrü üzrə hesablanmış, beş turizm destinasiyası sənədləşdirilmiş sübutlar əsasında qiymətləndirilmişdir. Regional orta hazırlıq göstəricisi 1–5 ballıq şkala üzrə 3,63 təşkil etmişdir. Xüsusi olaraq inşa edilmiş hava limanları və sıfırdan layihələndirilmiş yaşayış məntəqələri sayəsində Zəngilan (4,17) və Füzuli (4,03) yüksək hazırlıq kateqoriyasına daxil olmuş, mədəni irsə əsaslanan Şuşa (3,95) isə tələbat göstəricisinə görə liderlik etmişdir. Tədqiqatın əsas nəticəsi inkişaf mərhələlərinin xarakterik ardıcıllığının müəyyən edilməsidir: nəqliyyat infrastrukturunun əsasını təşkil edən sistemlər ilk növbədə və daha sürətlə qurulur, lakin əlçatan ərazini turistlər üçün faktiki istifadə oluna bilən destinasiyaya çevirən xidmətlərin inkişafı fiziki tikinti işlərindən sonrakı mərhələyə təxirə salınır. Tədqiqat hazırlıq səviyyəsini yenidənqurma mərhələsindən asılı dəyişən kimi yenidən nəzərdən keçirir və digər postmünaqişə şəraitlərində də tətbiq oluna bilən diaqnostik qiymətləndirmə aləti təqdim edir.

Açar sözlər: *ağıllı turizmə hazırlıq, müharibədən sonrakı bərpa, məkan qiymətləndirilməsi, Analitik İyerarxiya Prosesi, Qarabağ, turizm məkanının rəqabət qabiliyyəti*

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GEOTOURISM AND AZERBAIJAN'S MILITARY-HISTORICAL HERITAGE: ASSESSMENT OF THE TOURISM POTENTIAL OF THE CAUCASUS ISLAMIC ARMY ROUTE

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Summary. Growing demand for historically meaningful and place-based experiences has increased interest in transforming underutilized military heritage landscapes into sustainable tourism resources. This study evaluates the development potential of the Caucasian Islamic Army Heritage Route in Azerbaijan as an integrated military heritage, memorial tourism, and geotourism product. A mixed-methods approach combines field observations across historically significant territories, archival and documentary analysis, secondary tourism statistics, and evidence triangulation. The assessment is complemented by analogical comparison with established military heritage destinations in Gallipoli, Normandy, and Sakarya. Butler's Tourism Area Life Cycle (TALC) model is applied to determine the route's current development stage and construct future development scenarios. The findings position the proposed route within the exploration and early involvement stages, characterized by limited tourism infrastructure, fragmented heritage interpretation, weak destination integration, and low international visibility. Scenario modeling projects approximately 30,000 visitors in the short term, 120,000 in the medium term, and 300,000 in the long term. The results indicate that coordinated infrastructure development, coherent historical interpretation, destination branding, and stakeholder cooperation could transform dispersed military heritage sites into an integrated tourism corridor, supporting heritage preservation, tourism diversification, regional economic activity, and more geographically balanced tourism development across Azerbaijan.

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1. Introduction

Heritage tourism has become an increasingly important component of destination development, particularly where historical and cultural resources can be transformed into sustainable tourism experiences that preserve collective memory while supporting local and regional development (Gordon, 2018). Within this context, military heritage—including battlefields, memorials, cemeteries, historic settlements, and other places associated with conflict and national memory—offers distinctive opportunities for developing integrated tourism routes that connect historical narratives with the landscapes in which these events occurred (Bończak, 2013; Miles, 2017). In Azerbaijan, the legacy of the Caucasian Islamic Army provides a strong basis for such an approach, as historically significant sites associated with its 1918 military operations are distributed across several regions and could be integrated into a coherent heritage route that strengthens historical interpretation, increases the visibility of underutilized destinations, and promotes more geographically balanced tourism development.

Figure 1 illustrates the proposed Caucasian Islamic Army Heritage Route across Azerbaijan, connecting key historical sites, military memorials, and Turkish martyrs' cemeteries associated with the Army's 1918 campaign within an integrated heritage tourism corridor.



Fig. 1. Caucasian Islamic Army Heritage Tourism Route
Source: Authors`s finding

The Tourism Area Life Cycle (TALC) model provides a useful framework for assessing the development of emerging heritage routes through the stages of exploration, involvement, development, consolidation, stagnation, and potential decline or rejuvenation (Butler, 1980). Recent extensions emphasize that movement between these stages depends not only on visitor growth but also on institutional capacity, government intervention, infrastructure, conservation, and destination management (Kubickova & Martin, 2020). Empirical evidence further demonstrates that destination trajectories are not necessarily linear, as stagnation may be followed by decline or strategic rejuvenation depending on governance and investment (Kholis & Nugroho, 2023). Similarly, mature destinations may experience slower growth and structural adjustment while adopting diversification strategies to maintain competitiveness (Ramón-Cardona & Sánchez-Fernández, 2024). Accordingly, TALC offers both a conceptual basis for identifying the current position of an emerging military heritage route and a framework for developing alternative future scenarios.

2. Material and methods

The study adopts a mixed-methods tourism research design combining qualitative field observations, interviews with local residents, and secondary data analysis. It examines the historical and cultural heritage of the Caucasian Islamic Army in Azerbaijan and assesses its potential integration into a memorial-historical tourism route and transformation into an active tourism resource.

Official tourism statistics were obtained from the State Statistical Committee of the Republic of Azerbaijan (SSCRA, 2025). Using purposive sampling, field observations were conducted across nine historically significant territories along the proposed route: Baku, Ganja, Yevlakh, Agdash, Goychay, Agsu, Shamakhi, Hajigabul, and Kurdamir. Observations documented the condition of historical sites, local oral narratives, interpretative resources, and relevant photographic evidence.

The analysis was complemented by archival documents, periodicals, scholarly publications, encyclopedic sources, and institutional reports selected according to thematic relevance and academic reliability. To strengthen the credibility of the findings, evidence from field observations, archival materials, and academic literature was systematically cross-validated through triangulation (Bans-Akutey, 2021).

To evaluate the tourism potential of the Caucasian Islamic Army (CIA) memorial-historical route, an analogical comparison was conducted with the Gallipoli Memorial Tourism Route, the Normandy Landing Tourism Route, and the Sakarya Battle Tourism Route. The comparison was based on the following criteria: geographical location and route structure, historical significance and symbolic value, tourism infrastructure and interpretation opportunities, as well as visitor flows and market orientation. This comparative analysis enabled the identification of the strengths of internationally successful memorial tourism routes and the assessment of their applicability to the proposed CIA route (Bird et al., 2016.

To assess the development prospects of the Caucasian Islamic Army memorial tourism route, scenario modelling was conducted based on Butler's Tourism Area Life Cycle (TALC) model (Butler, 2008).

Within the framework of the study, the following formulas were used to forecast tourist flows associated with the CIA memorial tourism route. Forecasted Number of Tourists:

$$T = T_{max} \times k \quad (1)$$

where T represents the forecasted number of tourists, T_{max} denotes the maximum number of tourists that the region can accommodate, and k is the suitability coefficient. Forecasted Tourism Revenue:

$$R = T \times C_{avg} \quad (2)$$

where R denotes total tourism revenue, T represents the number of tourists, and C_{avg} is the average expenditure per tourist.

The suitability coefficient was determined using different percentage values corresponding to short-, medium-, and long-term development scenarios. Statistical data used for forecasting purposes were analyzed based on official sources, including the State Statistical Committee and the OECD (OECD, 2021; Song et al., 2013).

The integrated use of the selected methods was necessitated by the complexity of developing a memorial tourism route as a multifaceted tourism product. Each method employed in the study fulfilled a distinct analytical function:

- Field observations provided an assessment of the current conditions along the route traversed by the Caucasian Islamic Army;
- Archival and literature analyses established the historical foundations of the memorial tourism route;
- Analogical comparison enabled benchmarking against international best practices in memorial tourism route development;
- The TALC model facilitated the forecasting of the route's future development trajectory.

The integration of these methodological components contributed to a more comprehensive, reliable, and multidimensional interpretation of the research findings.

3. Results and discussion

The findings indicate that the Caucasian Islamic Army Heritage Route has substantial historical, symbolic, and tourism potential, connecting dispersed military, memorial, and cultural sites into a distinctive heritage corridor across Azerbaijan. Field and archival evidence confirms the preservation of important tangible and intangible heritage, while comparison with Gallipoli, Normandy, and Sakarya highlights limitations in infrastructure, route integration, destination management, and international visibility. Nevertheless, the route's combination of urban and rural settlements, battlefields, mountainous landscapes, memorials, and cemeteries provides a strong foundation for integrated military, memorial, and heritage tourism development.

From the perspective of symbolic value and historical meaning, all four routes share common characteristics. Gallipoli, Normandy, Sakarya, and the Caucasian Islamic Army routes function as important sites of remembrance that embody narratives of sacrifice, resistance, and national identity. While the Normandy route possesses a distinctly global profile, the Gallipoli, Sakarya, and Caucasian Islamic Army routes primarily hold national and regional significance. The Caucasian Islamic Army route, in particular, represents a shared historical memory linking Azerbaijan and Türkiye and serves as a symbol of enduring historical solidarity between the two nations (Yeneroğlu Kutbay & Aykaç, 2016).

Compared with established international military heritage routes, the Caucasian Islamic Army Heritage Route remains at an early development stage, characterized by limited visitor infrastructure, fragmented interpretation, weak destination integration, and low international visibility, particularly in regions with relatively modest tourism flows (Köylü, 2023). Nevertheless, its shared historical significance for Azerbaijan and Türkiye provides considerable potential to attract domestic, Turkish, and wider Turkic-world visitors.

The TALC assessment places the route within the **exploration and early involvement stages**, but indicates substantial growth potential under effective planning, investment, management, and marketing. Scenario projections suggest approximately **30,000 visitors in the short term, 120,000 in the medium term, and 300,000 in the long term**, highlighting the route's potential to develop into a significant military heritage tourism destination in Azerbaijan and the wider Turkic world.

Figure 2 illustrates the TALC-based development trajectory of selected military heritage tourism routes, positioning the Caucasian Islamic Army Route at an early stage, compared with the developing Sakarya, maturing Gallipoli, and near-stagnation Normandy routes.

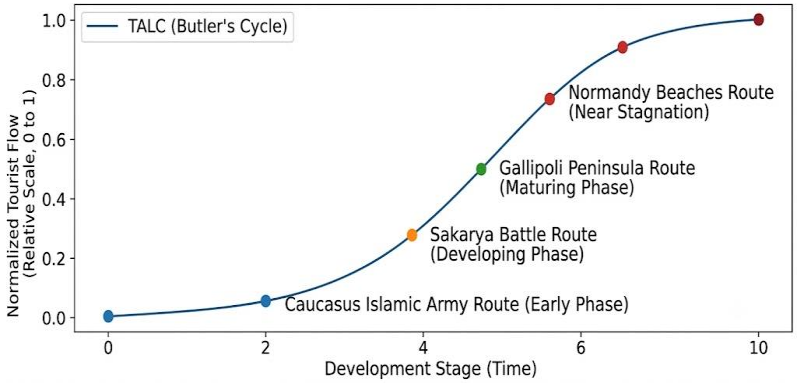


Fig. 2. Comparative Analysis of Tourism Routes According to the TALC Model
Source: Created by the authors in accordance with Butler's TALC model

Based on the TALC model, scenario-based forecasting was conducted to assess the potential future development of the proposed heritage tourism route. As illustrated in the figure, the Normandy Landing Route can be classified as being in the maturity stage, the Gallipoli Heritage Route has reached a consolidated stage of development, while the Sakarya Battlefields Route remains in the development stage of the tourism life cycle.

The forecasting results indicate substantial potential for increasing tourist arrivals and tourism revenues across all districts along the proposed route, including areas where tourism activity is currently limited. Systematic development of the Caucasian Islamic Army Heritage Route could therefore diversify regional tourism, stimulate infrastructure investment, create employment, support local businesses, and strengthen heritage preservation. In this context, the route could serve as a catalyst for sustainable regional development by extending tourism-related economic and socio-cultural benefits to historically significant but underutilized destinations.

Figure 3 illustrates the TALC-based development trajectory of the proposed heritage route under low, medium, and high tourism scenarios, demonstrating how different development conditions may shape the growth of tourist flows over time.

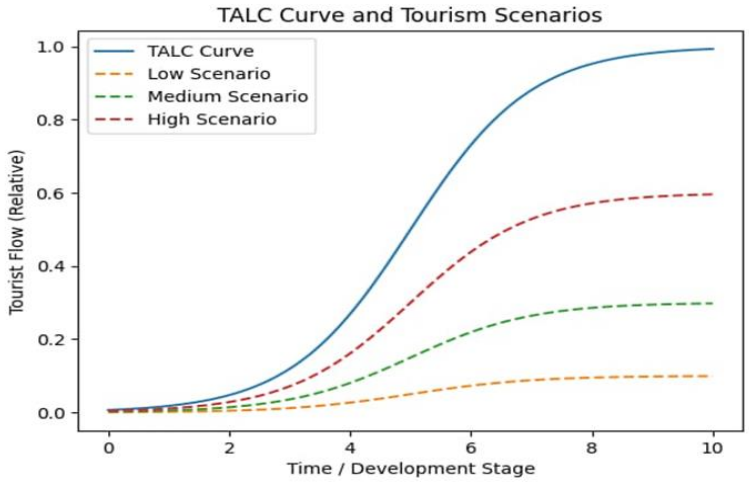


Fig. 3. Scenario-based modeling of the TALC trajectory
Source: Compiled by the author

To estimate the potential tourism demand for the proposed Caucasian Islamic Army Heritage Route, a comparative benchmarking approach was employed using established military heritage tourism destinations. Available tourism statistics indicate that the Gallipoli Heritage Route attracts approximately 2–4 million visitors annually, the Normandy Landing Route receives between 2 and 6 million visitors, and the Sakarya Battlefields Route attracts approximately 0.6–2 million visitors per year (Aliağaoğlu, 2008). Based on average annual visitation figures reported in the literature, the Normandy route receives approximately 4 million visitors annually, the Gallipoli route around 2 million, and the Sakarya route approximately 600,000 visitors.

To establish a benchmark value for forecasting purposes, the average annual visitor number was calculated using the following formula:

$$T_{\max} = \frac{(T_1 + T_2 + \ldots + T_n)}{n} \quad (1)$$

where T_{max} represents the benchmark average annual visitor level and T_1, T_2, T_n represent the annual visitor numbers of comparable military heritage routes. Based on this calculation and considering the characteristics of the selected benchmark destinations, an average reference value of approximately 2 million annual visitors was adopted for subsequent scenario modeling.

Drawing upon Butler's Tourism Area Life Cycle (TALC) model, development coefficients were assigned according to the anticipated stages of tourism evolution. Given that the Caucasian Islamic Army Heritage Route represents a newly proposed tourism product characterized by limited infrastructure, low market recognition, and an early stage of destination development, conservative growth assumptions were applied. Accordingly, suitability coefficients of 1.5% for the short term, 6% for the medium term, and 15% for the long term were adopted (Butler, 2008).

The projected visitor numbers were calculated as follows:

- Short-term scenario:
  2,000,000 x 1.5% = 30,000 visitors
- Medium-term scenario:
  2,000,000 x 6% = 120,000 visitors
- Long-term scenario:
  2,000,000 x 15% = 300,000 visitors

The forecasting results suggest that, under appropriate planning, infrastructure development, destination management, and marketing strategies, the Caucasian Islamic Army Heritage Route could attract approximately 30,000 visitors in the short term, 120,000 visitors in the medium term, and up to 300,000 visitors in the long term. These projections indicate a substantial growth potential and support the feasibility of developing the route as a significant military heritage tourism destination within Azerbaijan and the broader Turkic world.

Table 1 presents the 2024 tourism indicators of the regions along the proposed route and estimates their short-medium and long-term potential for growth in tourist arrivals and tourism revenues under the scenario-based development framework.

Table 1

Regional Tourism Indicators and Scenario-Based Projections of Tourist Arrivals and Revenues along the Caucasian Islamic Army Heritage Route

Region	2024 Tourist Arrivals (persons)	2024 Tourism Revenue (thousand AZN)	Per Capita Expenditure (AZN)	Short-Term Benefit	Medium-Term Benefit	Long-Term Benefit
Ganja	28,247	3,654.8	129.3	~58,000 / 7,482	~148,000 / 16,550	~328,000 / 42,410
Yevlakh	–	–	~30.00	~30,000 / 900	~120,000 / 3,600	~300,000 / 9,000
Aghdash	666	20.0	30.03	~31,000 / 930	~121,000 / 3,634	~301,000 / 9,039
Goychay	1,261	83.9	66.53	~31,000 / 2,062	~122,000 / 8,117	~302,000 / 20,092
Aghsu	553	31.6	57.14	~31,000 / 1,767	~121,000 / 6,897	~301,000 / 17,157
Shamakhy	49,064	7,119.6	145.10	~79,000 / 11,463	~170,000 / 24,667	~349,000 / 50,640
Hajigabul	–	–	~49.00	~31,000 / 1,519	~120,000 / 5,880	~300,000 / 14,700
Kurdamir	3,186	156.4	49.08	~33,000 / 1,619	~123,000 / 6,036	~303,000 / 14,871

Source: Authors` finding

As demonstrated in the forecast table, a minimum twofold increase in both tourist arrivals and tourism revenues is projected across all regions located along the route, including the Hajigabul and Yevlakh districts, which currently exhibit the lowest tourism indicators for 2024. These results suggest that even peripheral and less-developed destinations possess significant untapped tourism potential when integrated into a structured heritage route framework.

The relevance of military heritage in Azerbaijan should also be understood within the broader geopolitical context of the South Caucasus, where military and security dynamics have historically interacted with economic development, sovereignty, and national identity (Hasanov et al., 2025). From this perspective, the Caucasian Islamic Army Heritage Route represents not merely a collection of historical military sites but a spatial expression of collective memory that can be interpreted and communicated through heritage tourism.

The findings show that the Caucasian Islamic Army Heritage Route has considerable potential as a military heritage tourism product, but its transition from the early TALC stage toward sustained development requires stronger infrastructure, spatial integration, destination branding, coherent historical storytelling, and coordinated management, consistent with evidence from Gallipoli, Normandy, Extremadura, and Kermanshah (Hosseini et al., 2024; Guerra et al., 2026). Nevertheless, limitations related to available statistical data, scenario-based forecasting, geographically restricted field observations, and the scarcity of route-specific literature indicate that future research should incorporate visitor surveys and broader primary data to refine demand estimates, understand tourist behaviour, and support the route's competitive and sustainable development.

4. Conclusion

The study confirms that the historical landscapes associated with the Caucasian Islamic Army possess strong prospects for becoming a distinctive heritage tourism network in Azerbaijan. Although many relevant sites remain insufficiently connected and promoted, their historical authenticity, symbolic importance, and geographical distribution provide a valuable foundation for route formation. The TALC assessment suggests that the initiative is still at an initial phase, meaning that its future progress will largely depend on coordinated management, improved accessibility, interpretative facilities, and targeted promotion. Comparative experience from established military destinations also indicates that successful development requires more than the preservation of individual monuments; historical locations should be linked through a clear narrative and common destination identity. Importantly, bringing lesser-visited districts into the route may distribute tourism benefits beyond established destinations and encourage local economic activity. Therefore, long-term success requires cooperation among public authorities, communities, tourism stakeholders, and heritage institutions while ensuring that commercial development remains consistent with historical authenticity and commemorative values.

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ГЕОТУРИЗМ И ВОЕННО-ИСТОРИЧЕСКОЕ НАСЛЕДИЕ АЗЕРБАЙДЖАНА: ОЦЕНКА ТУРИСТИЧЕСКОГО ПОТЕНЦИАЛА МАРШРУТА КАВКАЗСКОЙ ИСЛАМСКОЙ АРМИИ

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Резюме. Растущий спрос на туристский опыт, связанный с исторически значимыми событиями и конкретными территориями, усилил интерес к преобразованию недостаточно используемых ландшафтов военно-исторического наследия в ресурсы устойчивого туризма. В исследовании оценивается потенциал развития Маршрута наследия Кавказской исламской армии в Азербайджане как интегрированного туристского продукта, объединяющего военно-историческое наследие, мемориальный туризм и геотуризм. Смешанный методологический подход сочетает полевые наблюдения на исторически значимых территориях, анализ архивных и документальных материалов, вторичные статистические данные о туризме и триангуляцию доказательств из различных источников. Оценка дополняется сравнением по аналогии с известными дестинациями военно-исторического туризма в Галлиполи, Нормандии и Сакарье. Для определения текущей стадии развития маршрута и построения сценариев его дальнейшего развития применяется модель жизненного цикла туристской территории Батлера (Tourism Area Life Cycle – TALC). Результаты позволяют отнести предлагаемый маршрут к стадиям исследования и начального вовлечения, характеризующимся ограниченностью туристской инфраструктуры, фрагментарностью интерпретации исторического наследия, слабой интеграцией туристских дестинаций и низкой международной узнаваемостью. Сценарное моделирование прогнозирует приблизительно 30 000 посетителей в краткосрочной перспективе, 120 000 — в среднесрочной и 300 000 — в долгосрочной перспективе. Полученные результаты показывают, что согласованное развитие инфраструктуры, последовательная и системная интерпретация исторического наследия, брендинг туристской дестинации и сотрудничество заинтересованных сторон способны преобразовать территориально разрозненные объекты военно-исторического наследия в единый туристский коридор. Это может способствовать сохранению историко-культурного наследия, диверсификации туристских продуктов, активизации региональной экономической деятельности и более сбалансированному в географическом отношении развитию туризма в Азербайджане.

Ключевые слова: *геотуризм; туризм военного наследия; жизненный цикл туристической территории (TALC); маршруты наследия; мемориальный туризм; Азербайджан*

GEOTURİZM VƏ AZƏRBAYCANIN HƏRBİ-TARİXİ İRSİ: QAFQAZ İSLAM ORDUSUNUN HƏRƏKƏT MARŞRUTUNUN TURİZM POTENSİALININ QİYMƏTLƏNDİRİLMƏSİ

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Xülasə. Tarixi əhəmiyyət daşıyan və konkret məkanlarla əlaqəli turizm təcrübələrinə artan tələbat kifayət qədər istifadə olunmayan hərbi irs landşaftlarının dayanıqlı turizm resurslarına çevrilməsinə marağı gücləndirmişdir. Tədqiqatda Azərbaycanda Qafqaz İslam Ordusunun İrs Marşrutunun hərbi irs, memorial turizm və geoturizmi birləşdirən inteqrasiya olunmuş turizm məhsulu kimi inkişaf potensialı qiymətləndirilir. Qarışıq metodoloji yanaşma tarixi əhəmiyyətli ərazilərdə aparılmış sahə müşahidələrini, arxiv və sənədli materialların təhlilini, ikinci dərəcəli turizm statistikası məlumatlarını və müxtəlif mənbələrdən əldə edilmiş sübutların trianqulyasiyasını birləşdirir. Qiymətləndirmə Gelibolu, Normandiya və Sakaryada formalaşmış hərbi irs turizmi destinasiyaları ilə

analoji müqayisə əsasında tamamlanır. Marşrutun mövcud inkişaf mərhələsini müəyyənləşdirmək və gələcək inkişaf ssenarilərini formalaşdırmaq üçün Batlerin Turizm Ərazisinin Həyat Dövrü (Tourism Area Life Cycle – TALC) modeli tətbiq edilmişdir. Nəticələr təklif olunan marşrutun turizm infrastrukturunun məhdudluğu, irsin interpretasiyasının parçalanmış xarakteri, turizm destinasiyalarının zəif inteqrasiyası və beynəlxalq səviyyədə tanınma dərəcəsinin aşağı olması ilə səciyyələnən kəşfiyyat və ilkin iştirak mərhələlərində olduğunu göstərir. Ssenari modelləşdirilməsi qısamüddətli perspektivdə təxminən 30 000, ortamüddətli perspektivdə 120 000 və uzunmüddətli perspektivdə 300 000 ziyarətçi proqnozlaşdırır. Nəticələr göstərir ki, infrastrukturun əlaqələndirilmiş inkişafı, tarixi irsin ardıcıl və sistemli interpretasiyası, turizm destinasiyasının brendləşdirilməsi və maraqlı tərəflər arasında əməkdaşlıq müxtəlif ərazilərdə yerləşən hərbi irs obyektlərini vahid turizm dəhlizinə çevirə bilər. Bu isə tarixi-mədəni irsin qorunmasına, turizm məhsullarının şaxələndirilməsinə, regional iqtisadi fəallığın artırılmasına və Azərbaycanda turizmin coğrafi baxımdan daha balanslı inkişafına töhfə verə bilər.

Açar sözlər: *geoturizm; hərbi irs turizmi; Turizm Ərazisinin Həyat Dövrü (TALC); irs marşrutları; memorial turizm; Azərbaycan*

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ASSESSMENT OF OPPORTUNITIES FOR THE DEVELOPMENT OF ALPINE SKIING TOURISM IN BALAKAN DISTRICT

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Summary. Balakan District, located in northwestern Azerbaijan, is characterized by diverse natural and geographical conditions that provide considerable potential for the development of ski tourism. Its mountainous terrain, favorable climatic conditions, and location along the border with Georgia create opportunities for developing winter tourism and associated recreational activities. This study aims to assess the suitability of the natural and geographical conditions of Balakan District for ski tourism, evaluate the potential for developing relevant tourism infrastructure, and identify existing constraints and risks. Particular attention is given to identifying suitable mountainous areas for the establishment of a ski resort. The study analyzes statistical indicators of tourism development in Balakan and applies ArcGIS-based spatial analysis to identify areas potentially suitable for ski tourism development. The identified areas may provide a practical basis for tourism planning, infrastructure development, and strategic decision-making. The findings demonstrate that Balakan possesses considerable potential for developing a competitive ski tourism destination and diversifying the tourism sector of northwestern Azerbaijan.

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Introduction

Tourism is one of the most significant sectors of economic activity worldwide, characterized by its broad scope and rapid growth. Although tourist arrivals constitute an important indicator of the sector's development, the significance of tourism extends beyond quantitative measures. Tourism generates impacts at local, regional, national, and global levels and, at the same time, reflects contemporary lifestyles, cultural preferences, and broader characteristics of (post)modern society (Pender & Sharpley, 2005, pp. 6–13).

Sports tourism is one of the major forms of tourism and has attracted increasing academic attention over the past fifteen years. As an independent and socially oriented field, sports tourism represents a lifestyle shared by a considerable segment of society and provides opportunities for both the physical and personal development of tourists (Gozalova et al., 2014). It integrates a range of economic, social, environmental, and health-related dimensions. In recent years, its development has become particularly evident in outdoor and adventure tourism, skiing, and other winter sports.

Among the various forms of tourism, winter tourism is particularly important because it not only promotes recreational activities during the winter season but also contributes to the modernization of tourism infrastructure in mountainous and remote regions. Ski tourism, as a major component of winter tourism, can increase tourist flows, stimulate regional economic activity, and create employment opportunities. Moreover, ski resorts can support tourism and recreational activities during warmer months, thereby facilitating the transition toward year-round tourism. Consequently, ski tourism has increasingly become an important

catalyst for economic and social development (Sharpley, 2002). Realizing this potential requires an attractive regional investment environment and a scientifically grounded assessment of tourism and recreational attractiveness (Imrani et al., 2025).

During the 2023–2024 winter season, more than 366 million skier visits were recorded worldwide. The United States, France, Switzerland, Canada, Italy, and Austria are among the countries with the most highly developed ski tourism industries (International Report on Snow & Mountain Tourism, 2025). In Azerbaijan, the principal ski tourism destinations include Shahdag in Gusar, Tufandag in Gabala, and Aghbulag in Shahbuz.

The infrastructure and service sectors developed around ski resorts contribute directly to the economies of mountainous regions and can significantly improve the socio-economic well-being of local communities (Nepal & Chipeniuk, 2005). In this context, the development of ski tourism in Balakan would not only create new sources of economic revenue but also contribute to the diversification of Azerbaijan's tourism product and strengthen its competitiveness in the international tourism market.

Located on the southern slopes of the Greater Caucasus Mountains, Balakan District is distinguished by its unique natural conditions, ethnocultural diversity, and considerable tourism potential (Imrani et al., 2024). Despite its mountainous landscapes, extensive forest resources, and villages characterized by distinctive local traditions, the district's winter tourism potential remains largely underutilized. Therefore, this study focuses on assessing the ski tourism potential of Balakan, examining the existing infrastructure, and identifying priority directions for tourism development and its potential economic impacts. The development of ski tourism in Balakan could attract both domestic and international visitors while stimulating local economic development through job creation, expansion of the service sector, and improvement of tourism-related infrastructure.

Literature review

Alternative forms of tourism reflect the diversification of global tourist interests and provide travelers with more authentic and sustainable experiences. In particular, alternative forms of sports tourism have gained increasing popularity in recent years, as they combine engagement with the natural environment, physical activity, and opportunities to support the development of local communities. Ibraimi et al. (2025) define sports tourism as a travel experience based on sporting activities in which tourists participate either actively or as spectators. The authors further report that sports tourism accounts for approximately 10% of tourism expenditure and emphasize the complementary relationship between sport and tourism, identifying sports tourism as one of the rapidly developing segments of the tourism industry.

Mountain tourism has also experienced substantial growth in recent years and is generally associated with tourism activities that utilize the natural characteristics and recreational opportunities of mountainous environments. It is particularly important in terms of stimulating regional economic development and generating employment. Wang et al. (2022), examining ski tourism in Chongli, China, demonstrated its positive contribution to regional economic development and poverty reduction. Their findings emphasize that appropriate policy frameworks, efficient use of local resources, and sustainable planning are essential for the successful development of mountain sports tourism. From a geographical perspective, Higham (2003) highlights the importance of altitudinal zonation, landscape attractiveness, and seasonal accessibility in determining the tourism appeal of mountain regions.

However, the long-term sustainability of ski tourism depends not only on the stability of natural snow cover but also on the capacity of destinations to adapt to climate change. Scott et al. (2006) demonstrate that increasing temperature variability and declining snow availability can substantially shorten ski seasons in many destinations, creating a need for adaptation measures such as snowmaking technologies and the diversification of ski resorts toward year-round tourism activities.

Among Azerbaijani researchers, Bayramli (2024) and Imrani et al. (2024) emphasize the considerable tourism potential of the northwestern districts of Azerbaijan, including Balakan, Zagatala, Gakh, Shaki, Oghuz, and Gabala, and highlight the importance of utilizing these resources to enhance the socio-economic well-being of the region. Mammadova (2022) similarly identifies substantial opportunities for the development of various forms of mountain tourism in the Shaki-Zagatala tourism region, one of Azerbaijan's border regions, and argues that ski tourism could generate significant economic benefits for the regional economy.

Overall, the existing literature and theoretical approaches indicate that ski tourism can contribute to local economic development when supported by integrated planning, environmental sensitivity, and stakeholder participation. However, the limited empirical research specifically addressing the ski tourism potential of Balakan District reveals an important research gap. The present study seeks to address this gap by providing an

empirical assessment of Balakan's potential for ski tourism development, thereby contributing to both the academic literature and evidence-based regional tourism planning.

Methodology

The study employed statistical analysis to assess the potential for ski tourism development in Balakan District. The analysis was based on tourism statistics covering a 19-year period, including data on the number of visitors accommodated in hotels and hotel-type establishments in Balakan District and Azerbaijan as a whole. The statistical data were organized into comparative tables and used to construct a scatter plot for the Shaki-Zagatala Economic Region, enabling the temporal dynamics of tourism activity in Balakan to be examined within the broader regional context.

Natural and geographical conditions of Balakan district

Balakan District is located in northwestern Azerbaijan, on the southern slopes of the Greater Caucasus Mountains and within the Ganikh-Ayrichay Valley. It borders the Russian Federation (Republic of Dagestan) to the north, Georgia to the west and southwest, and Zagatala District to the east. The district covers an area of 923 km². Of its total land area, 709 ha are classified as state reserve lands, 8.4 thousand ha as municipal lands, and 25 thousand ha as privately owned lands (State Statistical Committee of the Republic of Azerbaijan, 2024). The topography varies considerably, from predominantly mountainous terrain in the north and northwest to lowland areas in the south, with elevations ranging from approximately 200 to 3,500 m above sea level. This pronounced altitudinal variation has a substantial influence on local climatic conditions, vegetation patterns, and tourism potential (Budagov, 2003).

The mountainous areas of Balakan are predominantly forested, while the highest peaks may retain snow cover until August, creating favorable natural conditions for mountain tourism and, in particular, ski tourism development. Mount Guton, the highest peak in the district, reaches an elevation of 3,648 m and is characterized by prolonged snow cover during the winter season. Areas located at elevations of approximately 1,200–2,000 m, with moderate slopes of 15–30°, are considered potentially suitable for the development of ski slopes (Budagov, 2003). Climatic conditions also vary considerably with altitude: the lowland and foothill zones are characterized by a moderately warm and semi-humid to humid subtropical climate, whereas the high-mountain areas experience colder and more humid conditions (Mammadov et al., 2012).

Mountain tourism potential of Balakan district

Mountain areas rank second only to coastal destinations among the geographical environments used for tourism worldwide, accounting for approximately 15–20% of global tourism areas (Richins & Hull, 2016). Within this context, winter mountain tourism, particularly ski tourism, has become one of the most widespread and economically significant forms of sports tourism.

Azerbaijan's diverse natural landscapes provide considerable opportunities for the development of this tourism segment, and Balakan District represents one of the country's promising mountain tourism destinations. An analysis of tourism statistics for the 2006–2024 period (Table 1) indicates that Balakan has experienced notable dynamics in tourism activity within the Shaki-Zagatala Economic Region. This potential is supported by the district's rich cultural and historical heritage, diverse natural landscapes, and favorable mountain environment.

As shown in Table 1, tourism activity in both Azerbaijan as a whole and Balakan District has generally followed an upward but uneven trend since 2006. In Balakan, the number of visitors accommodated in hotels increased markedly after 2011, although substantial year-to-year fluctuations were observed. The decline recorded in 2020–2021 coincided with the COVID-19 pandemic, after which tourist numbers began to recover. Based on these statistical data, the tourism dynamics of Balakan District and the Shaki-Zagatala Economic Region are illustrated in Figure 1.

As illustrated in Figure 1, the Shaki-Zagatala Economic Region experienced a substantial increase in the number of persons accommodated in hotels after 2014. This growth coincided with the development of the Tufandag Winter-Summer Tourism Complex in Gabala, which contributed to strengthening the region's tourism infrastructure and attractiveness. Similarly, the establishment of a mountain sports complex in Balakan could contribute to increasing tourist flows and strengthening tourism activity at the district, regional, and national levels.

Balakan District possesses considerable potential for mountain tourism, particularly for the development of ski tourism during the winter season, which could contribute to increasing tourism revenues. The northern and northeastern parts of the district, particularly the foothill areas of the Guton and Tinov-Rosso peaks along

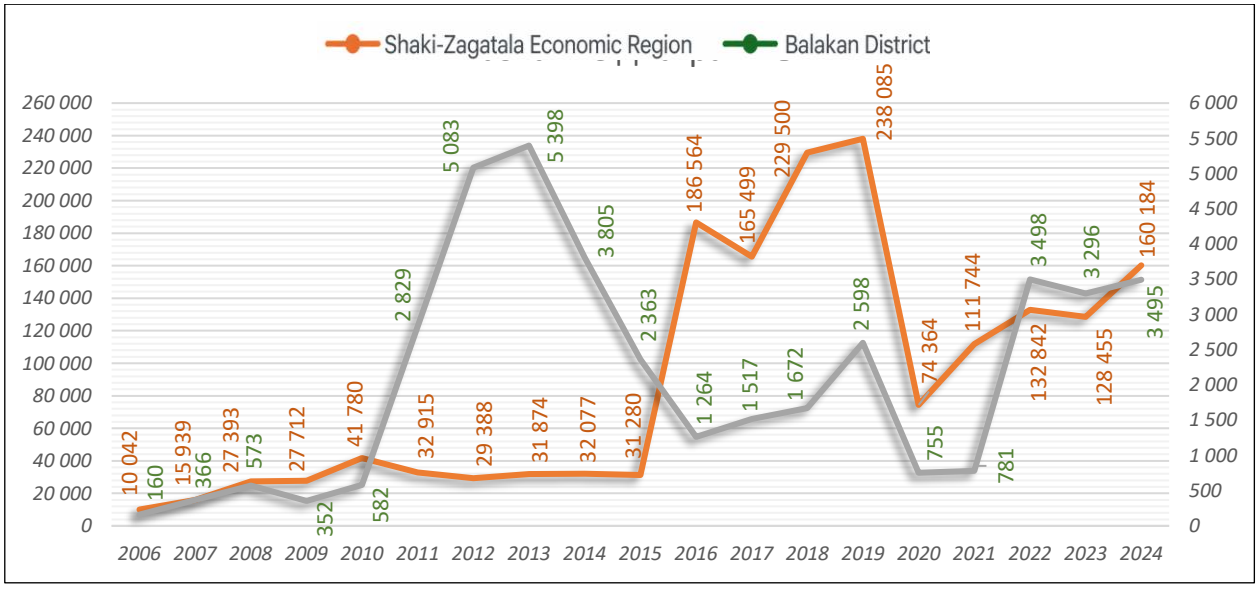
the watershed of the Greater Caucasus Range, offer favorable opportunities for ski tourism development. Moreover, integrating these mountainous areas with the natural landscapes of the Balakan, Mazim, Katekh, and Ganikh rivers could support tourism diversification by combining winter ski tourism with hydrotourism and other nature-based recreational activities during the summer season.

Table 1

Number of Persons Accommodated in Hotels and Similar Establishments, persons

İl	Azerbaijan	Balakan District
2006	291,617	160
2007	305,483	366
2008	431,574	573
2009	424,237	352
2010	438,479	582
2011	510,162	2,829
2012	624,924	5,083
2013	666,348	5,398
2014	672,345	3,805
2015	838,145	2,363
2016	1,122,068	1,264
2017	1,414,708	1,517
2018	1,749,475	1,672
2019	1,919,765	2,598
2020	668,813	755
2021	1,172,123	781
2022	1,697,358	3,498
2023	1,945,059	3,296
2024	2,380,247	3,495

Source: https://www.stat.gov.az/source/tourism/



Mənbə: https://www.stat.gov.az/source/tourism/

Fig. 1. Number of persons accommodated in hotels in the Shaki-Zagatala Economic Region and Balakan District, 2006–2024

Conclusion

The findings indicate that Balakan District has considerable potential for the development of ski tourism. The statistical analysis demonstrates an overall increase in tourism activity, suggesting favorable conditions for further diversification of the district's tourism sector through mountain and winter tourism. In this context, the development of ski tourism could enhance the attractiveness of Balakan as a tourism destination and contribute to increasing tourism-related revenues. However, several constraints may hinder this development, including insufficient tourism infrastructure, narrow and difficult-to-access roads, seasonal accessibility problems in mountain villages, and limited investment opportunities.

Overall, the findings demonstrate that Balakan possesses favorable natural and socio-economic conditions for ski tourism development. Nevertheless, the effective utilization of this potential requires sustainable and strategic planning, investment attraction, infrastructure improvement, and active participation of local communities.

Recommendations

To realize the ski tourism potential of Balakan District, strategic planning of ski routes and associated tourism infrastructure should be undertaken in accordance with internationally recognized sustainable tourism practices. Particular attention should be given to maximizing the economic and social benefits of tourism development for local communities.

Priority areas should include the development of tourism infrastructure, improvement of the investment environment for winter tourism, and efficient utilization of human resources. These measures would contribute to establishing a competitive and sustainable ski tourism destination in the district.

In areas identified as having potential for ski tourism development, priority should be given to road reconstruction and improvement, snow removal and safety measures, the establishment of small-scale eco-friendly accommodation facilities, and ski equipment rental services. These measures are essential for improving accessibility, visitor safety, and the overall quality of tourism services in Balakan District.

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ОЦЕНКА ПЕРСПЕКТИВ РАЗВИТИЯ ГОРНОЛЫЖНОГО ТУРИЗМА В БАЛАКЕНСКОМ РАЙОНЕ.

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Резюме. Балакенский район, расположенный на северо-западе Азербайджана, характеризуется разнообразными природно-географическими условиями, создающими значительный потенциал для развития горнолыжного туризма. Горный рельеф района, благоприятные климатические условия и приграничное положение с Грузией формируют возможности для развития зимнего туризма и связанных с ним рекреационных видов деятельности. Цель исследования заключается в оценке пригодности природно-географических условий Балакенского района для развития горнолыжного туризма, определении потенциала создания соответствующей туристской инфраструктуры, а также выявлении существующих ограничений и рисков. Особое внимание уделяется определению горных территорий, подходящих для создания горнолыжного курорта. В исследовании анализируются статистические показатели развития туризма в Балакенском районе и применяется пространственный анализ на основе ArcGIS для выявления территорий, потенциально пригодных для развития горнолыжного туризма. Выявленные территории могут служить практической основой для планирования туристской деятельности, развития инфраструктуры и принятия стратегических решений. Полученные результаты свидетельствуют о том, что Балакенский район обладает значительным потенциалом для формирования конкурентоспособной горнолыжной туристской дестинации и диверсификации туристского сектора северо-западного региона Азербайджана.

Ключевые слова: *природно-географические условия, спортивный туризм, горнолыжный туризм, туристическая инфраструктура, устойчивый туризм*

BALAKƏN RAYONUNDA DAĞ-XİZƏK TURİZMİNİN İNKİŞAF İMKANLARININ QİYMƏTLƏNDİRİLMƏSİ

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Xülasə. Azərbaycanın şimal-qərbində yerləşən Balakən rayonu xizək turizminin inkişafı üçün əhəmiyyətli potensial yaradan müxtəlif təbii-coğrafi şəraitlə səciyyələnir. Rayonun dağlıq relyefi, əlverişli iqlim şəraiti və Gürcüstanla sərhəddə yerləşməsi qış turizminin və onunla əlaqəli rekreasiya fəaliyyətlərinin inkişafı üçün imkanlar yaradır. Tədqiqatın məqsədi Balakən rayonunun təbii-coğrafi şəraitinin xizək turizmi üçün əlverişliliyini qiymətləndirmək, müvafiq turizm infrastrukturunun inkişaf potensialını müəyyənləşdirmək, eləcə də mövcud məhdudiyyətləri və riskləri aşkar etməkdir. Xizək kurortunun yaradılması üçün əlverişli dağlıq ərazilərin müəyyənləşdirilməsinə xüsusi diqqət yetirilir. Tədqiqatda Balakən rayonunda turizmin inkişafına dair statistik göstəricilər təhlil edilir və xizək turizminin inkişafı üçün potensial əlverişli ərazilərin müəyyənləşdirilməsi məqsədilə ArcGIS proqramı əsasında məkan təhlili aparılır. Müəyyən edilmiş ərazilər turizmin planlaşdırılması, infrastrukturun inkişafı və strateji qərarların qəbul edilməsi üçün praktiki əsas rolunu oynaya bilər. Əldə edilən nəticələr Balakən rayonunun rəqabətqabiliyyətli xizək turizmi destinasiyasının formalaşdırılması və Azərbaycanın şimal-qərb bölgəsində turizm sektorunun şaxələndirilməsi üçün əhəmiyyətli potensiala malik olduğunu göstərir.

Açar sözlər: *təbii-coğrafi şərait, idman turizmi, dağ-xizək turizmi, turizm infrastrukturu, dayanıqlı turizm*

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ETHNOTOPONYMY AND HISTORICAL GEOGRAPHY OF ZANGEZUR: A COMPARATIVE ANALYSIS OF THE ZANGI/ZANGILAR COMPONENT

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Keywords: *Zangezur, Turkic ethnonym, Zangi/Zangilar, ethnotoponymy, toponym, South Caucasus*

Summary. This study examines the origin of the toponym "Zangezur" within the Turkic onomastic tradition and the historical-geographical context of the South Caucasus, with particular emphasis on the Zangi/Zangilar ethnonym. Comparative-historical linguistic, structural-semantic, and historical-geographical methods are applied to evaluate the relationship between the ethnonym and the formation of the geographical name. Historical sources and regional toponymic evidence indicate that Zangi/Zangilar was recorded as an ethnonym and subsequently preserved in various geographical names, reflecting its continuity as a nominative element within the regional toponymic system. The findings support the interpretation of the Zangi/Zangilar component as the principal ethnonymic element underlying the formation of "Zangezur" and correspond to the widespread Turkic naming model in which ethnonyms develop into geographical names. Although the etymology of the second component, "-zur," remains unresolved, this uncertainty does not invalidate the ethnonym-based interpretation. The study therefore considers the ethnotoponymic explanation of "Zangezur" to be one of the scientifically substantiated approaches to the origin of the toponym.

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Problem definition

Zangezur is a historically and geographically significant region of the South Caucasus with a multilayered toponymic system reflecting long-term ethnic, linguistic, and cultural processes. Consequently, the origin of the toponym "Zangezur" is important not only from an etymological perspective but also for understanding the historical-geographical and ethnotoponymic development of the region. Among the existing hypotheses, one of the principal approaches associates the name with the Zangi/Zangilar ethnonym, while other interpretations propose hydronymic or alternative linguistic origins.

Within the Turkic onomastic tradition, the transformation of ethnonyms into geographical names is a widespread naming pattern. The preservation of ethnic and tribal names in settlements, hydronyms, and other geographical features may therefore reflect historical settlement and territorial continuity rather than accidental phonetic similarity (Aghasioglu, 2014). Accordingly, this study aims to evaluate the role of the Zangi/Zangilar ethnonym in the formation of "Zangezur" through comparative-historical linguistic, structural-semantic, and historical-geographical analysis, while also considering existing interpretations of the "-zur" formant.

Comparative-historical linguistic and phonetic analysis

The Zangi component of the toponym "Zangezur" can be examined within the comparative-historical framework of Turkic onomastics. Historical sources record Zangi/Zangilar as an ethnonym, while its occurrence in different geographical areas indicates its continuity within the regional naming system.

The historical development of Turkic languages has involved phonetic changes, dialectal variation, and regional differences in pronunciation, while lexical roots have often remained recognizable in different forms

(Johanson, 2009; Clauson, 1972; Radlov, 1893–1911). Accordingly, variants of the Zangi component occurring in geographical names may reflect a common historical-linguistic origin rather than accidental phonetic similarity. Its historical distribution and preservation in regional toponymy therefore provide an important basis for evaluating its ethnonymic origin.

Research methods. The analysis of the semantic and morphological characteristics of the Zangi component in the toponym "Zangezur" is of considerable importance for identifying its ethnonymic origin. Geographical names derived from ethnonyms not only serve to distinguish specific geographical features but also preserve the linguistic and historical memory of the ethnic communities that once inhabited or left their mark on a particular territory.

The occurrence of the Zangi component in the names of various settlements, hydronyms, and other geographical features demonstrates that it functions as a stable nominative element within the regional toponymic system. This distribution cannot be explained as a result of accidental naming; rather, it reflects a long-standing historical naming tradition.

In Turkic toponymy, the combination of ethnonyms with various lexical and morphological elements to create new geographical names represents one of the most productive naming patterns. Within this model, an ethnonym initially denotes a tribe or ethnic community and subsequently becomes associated with the territory inhabited by that community, eventually stabilizing as an oikonym, hydronym, or oronym. As a result of this transformation, the ethnonym does not lose its original ethnic meaning; instead, it preserves the historical and ethnic memory within the semantic structure of the geographical name.

From this perspective, the toponym "Zangezur" may be regarded as a multilayered nominative formation reflecting the transformation of an ethnonym into a geographical name. In this process, the Zangi component has retained its original function as an indicator of ethnic identity while gradually becoming established as the name of a specific geographical area.

Thus, the structural-semantic analysis provides a scientific basis for interpreting the Zangi component as a nominative unit that originated from a Turkic ethnonym and subsequently underwent the process of toponymization.

The main material

The historical-geographical approach constitutes one of the principal methodological frameworks for investigating the origin of the toponym "Zangezur." The formation of geographical names is determined not only by linguistic processes but also by the historical, ethnic, and social developments that have taken place within a particular territory. In this context, the analysis of the geographical distribution of the Zangi/Zangilar ethnonym and the geographical names derived from this component provides an important scientific basis for clarifying the etymology of the toponym.

Medieval sources, as well as later scholarly studies, record Zangi/Zangilar as an ethnonym in various historical and geographical contexts. In particular, the works of Yāqūt al-Hamavī, V. Minorsky, and V. V. Bartold contain valuable information on the ethnic and geographical characteristics of the region and constitute important sources for reconstructing the historical distribution of this ethnonym (Yāqūt al-Hamavī; Minorsky, 1953; Bartold, 1966).

The historical geography of the Caucasus demonstrates that the names of ethnic communities that inhabited the region in different periods were preserved in the system of geographical names during subsequent historical stages. This phenomenon is especially characteristic of ethnonyms of Turkic origin. The preservation of ethnic names in settlements, hydronyms, and other geographical features is regarded as an important indicator of the historical settlement patterns of these communities.

The presence of the Zangi component in various historical-geographical areas of the South Caucasus further demonstrates that it is not an incidental element within the regional toponymic system. Geographical names formed on the basis of this component reflect the continuity of both historical settlement processes and traditional naming practices (Geybullayev & Budagov, 1998).

Thus, the historical-geographical analysis indicates that the Zangi/Zangilar ethnonym represents one of the principal nominative components underlying the formation of the toponym "Zangezur."

The transformation of ethnonyms into geographical names within the historical settlement areas of the Turkic peoples represents one of the characteristic features of the Turkic toponymic tradition. This phenomenon constitutes one of the most widespread naming patterns in the Turkic onomastic system and is observed across different historical and geographical regions (Babayev, Imrani, & Zakirova, 2023).

The preservation of the Zangi/Zangilar ethnonym within the system of geographical names should likewise be interpreted within the framework of this broader historical process. The recurrence of the same component in different geographical names demonstrates that it functions as a stable nominative element associated with a particular historical and ethnic memory.

In Turkic toponymy, geographical names derived from ethnonyms do not represent isolated or accidental examples but rather reflect a typologically recurrent naming pattern. The structural characteristics observed in ethnonym-based toponyms such as Bayat, Kangarli, Gargar, Avshar, and Kipchak indicate that the toponym "Zangezur" was formed according to the same nominative principle. The defining feature of this model is the association of an ethnic name with a particular historical territory, where it becomes established and preserved as a geographical name over an extended period.

Such typological parallels make it possible to interpret the ethnonym-based explanation of the toponym "Zangezur" not as an isolated case but within the broader framework of the general principles governing Turkic toponymic formation.

As in the ethnonym-derived toponyms Gargar, Bayat, Kangarli, and others, the Zangi component likewise demonstrates the preservation of an ethnic name within the geographical memory of the region (Babayev, 2022). From this perspective, the ethnographic comparison supports the historical and ethnocultural foundations of the proposed model that explains the origin of the toponym "Zangezur" on the basis of a Turkic ethnonym.

One of the key issues in the etymological analysis of the toponym "Zangezur" is the identification of the origin and historical function of its Zangi/Zangilar component. Historical sources record this name as an ethnonym, which was subsequently preserved in the structure of various geographical names and became one of the stable elements of the regional toponymic system.

A comparative analysis of historical sources, regional toponymic evidence, and the Turkic onomastic tradition demonstrates that the Zangi/Zangilar component is not the result of an accidental lexical resemblance but rather a nominative unit of historical and ethnic origin. Its preservation in numerous toponyms indicates the continuity of the process through which ethnonyms are transformed into geographical names, a characteristic feature of the Turkic naming tradition.

From both a historical and an onomastic perspective, the Zangi/Zangilar component represents a persistent ethnonymic element that has retained its function within the regional toponymic system over an extended historical period. The continuity of its distribution across different geographical names provides additional evidence for its historical authenticity and nominative stability.

Thus, the Zangi/Zangilar component may be regarded as the principal nominative element supporting the ethnotoponymic interpretation of the toponym "Zangezur."

Toponymic evidence demonstrates that the Zangi component has been preserved in the structure of various geographical names throughout Zangezur and the adjacent historical-geographical region. This component occurs in oikonyms, hydronyms, microtoponyms, and other categories of geographical names, indicating its long-term continuity within the regional toponymic system (Geybullayev & Budagov, 1998).

The principal regional examples associated with this component include:

- **Zangilan** – an oikonym formed on the basis of the Zangi component and interpreted within the framework of the ethnotoponymic model.
- **Zangibasar** – an oikonym created through the combination of the Zangi component with a second lexical element denoting locality or territory.
- **Zangarli** – a toponym reflecting a phonetic variant of the Zangi component.
- **Zangishali,** Zangi Valley (Zangi Dərəsi), Zangi Spring (Zangi Bulağı), and other microtoponyms, which demonstrate the continued preservation of the component within the local toponymic system (Babayev, 2022).

The occurrence of these examples within the same historical-geographical area and across different categories of geographical names indicates that the Zangi component represents one of the stable and persistent elements of the regional ethnotoponymic system.

A comparative analysis of these regional examples demonstrates that the Zangi component is not merely a linguistic element preserved in individual place names, but rather an integral part of a nominative system reflecting the historical relationship between ethnic settlement and geographical naming. These relationships are summarized in the conceptual model presented below.

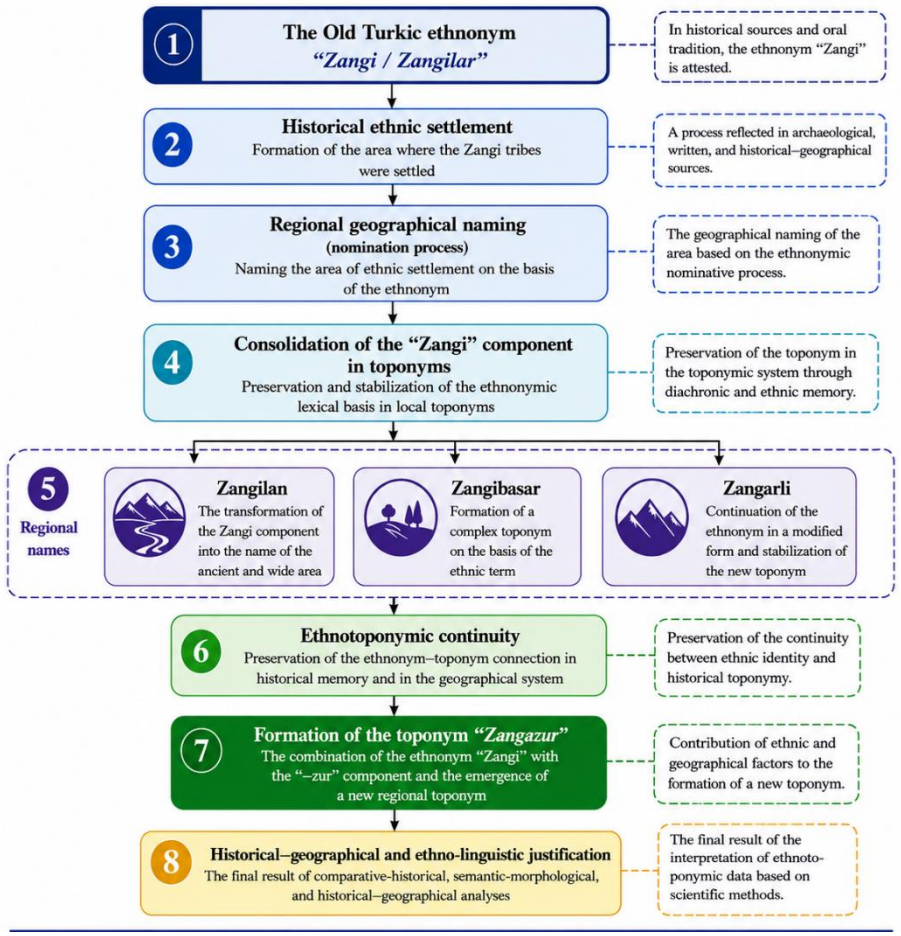


Fig. 1. Ethnotoponymic Formation Model of the Toponym "Zangezur"
Note: This conceptual model was developed based on comparative-historical, structural-semantic, historical-geographical, and ethnotoponymic analyses.

The conceptual model presented in Figure 1 demonstrates that the formation of the toponym "Zangezur" cannot be interpreted as an isolated linguistic phenomenon. Rather, it represents the outcome of a historical process in which an ancient ethnonym became firmly established within the geographical naming system through successive stages of ethnic settlement, regional nomination, and toponymic formation.

Accordingly, the Zangi/Zangilar ethnonym functions as the primary nominative element underlying the formation of the toponym, while its preservation in a series of geographically related place names reflects the continuity of historical settlement patterns and the persistence of the Turkic naming tradition. The recurrence of this component across different categories of geographical names further supports its role as a stable element within the regional ethnotoponymic system.

The conceptual model therefore provides a visual synthesis of the principal findings obtained through the comparative-historical, structural-semantic, and historical-geographical analyses presented in this study (Babayev, Hadjiyeva, & Yusifova, 2024). It illustrates the historical relationship between ethnic identity, territorial continuity, and geographical naming, thereby reinforcing the interpretation of "Zangezur" as a toponym derived from the Zangi/Zangilar ethnonym.

The origin of the "-zur" formant, which constitutes the second component of the toponym "Zangezur," has been interpreted in different ways within the scholarly literature. However, the currently available historical and linguistic evidence does not permit a single, generally accepted conclusion regarding either its etymology or its semantic function.

On the basis of certain phonetic and semantic parallels observed in the Turkic languages, the "-zur" component may be compared with archaic elements such as sur, shor/chor, and sar. In the etymological analysis of toponyms, it is not always possible to explain every component with the same degree of certainty. In international toponymic research, once the principal nominative component of a complex geographical name has been reliably identified, the etymology of the remaining elements may legitimately remain unresolved. In such

cases, the etymological interpretation is primarily based on the historical, linguistic, and areal characteristics of the principal component (Babayev, 2026).

From this perspective, the identification of the Zangi/Zangilar component as an ethnonymic element underlying the toponym "Zangezur" remains scientifically well founded, even though the etymology of the "-zur" formant has not yet been conclusively established. Consequently, the unresolved origin of the second component does not diminish the validity of the ethnotoponymic model proposed in this study.

Conclusions

The comparative-historical linguistic, structural-semantic, and historical-geographical analyses conducted in this study demonstrate that the Zangi/Zangilar ethnonym constitutes the principal nominative component underlying the ethnotoponymic interpretation of the toponym "Zangezur."

The preservation of the Zangi component in numerous oikonyms, hydronyms, and microtoponyms indicates that it represents a persistent element within the historical toponymic system of the South Caucasus. This pattern is consistent with one of the productive naming models of the Turkic toponymic tradition, in which ethnonyms are transformed into geographical names while preserving their historical and ethnocultural associations.

The findings further demonstrate that historical sources, comparative linguistic evidence, and regional toponymic data collectively support the interpretation of "Zangezur" as a toponym derived from the Zangi/Zangilar ethnonym. Accordingly, the proposed ethnotoponymic explanation may be regarded as one of the scientifically well-substantiated approaches to the origin of this place name.

The results of the study show that historical sources, comparative linguistic materials, and regional toponymic facts allow us to evaluate the ethnotoponymic explanation of the toponym "Zangezur" associated with the ethnonym "Zangi/Zangiler" as one of the scientifically substantiated approaches.

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ИСТОРИЧЕСКАЯ ГЕОГРАФИЯ И ЭТНОТОПОНИМИЯ ЗАНГЕЗУРА: ПРОИСХОЖДЕНИЕ И РАСПРОСТРАНЕНИЕ НАЗВАНИЙ «ЗАНГИ/ЗАНГИЛАР»

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Резюме. В исследовании рассматривается происхождение топонима «Зангезур» в контексте тюркской ономастической традиции и историко-географических особенностей Южного Кавказа с особым акцентом на этнониме Занги/Зангилар. Для оценки взаимосвязи между этнонимом и формированием географического названия применяются сравнительно-исторический лингвистический, структурно-семантический и историко-географический методы. Исторические источники и региональные топонимические данные свидетельствуют о том, что название Занги/Зангилар было зафиксировано в качестве этнонима и впоследствии сохранилось в различных географических названиях, отражая его преемственность как номинативного элемента региональной топонимической системы. Результаты исследования подтверждают интерпретацию компонента Занги/Зангилар как основного этнонимического элемента, лежащего в основе формирования топонима «Зангезур», и соответствуют широко распространённой тюркской модели наименования, при которой этнонимы преобразуются в географические названия. Несмотря на то что этимология второго компонента «-зур» остаётся невыясненной, данная неопределённость не опровергает интерпретацию, основанную на этнониме. Таким образом, в исследовании этнотопонимическое объяснение названия «Зангезур» рассматривается как один из научно обоснованных подходов к установлению происхождения данного топонима.

Ключевые слова: *Зангезур, тюркский этноним, Занги/Зангилар, этнотопонимия, топоним, Южный Кавказ*

ZƏNGƏZURUN ETNOTOPONİMİYASI VƏ TARİXİ COĞRAFİYASI: ZƏNGİ/ZƏNGİLƏR KOMPONENTİNİN MÜQAYİSƏLİ TƏHLİLİ

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Xülasə. Tədqiqatda "Zəngəzur" toponiminin mənşəyi türk onomastik ənənəsi və Cənubi Qafqazın tarixi-coğrafi konteksti çərçivəsində, xüsusilə Zəngi/Zəngilər etnoniminə diqqət yetirilməklə araşdırılır. Etnonimlə coğrafi adın formalaşması arasındakı əlaqəni qiymətləndirmək məqsədilə müqayisəli-tarixi linqvistik, struktur-semantik və tarixi-coğrafi metodlar tətbiq edilmişdir. Tarixi mənbələr və regional toponimik faktlar göstərir ki, Zəngi/Zəngilər adı etnonim kimi qeydə alınmış və sonradan müxtəlif coğrafi adlarda qorunub saxlanılmışdır. Bu isə həmin adın regional toponimik sistemdə adlandırma elementi kimi davamlılığını əks etdirir. Tədqiqatın nəticələri Zəngi/Zəngilər komponentinin "Zəngəzur" toponiminin formalaşmasının əsasında duran əsas etnonimik element kimi şərhini dəstəkləyir və etnonimlərin coğrafi adlara çevrildiyi geniş yayılmış türk adlandırma modelinə uyğun gəlir. İkinci komponent olan "-zur"un etimologiyası hələ də tam aydınlaşdırılmasa da, bu qeyri-müəyyənlik etnonimə əsaslanan izahın etibarlılığını aradan qaldırmır. Beləliklə, tədqiqatda "Zəngəzur" toponiminin etnotoponimik izahı onun mənşəyinə dair elmi cəhətdən əsaslandırılmış yanaşmalardan biri kimi qiymətləndirilir.

Açar sözlər: *Zəngəzur, türk etnonimi, Zəngi/Zəngilər, etnotoponimiya, toponim, Cənubi Qafqaz*

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INTEGRATING GIS TECHNOLOGIES INTO GEOGRAPHY EDUCATION: MODERN TEACHING APPROACHES

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Summary. The increasing use of geospatial technologies has created new opportunities for improving the teaching and learning of geography. This study examines the integration of Geographic Information Systems (GIS) into geography education, with particular attention to teaching approaches that promote spatial thinking, inquiry, and active student participation. The study analyzes the educational potential of GIS in relation to inquiry-based learning, problem-based learning, project-based learning, fieldwork, and digital mapping activities. Particular attention is given to the transition from the traditional presentation of geographical information to learning environments in which students collect, visualize, interpret, and compare spatial data and use the results to investigate geographical problems. The analysis indicates that effective GIS integration depends not only on access to geospatial technologies but also on appropriate teaching methods, teacher competence, curriculum design, and the selection of learning activities suitable for students' abilities. Based on these considerations, the study proposes a practical framework that connects geographical problems, spatial data, GIS-based analysis, interpretation, and student decision-making within a unified learning process. The proposed approach can support the development of geographical knowledge, spatial reasoning, digital skills, and independent problem-solving in contemporary geography education.

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1. Introduction

Geography education is closely connected with the ability to understand spatial relationships, interpret patterns, and explain interactions between natural and human processes. The increasing availability of digital geospatial data has expanded the ways in which these skills can be developed in the classroom. Geographic Information Systems (GIS), in particular, allow students to work with location-based information through mapping, visualization, comparison, and spatial analysis rather than relying only on static maps and descriptive materials. Consequently, GIS has become an increasingly important component of contemporary geography education (Bondarenko, 2025).

The educational value of GIS extends beyond the acquisition of technical mapping skills. When incorporated into appropriate learning activities, GIS can support spatial thinking, geographical inquiry, problem-solving, and the interpretation of relationships between different geographical phenomena. Web-based GIS platforms and increasingly accessible geospatial datasets have also created opportunities for students to investigate real geographical problems using interactive maps and spatial information (Fargher, 2018). Such an approach changes the role of the learner from a passive recipient of geographical information to an active participant in its collection, analysis, and interpretation.

The effectiveness of GIS-supported learning, however, depends strongly on how the technology is integrated into the teaching process. Simply providing GIS software or digital maps does not necessarily improve learning outcomes. Research has identified teacher preparedness, technical resources, curriculum requirements, and the design of appropriate learning activities among the major factors influencing successful GIS

implementation in education (Kerski et al., 2022). Recent empirical evidence also indicates that combining GIS with inquiry-based learning can improve students' academic achievement, attitudes toward geography, and some dimensions of geographical literacy (Hursen & Beyoğlu, 2025).

Despite the growing use of geospatial technologies, a gap remains between the technical possibilities offered by GIS and their systematic pedagogical integration into geography lessons. GIS is still frequently approached primarily as a technological tool rather than as part of a broader learning process connecting geographical questions, spatial data, analysis, interpretation, and decision-making. Therefore, greater attention is needed to teaching approaches that integrate GIS with inquiry-based, problem-based, project-based, and field-oriented learning.

The aim of this study is to examine the educational role of GIS in modern geography teaching and to identify effective approaches for its integration into the learning process. The study also proposes a practical framework linking geographical problems, spatial data, GIS-based analysis, interpretation, and student decision-making.

2. Materials and methods

This study employs a qualitative analytical approach to examine the integration of Geographic Information Systems (GIS) into contemporary geography education. Relevant academic literature on GIS-supported teaching, spatial thinking, geographical inquiry, problem-based learning, project-based learning, and digital mapping was reviewed and comparatively analyzed. Particular attention was given to studies addressing the educational use of desktop GIS, Web GIS, interactive mapping, and other geospatial learning environments.

The analysis focused on four interconnected dimensions**:** (1) the educational functions of GIS, (2) teaching approaches used with GIS, **(3)** learning outcomes associated with geospatial activities, and (4) barriers affecting effective classroom implementation. Previous systematic research demonstrates that GIS-related educational studies commonly address curriculum integration, teacher preparation, student learning, pedagogical strategies, implementation barriers, and technological development (Bondarenko, 2025).

Based on the comparative analysis of these dimensions, the study develops a conceptual teaching framework in which GIS is treated not simply as a mapping technology but as part of a structured learning sequence. As illustrated in Figure 1, the proposed framework organizes GIS-supported geography learning as a sequential process beginning with the identification of a geographical problem and progressing through spatial data analysis and interpretation to discussion and evidence-based decision-making.

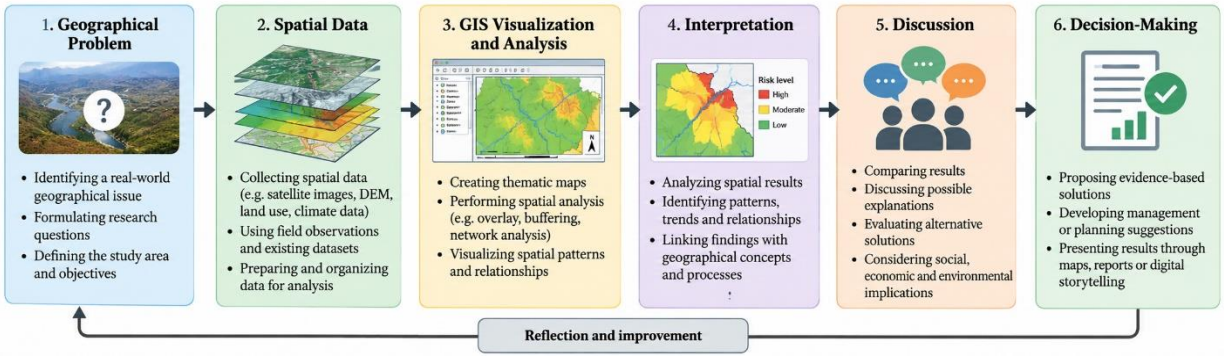


Fig. 1. Conceptual framework for integrating GIS into the geography teaching and learning process
Source: Developed by the authors

This framework is used to evaluate how inquiry-based, problem-based, project-based, and field-oriented teaching approaches can be combined with GIS to develop students' geographical knowledge, spatial thinking, digital competence, and problem-solving skills.

3. Results and discussion

The analysis shows that the educational value of GIS is determined not simply by the availability of digital maps or software, but by the way geospatial technologies are incorporated into the learning process. In geography lessons, GIS can connect theoretical concepts with real spatial problems by allowing students to work directly with geographical data. Instead of only observing a completed map, students can select data, create thematic layers, compare locations, identify spatial patterns, and interpret the causes and consequences of ge-

ographical processes. This makes GIS particularly suitable for teaching topics such as land-use change, population distribution, climate variability, natural hazards, water resources, urban development, and environmental management.

A major advantage of GIS-supported teaching is its contribution to spatial thinking. Students are required to consider location, distance, distribution, scale, spatial association, and change while interpreting geographical information. These operations are central to geographical reasoning and allow learners to move beyond the memorization of place names and definitions. Previous research has similarly emphasized that GIS-supported learning can contribute to the development of spatial thinking when geospatial tools are integrated with clearly defined educational objectives.

3.1. Inquiry-based learning with GIS

Inquiry-based learning is particularly compatible with GIS because both approaches begin with questions rather than predetermined descriptions. A lesson may start with a geographical problem such as: *Why are flood-risk areas concentrated in particular parts of a river basin?* Students can then examine elevation, slope, drainage, precipitation, land-use, and settlement layers to identify possible relationships.

In this process, GIS becomes an analytical environment rather than simply a map-production tool. Students formulate questions, select relevant spatial data, compare layers, identify patterns, and use geographical evidence to develop explanations. Recent research has shown that GIS-supported inquiry-based instruction can positively influence students' academic achievement and attitudes toward geography, although the effectiveness of the approach depends on the design of the learning activities and the level of guidance provided by the teacher.

3.2. Problem - and project-based learning

GIS can also be effectively integrated into problem-based and project-based learning. These approaches are especially useful when students investigate issues connected with their own region or community. For example, students may examine changes in urban land use, identify areas exposed to environmental risk, evaluate accessibility to public services, analyze local water resources, or investigate changes in vegetation cover.

A GIS-based project can follow a sequence from defining the problem and collecting spatial information to creating maps, interpreting results, and proposing solutions. In this way, students are not limited to learning how GIS functions technically; they learn how geospatial information can be used to support geographical arguments and decisions. The final product may include a thematic map, a short analytical report, a digital presentation, or an interactive story map.

3.3. Integrating GIS with fieldwork

The combination of GIS and field-based geography education provides another important teaching opportunity. Field observations can be georeferenced and subsequently incorporated into a GIS environment together with satellite images, topographic information, land-use data, or other spatial datasets. Students can therefore compare what they observe directly in the field with broader spatial patterns visible through digital data.

This approach establishes a connection between observation, location, mapping, analysis, and interpretation. For instance, students investigating a river can record sampling or observation points, photograph environmental conditions, identify potential pollution sources, and map the collected information. Such activities help students understand that geographical data are not abstract values but representations of real places and processes.

3.4. Web GIS and digital storytelling

The development of Web GIS has made geospatial technologies more accessible for geography education. Unlike traditional desktop GIS, web-based platforms can often be used directly through a browser and allow students to explore spatial data without extensive technical preparation. Interactive maps can be used to compare regions, examine environmental change, visualize demographic patterns, and investigate relationships between natural and socioeconomic processes.

Digital storytelling further extends these possibilities by combining maps with text, photographs, graphs, and other multimedia materials. In geography education, this approach is useful because students can present not only *where* a phenomenon occurs but also *why* it occurs and *how* it affects people and places. Student-created story maps can therefore serve both as a learning activity and as a form of assessment. They require students to select relevant information, organize spatial evidence, and communicate geographical findings in a clear and logically structured form.

3.5. Challenges of GIS Integration

Despite its educational potential, the effective integration of GIS into geography teaching remains associated with several practical and pedagogical challenges. Limited access to appropriate hardware and software,

differences in students' digital skills, insufficient teacher preparation, restricted classroom time, and difficulties in selecting suitable spatial datasets may reduce the effectiveness of GIS-supported activities. These challenges are particularly important when GIS tasks require considerable technical preparation but have only a weak connection with the intended geographical learning outcomes.

For this reason, GIS should not be introduced merely to increase the use of technology in the classroom. The selected GIS activity should correspond to the topic, students' level of preparation, available resources, and clearly defined learning objectives. Simple mapping and visualization may be sufficient at introductory levels, whereas more advanced students can perform overlay analysis, examine spatial relationships, and evaluate alternative solutions to geographical problems. A gradual progression from map interpretation to independent spatial analysis can therefore provide a more practical model for GIS integration in geography education.

Table 1

GIS-supported teaching approaches and their educational applications

Teaching approach	GIS-based activity	Expected learning outcome
Inquiry-based learning	Exploring spatial questions and comparing thematic layers	Spatial thinking and geographical inquiry
Problem-based learning	Analyzing real geographical or environmental problems	Problem-solving and evidence-based reasoning
Project-based learning	Creating thematic maps and regional projects	Independent research and digital competence
Field-oriented learning	Mapping field observations and georeferenced data	Connection between field evidence and spatial patterns
Web GIS	Exploring and comparing interactive spatial datasets	Data interpretation and digital map literacy
Digital storytelling	Combining maps, text, images, and analytical findings	Geographical communication and synthesis

Source: Developed by the authors

3.6. Pedagogical implications of GIS integration

The findings suggest that effective GIS integration requires a shift from technology-centered instruction to learning-centered application. Teaching students how to operate GIS software is useful, but technical competence alone does not constitute geographical learning. The educational value of GIS becomes more evident when students use spatial data to investigate questions, recognize geographical relationships, interpret patterns, and justify conclusions.

As summarized in Table 1, different teaching approaches emphasize different stages of this process. Inquiry-based activities are particularly suitable for developing geographical questioning and spatial reasoning, whereas problem-based and project-based activities encourage students to apply geographical knowledge to real situations. Field-oriented learning connects spatial datasets with direct observation, while Web GIS and digital storytelling provide accessible environments for visualization, interpretation, and communication.

The framework proposed in Figure 1 therefore places the geographical problem, rather than the GIS software, at the beginning of the learning process. GIS functions as a means of moving from spatial information to interpretation and, ultimately, evidence-based decision-making. This distinction is important because the same technology may produce very different educational outcomes depending on the task assigned to students and the degree of analytical thinking required.

For practical implementation, GIS activities should be introduced progressively. Students may initially work with existing digital maps and basic visualization before moving to data comparison, thematic mapping, field-data integration, and independent spatial analysis. Such progression can reduce technical difficulties while allowing GIS skills to develop alongside geographical knowledge and spatial reasoning.

4. Conclusion

The integration of GIS technologies into geography education provides opportunities to move beyond the traditional presentation of geographical information toward a more analytical and student-centered learning process. GIS enables students to visualize spatial relationships, work with geographical data, investigate real-world problems, and develop evidence-based explanations. Its educational value, however, depends less on the technology itself than on the teaching approach through which it is applied.

The analysis demonstrates that GIS can be effectively combined with inquiry-based, problem-based, project-based, and field-oriented learning, as well as Web GIS and digital storytelling. The conceptual framework proposed in this study emphasizes a progression from identifying a geographical problem to working with spatial data, conducting GIS-based analysis, interpreting results, and making evidence-based decisions. This approach places geographical reasoning at the center of GIS-supported learning rather than treating GIS primarily as a technical mapping tool.

Effective implementation also requires appropriate teacher preparation, access to suitable geospatial resources, and GIS activities adapted to students' knowledge and digital skills. A gradual transition from basic map interpretation and visualization to independent spatial analysis may facilitate the integration of GIS into geography curricula. Future empirical studies should test the proposed framework in different educational settings and examine its effects on students' spatial thinking, geographical knowledge, digital competence, and problem-solving skills.

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ИНТЕГРАЦИЯ ГЕОИНФОРМАЦИОННЫХ ТЕХНОЛОГИЙ В ПРЕПОДАВАНИЕ ГЕОГРАФИИ: СОВРЕМЕННЫЕ МЕТОДИЧЕСКИЕ ПОДХОДЫ

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Резюме. Расширяющееся использование геопространственных технологий создаёт новые возможности для совершенствования преподавания и изучения географии. В исследовании рассматривается интеграция географических информационных систем (ГИС) в географическое образование с особым вниманием к педагогическим подходам, способствующим развитию пространственного мышления, исследовательской деятельности и активного участия учащихся. В работе анализируется образовательный потенциал ГИС в контексте исследовательского обучения, проблемно-ориентированного обучения, проектного обучения, полевых исследований и деятельности по цифровому картографированию. Особое внимание уделяется переходу от традиционного представления географической информации к образовательной среде, в которой учащиеся собирают,

визуализируют, интерпретируют и сопоставляют пространственные данные, а также используют полученные результаты для исследования географических проблем. Анализ показывает, что эффективная интеграция ГИС зависит не только от доступности геопространственных технологий, но и от соответствующих методов преподавания, профессиональной компетентности учителей, разработки учебных программ и выбора учебных видов деятельности, соответствующих способностям учащихся. На основе указанных положений в исследовании предлагается практическая модель, объединяющая географические проблемы, пространственные данные, анализ на основе ГИС, интерпретацию результатов и принятие решений учащимися в рамках единого образовательного процесса. Предлагаемый подход может способствовать развитию географических знаний, пространственного мышления, цифровых навыков и способности к самостоятельному решению проблем в современном географическом образовании.

Ключевые слова: *географические информационные системы (ГИС), географическое образование, пространственное мышление, исследовательское обучение, проектное обучение, геопространственные технологии, цифровое обучение*

CİS TEXNOLOGİYALARININ COĞRAFİYA TƏHSİLİNƏ İNTEQRASİYASI: MÜASİR TƏDRİS YANAŞMALARI

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Xülasə. Geoməkan texnologiyalarından istifadənin getdikcə genişlənməsi coğrafiyanın tədrisi və öyrənilməsinin təkmilləşdirilməsi üçün yeni imkanlar yaratmışdır. Tədqiqatda Coğrafi İnformasiya Sistemlərinin (CİS) coğrafiya təhsilinə inteqrasiyası araşdırılır və məkan təfəkküründü, tədqiqata əsaslanan öyrənməni və şagirdlərin fəal iştirakını təşviq edən tədris yanaşmalarına xüsusi diqqət yetirilir. Tədqiqatda CİS-in təhsil potensialı tədqiqata əsaslanan öyrənmə, problem əsaslı öyrənmə, layihə əsaslı öyrənmə, çöl tədqiqatları və rəqəmsal xəritələşdirmə fəaliyyətləri kontekstində təhlil edilir. Coğrafi informasiyanın ənənəvi təqdimatından şagirdlərin məkan məlumatlarını topladığı, vizuallaşdırdığı, şərh etdiyi və müqayisə etdiyi, həmçinin əldə olunan nəticələrdən coğrafi problemlərin araşdırılmasında istifadə etdiyi təlim mühitinə keçidə xüsusi diqqət yetirilir. Təhlil göstərir ki, CİS-in səmərəli inteqrasiyası yalnız geoməkan texnologiyalarına çıxış imkanlarından deyil, həm də müvafiq tədris metodlarından, müəllimlərin peşəkar səriştəliliyindən, tədris proqramlarının hazırlanmasından və şagirdlərin qabiliyyətlərinə uyğun təlim fəaliyyətlərinin seçilməsindən asılıdır. Bu mülahizələr əsasında tədqiqatda coğrafi problemləri, məkan məlumatlarını, CİS əsaslı təhlili, nəticələrin şərhini və şagirdlərin qərar qəbuletmə prosesini vahid təlim prosesi çərçivəsində əlaqələndirən praktik model təklif olunur. Təklif edilən yanaşma müasir coğrafiya təhsilində coğrafi biliklərin, məkan təfəkküründün, rəqəmsal bacarıqların və problemləri müstəqil həll etmək qabiliyyətinin inkişafını dəstəkləyə bilər.

Açar sözlər: *coğrafi informasiya sistemləri (CİS), coğrafiya təhsili, məkan təfəkkürü, tədqiqata əsaslanan təlim, layihə əsaslı təlim, geoməkan texnologiyaları, rəqəmsal təlim*

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VIRTUAL FIELD PRACTICAL TRAINING ON CLIMATE CHANGE: ARTIFICIAL INTELLIGENCE-BASED PEDAGOGICAL MODELS

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Keywords: *climate change education, AI-supported virtual fieldwork, geographic inquiry, spatial thinking, pedagogical design framework*

Summary. Climate change has become a global educational priority that requires learners to interpret scientific evidence, understand spatial relationships, and develop sustainable solutions. In this context, geography education plays a key role in fostering climate literacy, spatial thinking, and geographic inquiry. However, traditional fieldwork is constrained by limitations related to time, cost, accessibility, and safety. Although advances in virtual fieldwork and generative artificial intelligence (AI) provide new opportunities to address these challenges, systematic pedagogical approaches for integrating AI into virtual fieldwork remain limited. This study aims to develop a pedagogically grounded framework for AI-supported virtual fieldwork in climate change education and to demonstrate its application through representative learning activities. The study adopts a conceptual design based on a synthesis of contemporary literature on climate change education, geography education, virtual fieldwork, artificial intelligence, spatial thinking, and educational technologies. The proposed framework is structured around seven pedagogical design principles: beginning with authentic climate change problems, promoting spatial evidence-based learning, positioning AI as a cognitive learning partner, placing geographic inquiry at the centre of learning, fostering solution-oriented learning, employing process-oriented assessment, and ensuring the ethical and responsible use of AI. To illustrate the framework, three representative virtual fieldwork activities focusing on glacier retreat, drought, and urban heat islands were developed. The proposed framework provides a pedagogical foundation for strengthening climate literacy, spatial thinking, geographic inquiry, critical thinking, and AI literacy in geography education.

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Introduction

Climate change is one of the defining challenges of the twenty-first century, reaching far beyond environmental systems to touch economic development, social wellbeing, and education policy alike. As climate-related hazards grow more frequent and more severe, it becomes increasingly important for people to understand climate processes, weigh scientific evidence critically, and imagine workable, sustainable solutions. Contemporary climate change education reflects this shift: rather than simply transmitting facts, it aims to build climate literacy, critical thinking, evidence-based decision-making, and genuine engagement with sustainability (IPCC, 2023; UNESCO, 2021). Systematic reviews of the field point in the same direction, showing that effective climate change education needs to be student-centred, inquiry-driven, and oriented toward action rather than passive learning (Monroe et al., 2019).

Geography education has a particularly important role to play here, precisely because climate change is not a uniform, placeless phenomenon — its causes, impacts, and possible solutions look different from one place, region, and scale to another. Making sense of processes such as retreating glaciers, rising sea levels, drought, wildfires, or urban heat islands requires students to ask where these things are happening, why, and how they connect to both natural and human systems. This is why geography education leans so heavily on maps, satellite imagery, Geographic Information Systems (GIS), remote sensing data, and direct field observation: these tools are what turn spatial thinking and evidence-based reasoning from abstract skills into something students can actually practice (National Research Council, 2006; Bednarz et al., 2013).

Fieldwork has long been considered one of geography education's most powerful pedagogical tools. By giving students the chance to observe environmental processes firsthand and connect theoretical knowledge to the real world, fieldwork strengthens observation, inquiry, problem-solving, and experiential learning in ways that classroom instruction alone rarely can (Kent et al., 1997; Fuller et al., 2006). Yet traditional fieldwork comes with real constraints — cost, time, accessibility, safety, and weather, among others — and these constraints are often felt most acutely in climate change education specifically, where the very phenomena being studied (glaciers, droughts, extreme heat) can make field visits impractical or even hazardous. This is precisely the gap that virtual fieldwork has come to fill. Using satellite imagery, digital maps, GIS, and 3D visualization, virtual fieldwork allows students to compare different geographic environments and examine environmental change across a range of spatial and temporal scales that would be difficult, if not impossible, to access in person (Stainfield et al., 2000; Cliffe, 2017). Hybrid approaches, in particular, have been shown to widen access while preserving much of fieldwork's pedagogical value (France & Haigh, 2018).

More recently, advances in digital technology — and generative artificial intelligence in particular — have begun to change what virtual fieldwork can actually be. Rather than functioning as static repositories of digital content, AI-enhanced virtual fieldwork environments can become interactive, adaptive learning spaces. Artificial intelligence can help generate inquiry questions, support the interpretation of spatial data, and offer adaptive feedback tailored to individual learners. When grounded in sound pedagogical principles, AI need not replace the teacher's role at all; instead, it can act as a cognitive learning partner that supports inquiry and critical thinking rather than substituting for it (Holmes et al., 2019; UNESCO, 2023). Even so, the literature currently offers little in the way of a coherent framework for how AI-supported virtual fieldwork should actually be designed and pedagogically structured within climate change education specifically. The present study responds to this gap: it proposes a set of pedagogical design principles for AI-supported virtual fieldwork in climate change education, illustrates how these principles can be translated into practice through sample activities, and considers what this approach might offer geography education more broadly.

Purpose of the study

This study aims to develop a pedagogically grounded framework for integrating artificial intelligence into virtual fieldwork for climate change education. The framework positions AI as a cognitive learning partner that supports, rather than replaces, geographic inquiry, spatial evidence interpretation, critical thinking, and human judgement. It brings together climate change education, geography education, virtual fieldwork, and generative AI within a coherent instructional approach.

Based on a synthesis of relevant literature, the study proposes seven interrelated pedagogical design principles and demonstrates their application through three illustrative virtual fieldwork activities focusing on glacier retreat, drought, and urban heat islands. The study is conceptual and design-oriented; therefore, the proposed framework and activities are presented as a foundation for subsequent expert validation, classroom implementation, and empirical research.

Research questions

Climate change education, virtual fieldwork, and artificial intelligence have each generated a substantial body of research in recent years. What's still missing, though, is work that brings these three areas together within geography education through a coherent, pedagogically grounded approach. Virtual fieldwork is widely recognized as an effective way to support geographic learning, and generative AI is understood to have real potential for inquiry-based, interactive, and adaptive learning — yet there is still no systematic design approach for how these two things might be combined in service of climate change education specifically. To the best of the authors' knowledge, no existing study has integrated generative AI, virtual fieldwork, and climate change education within geography education through a unified set of pedagogical design principles. This gap is what motivates the present study.

Within this framework, the study sets out to identify the pedagogical principles that should guide the design of AI-supported virtual fieldwork, and to show how those principles can be reflected in learning activities for climate change education. To that end, the study addresses the following research questions:

RQ1. How can artificial intelligence be integrated into virtual fieldwork for climate change education in a pedagogically meaningful and effective way?

RQ2. What pedagogical design principles should guide the design and implementation of AI-supported virtual fieldwork?

RQ3. How can the proposed pedagogical design principles be translated into sample learning activities for AI-supported virtual fieldwork?

RQ4. What learning outcomes can theoretically be supported through AI-supported virtual fieldwork in climate change education?

Literature review

The proposed framework draws on four interconnected areas of scholarship: climate change education, geography education, virtual fieldwork, and artificial intelligence in education. Climate change education emphasizes climate literacy, sustainability awareness, inquiry, and action-oriented learning (Monroe et al., 2019; UNESCO, 2021), while virtual fieldwork supports accessibility, experiential learning, and the development of spatial understanding (Cliffe, 2017; France & Haigh, 2018). Research on generative AI highlights its potential for personalized learning, adaptive support, inquiry, and learning analytics, while also emphasizing the importance of pedagogically responsible integration (Kasneci et al., 2023; UNESCO, 2023). Bringing these strands together provides the theoretical basis for developing a pedagogically grounded approach to AI-supported virtual fieldwork in climate change education.

Climate change education

Climate change education extends beyond the transmission of scientific knowledge by developing learners' climate literacy, critical evaluation of evidence, informed decision-making, and capacity to engage with adaptation and mitigation challenges (UNESCO, 2021; IPCC, 2023). Effective approaches are increasingly student-centred, inquiry-based, and action-oriented, encouraging learners to connect scientific understanding with meaningful responses to environmental problems (Monroe et al., 2019).

Geography education provides a particularly relevant context for these goals because climate change is inherently spatial and varies across places and scales. Maps, GIS, remote sensing, and satellite imagery enable students to investigate environmental change through spatial evidence and strengthen geographic reasoning and spatial thinking (National Research Council, 2006; Bednarz et al., 2013). These characteristics make climate change education well suited to virtual fieldwork environments in which learners can examine spatial and temporal patterns that may be difficult to observe directly.

Virtual fieldwork in Geography education

Virtual fieldwork enables students to explore geographic environments through digital maps, satellite imagery, GIS, remote sensing data, and 3D visualization, reducing constraints associated with location, time, accessibility, and cost. Rather than functioning merely as virtual tours, well-designed virtual field experiences can support spatial thinking, geographic inquiry, and the analysis of environmental processes (Stainfield et al., 2000; Cliffe, 2017).

Virtual fieldwork is particularly valuable for examining environmental change across spatial and temporal scales that are difficult to observe directly, including glacier retreat, drought, and urban transformation. However, it should generally complement rather than replace direct field experience, since virtual environments cannot fully reproduce observation and interaction in real-world settings (Kent et al., 1997; France & Haigh, 2018). This complementary role provides a useful foundation for integrating AI as an additional form of inquiry and learning support.

Artificial Intelligence in Geography Education

Generative AI offers new opportunities for personalized learning, inquiry support, formative feedback, and higher-order thinking, but its educational value depends on alignment with clear pedagogical objectives rather than technological capability alone (Kasneci et al., 2023; UNESCO, 2023; OECD, 2024). In geography education, AI can support students in formulating questions, comparing explanations, and interpreting maps, GIS, remote sensing, and other spatial evidence, while responsibility for evaluation and decision-making remains with the learner and teacher.

Integrating AI with virtual fieldwork therefore has potential to strengthen geographic inquiry and evidence-based reasoning when it is grounded in appropriate pedagogical design. This approach is consistent with technology-integration frameworks such as TPACK and SAMR, which emphasize meaningful relationships among disciplinary knowledge, pedagogy, and technology (Mishra & Koehler, 2006; Puentedura, 2006). At the same time, responsible implementation requires attention to academic integrity, privacy, bias, and the critical verification of AI-generated information (UNESCO, 2023).

Methodology

This study employs a conceptual and design-oriented research approach to develop a pedagogical framework for AI-supported virtual fieldwork in climate change education. The methodological process was informed by the early analytical and design phases of educational design research, in which a practical educational problem is identified, relevant theoretical and empirical literature is synthesized, and theoretically grounded design principles are formulated for subsequent evaluation and refinement (Design-Based Research Collective, 2003; McKenney & Reeves, 2012). No classroom intervention or experimental evaluation was conducted at this stage; accordingly, the proposed framework should be understood as an initial design iteration rather than an empirically validated instructional model.

The theoretical foundation of the framework was developed through a narrative and purposive synthesis of literature on climate change education, geography education, virtual fieldwork, spatial thinking, and generative AI in education. Sources were selected for their conceptual relevance to the research questions and included both foundational scholarship and recent literature on AI-supported learning. This approach was chosen to support theoretical integration and framework development rather than exhaustive literature retrieval (Baumeister & Leary, 1997; Grant & Booth, 2009). Accordingly, the literature synthesis should not be interpreted as a systematic review.

The design principles were developed through a thematic synthesis of the selected literature. Recurring pedagogical concepts were identified across the reviewed sources, including inquiry-based learning, spatial evidence use, experiential learning, learner–AI interaction, solution-oriented learning, assessment, and responsible AI use. These concepts were grouped into broader themes and iteratively refined by examining their relevance to the four research questions. The resulting themes were also considered in relation to established technology-integration perspectives, particularly TPACK and SAMR (Mishra & Koehler, 2006; Puentedura, 2006). This process resulted in the seven interrelated pedagogical design principles presented in Section 4.

Design principles for AI-Supported virtual fieldwork in climate change education

Based on the synthesis described above, seven interrelated design principles are proposed for AI-supported virtual fieldwork in climate change education: (1) starting with authentic climate change problems, (2) supporting spatial evidence-based learning, (3) positioning AI as a cognitive learning partner, (4) centring geographic inquiry, (5) encouraging solution- and action-oriented learning, (6) using process-oriented assessment, and (7) ensuring the ethical and responsible use of AI. Together, these principles provide a pedagogically grounded but flexible guide for designing learning activities in which technology supports, rather than determines, geographic inquiry and climate change learning.

Principle 1. Start with real climate change problems

AI-supported virtual fieldwork should be organized around authentic climate change problems that connect learning with real-world environmental challenges. Problem-based learning provides a meaningful context for investigating environmental issues, evaluating scientific evidence, and developing possible solutions (Bransford et al., 2000; Monroe et al., 2019). Issues such as glacier retreat, drought, wildfires, sea-level rise, and urban heat islands can provide relevant contexts for inquiry, while AI can support the process through adaptive questions, alternative scenarios, and prompts for evidence-based discussion.

Principle 2. Support spatial evidence-based learning

Learning activities should require students to construct explanations from reliable spatial evidence rather than rely on AI-generated responses alone. Satellite imagery, GIS, remote sensing products, digital elevation models, and thematic maps provide important evidence for examining environmental change (National Research Council, 2006). AI can assist students in identifying patterns, comparing interpretations, and questioning relationships within spatial data, but conclusions should remain grounded in geographic evidence.

Principle 3. Position AI as a Cognitive Learning Partner

AI should support students' reasoning rather than replace it. Its role can include prompting questions, supporting hypothesis formation, suggesting alternative explanations, and providing formative feedback during inquiry (Luckin, 2018; UNESCO, 2023). Students should remain responsible for evaluating AI-generated information, interpreting evidence, and making decisions, thereby maintaining human judgement at the centre of the learning process.

Principle 4. Put Geographic inquiry at the centre of learning

Geographic inquiry should provide the organizing structure for AI-supported virtual fieldwork. Students can investigate environmental phenomena through questions such as: Where is it occurring? Why there? How is it changing? What might happen next? What responses are possible? (Lambert & Morgan, 2010; Maude, 2016). AI can support this inquiry by generating prompts, suggesting additional data sources, and facilitating

comparisons across places and scales, while students remain responsible for evidence-based interpretation and conclusions.

Principle 5. Encourage solution- and action-oriented learning

Climate change education should enable students not only to understand environmental problems but also to consider possible adaptation and mitigation responses (UNESCO, 2021; Monroe et al., 2019). Within virtual fieldwork, students can compare alternative strategies, examine their potential consequences, and develop evidence-based recommendations. AI can support this process by helping generate scenarios and alternative courses of action that students subsequently evaluate against scientific and geographic evidence.

Principle 6. Use process-oriented assessment

Assessment should address the inquiry process as well as the final product, including how students formulate questions, interpret spatial evidence, evaluate AI-generated information, justify conclusions, and reflect on their learning (Bransford et al., 2000; Kolb, 2015). AI may provide formative prompts and opportunities for self-assessment, but responsibility for evaluating student learning should remain with the teacher.

Principle 7. Ensure the ethical and responsible use of AI

AI-supported virtual fieldwork should be grounded in transparency, academic integrity, fairness, privacy, and critical use of technology. Students should verify AI-generated information against reliable scientific sources and geographic evidence rather than accept it uncritically (UNESCO, 2023; OECD, 2024). Attention should also be given to potential errors, bias, appropriate attribution, and data privacy, making responsible AI use an integral component of the learning process.

The Proposed AI-supported virtual fieldwork framework

The proposed framework integrates climate change education, geography education, virtual fieldwork, and artificial intelligence within a pedagogically coherent structure based on the seven design principles. Authentic climate change problems, spatial evidence, and geographic inquiry form the core of the framework, while AI functions as a supporting tool for inquiry, reflection, and evidence-based reasoning.

The framework is intentionally flexible rather than prescriptive. It is not tied to a specific AI platform, curriculum, educational level, or geographic topic and can therefore be adapted to different learning objectives, technological conditions, and climate-related phenomena.

Learning scenario and ıllustrative applications

The framework is operationalized through six interconnected stages: (1) identifying an authentic climate change problem, (2) collecting relevant spatial evidence, (3) formulating geographic inquiry questions, (4) conducting AI-supported analysis, (5) constructing evidence-based explanations and possible solutions, and (6) reflecting on both the learning process and the use of AI. The stages provide a common structure for virtual fieldwork while allowing adaptation to different educational contexts.

Throughout the process, students work with relevant geographic evidence, such as satellite imagery, GIS data, thematic maps, remote sensing products, climate records, drought indices, and land-use data. AI may provide guiding questions, alternative explanations, and formative feedback, while students remain responsible for verifying information, interpreting evidence, and developing conclusions.

Three illustrative activities demonstrate how the framework can be applied at different geographic scales: glacier retreat at the global scale, drought at the regional scale, and urban heat islands at the local scale. Although the activities differ in topic and spatial scale, each follows the same inquiry-oriented structure and requires students to analyse spatial evidence and critically evaluate AI-supported interpretations. The activities are illustrative applications of the framework rather than empirically validated lesson plans.

Expected educational outcomes and practical ımplications

The framework has the potential to support spatial thinking, geographic inquiry, and evidence-based decision-making through the use of satellite imagery, GIS, and remote sensing data (National Research Council, 2006; Bednarz et al., 2013). It may also contribute to climate literacy and AI literacy by encouraging students to examine climate-related problems across geographic scales while critically evaluating the reliability and limitations of AI-generated information.

Because the framework is not tied to a specific curriculum, grade level, geographic topic, or AI platform, it may provide a flexible reference for teachers, curriculum developers, and researchers. However, these outcomes are theoretically expected rather than empirically demonstrated. Future research should evaluate the framework through expert review, classroom implementation, and empirical studies examining student learning, teacher experience, feasibility, and the ethical dimensions of AI-supported virtual fieldwork.

AI-supported virtual fieldwork for climate change education: three sample activities

The activities below are built directly on the seven pedagogical design principles outlined earlier. The three illustrative activities summarized here — glacier retreat, drought, and urban heat islands — have been turned into short, focused lesson plans intended as adaptable starting points for high-school-level instruction, pending classroom piloting and teacher feedback.

Each one includes a learning objective, materials, the role AI plays, a step-by-step learning sequence, sample prompts, inquiry questions, and brief reflection prompts for process-oriented assessment. All three are designed to fit within a single 40-minute class period and can be adjusted depending on what a given school has available.

Activity 1: Glacier Retreat

Level	High school
Duration	40 minutes
Geographic scale	Global
Group structure	Groups of 3–4
Technology needed	Computer/tablet, internet access; an AI chat tool (teacher-supervised)

1. Climate Change Context

Students examine glacier retreat in a selected mountain region (e.g., the Alps, Kilimanjaro, Mount Ararat) using real satellite imagery, and explore how it connects to rising global temperatures, glacial mass loss, and the regional and global consequences that follow.

2. Learning Objective and Outcomes

The goal is for students to compare multi-temporal satellite images and, with AI support, build evidence-based explanations of glacier retreat as an indicator of climate change.

By the end of the activity, students should be able to:

- explain glacier retreat using scientific evidence,
- critically evaluate AI-generated information and verify it against independent sources,
- propose an evidence-based adaptation or mitigation strategy for glacier loss.

3. Digital Resources and Materials

- Google Earth (Timelapse) or Sentinel Hub EO Browser — satellite imagery from different years
- NASA Worldview / Global Ice Viewer — glacier time-series visuals
- Publicly available temperature data (e.g., NASA GISS) and a comparison worksheet

4. The Role of AI

Here, AI is a learning partner that accompanies inquiry rather than handing out answers: it suggests observation criteria, offers alternative explanations, and gives feedback. Interpretation and drawing conclusions stay with the student, and every claim needs to be checked against spatial evidence.

Sample AI Prompts (for students to use)

"Connect the three main reasons the [region name] glacier is shrinking to clues I could look for in a satellite image."

"Suggest two alternative scenarios for how glacier loss could affect water resources — what evidence should I check for each one?"

5. Step-by-Step Learning Process

Stage 1: Identifying the Problem and Gathering Evidence (15 min)

- The teacher opens with a current image or news story and the question "Why is this glacier shrinking?"; groups pick a glacier region to study.
- Groups compare satellite images from at least two different years and note changes in the glacier boundary on their worksheet.
- "Suggest three observation criteria I can use to compare the glacier front's position in these two images."

Stage 2: Inquiry and Verification (15 min)

- Groups formulate "Why, How, What might happen next?" questions and ask AI for alternative explanations.
- They check the explanation they receive against temperature data or a reliable source (IPCC/NASA), then write a short evidence report.

Stage 3: Proposing a Solution, Presenting, and Reflecting (10 min)

- Each group develops a brief adaptation or mitigation proposal for the region and shares it in 1–2 minutes.
- Students reflect briefly: how did I use AI, and what did I need to verify?

6. Geographic Inquiry Questions

Throughout the activity, students are expected to build evidence-based answers to:

- Where is glacier retreat happening, and to what extent?
- How has the glacier's area changed over time, and why?
- What adaptation or mitigation measures could be taken at the regional scale?

Activity 2: Assessing Drought
Rainfall Variability and Land-Use Analysis

Level	High school
Duration	40 minutes
Geographic scale	Regional
Group structure	Groups of 3–4
Technology needed	Computer/tablet, internet access; an AI chat tool (teacher-supervised)

1. Climate Change Context

Students examine a water-stressed region (e.g., Türkiye's Konya Closed Basin), looking at rainfall variability, drought indices, and land-use patterns, and investigate how natural (climatic) and human (over-extraction of water, land-use change) factors both contribute to drought.

2. Learning Objective and Outcomes

The goal is for students to analyse rainfall and drought data alongside land-use maps, and to build evidence-based explanations of drought's causes through AI-supported inquiry.

By the end of the activity, students should be able to:

- interpret the relationship between rainfall variability and drought indices,
- distinguish between natural and human factors and build a multi-causal explanation,
- propose an evidence-based, region-specific water management or drought-response strategy.

3. Digital Resources and Materials

- Rainfall map / time-series chart (e.g., from Türkiye's State Meteorological Service open data portal)
- Sample drought index map (SPI/PDSI) and an NDVI (vegetation cover) visual
- Land-use map and a comparison worksheet

4. The Role of AI

AI acts as a learning partner that helps students connect different data layers — rainfall, NDVI, land use — offering alternative scenarios involving natural and human causes and providing feedback. Students always check any proposed causal relationship against the actual data.

Sample AI Prompts (for students to use),

"List three things I should pay attention to when interpreting this graph showing a drop in SPI values." "Give examples of human factors — besides reduced rainfall — that could make drought worse. What data should I look at?"

5. Step-by-Step Learning Process

Stage 1: Introducing the Problem and Gathering Evidence (15 min)

- The teacher opens with a drought-related news story or image and the question "Why is this region drying out?"; groups select a sub-region or time period.
- Groups examine the rainfall chart and NDVI visual, and note the severity and distribution of drought on their worksheet.
- "What order should I follow to interpret the rainfall chart together with the NDVI map?"

Stage 2: Investigating Multiple Causes and Verification (15 min)

- Groups formulate "Why, How, What might happen next?" questions and ask AI for both natural and human explanations.
- They check the proposed causes against the land-use map and prepare a short cause-and-effect diagram.

Stage 3: Proposing a Solution, Presenting, and Reflecting (10 min)

- Each group develops 1–2 water management or drought-response proposals and shares them briefly.
- Individual reflection: why does it matter to distinguish between natural and human causes?

6. Geographic Inquiry Questions

Throughout the activity, students are expected to build evidence-based answers to:

- Where in this region is drought occurring, and how severe is it?
- What role do natural versus human factors play in causing it?
- What measures could help protect water resources?

Activity 3: Urban Heat Islands
Thermal Satellite Imagery and Land Cover Analysis

Level	High school
Duration	40 minutes
Geographic scale	Local (city/district level)
Group structure	Groups of 3–4
Technology needed	Computer/tablet, internet access; an AI chat tool (teacher-supervised)

1. Climate Change Context

Students examine the urban heat island effect in their own city using Landsat thermal bands and land cover maps, investigating why surface temperatures differ between densely built-up areas and green spaces or bodies of water, and how this connects to sustainable urban planning.

2. Learning Objective and Outcomes

The goal is for students to analyse thermal satellite imagery and land cover data to explain, through AI-supported inquiry, the spatial pattern and causes of the urban heat island effect, and to develop sustainable solutions.

By the end of the activity, students should be able to:

- interpret the distribution of urban surface temperature from thermal imagery,
- connect temperature differences to land cover (built-up areas, green space, water bodies),
- propose a practical cooling or planning strategy for their own environment.

3. Digital Resources and Materials

- Landsat thermal band imagery / a ready-made Land Surface Temperature (LST) map
- Land cover map (satellite imagery or an OpenStreetMap layer)
- Google Earth/Maps satellite view and a comparison worksheet

4. The Role of AI

AI acts as a learning partner that helps students interpret thermal imagery and land cover data together, offering alternative explanations for temperature differences (albedo, built-up density, human-generated heat). Students verify these explanations against map or observational evidence.

Sample AI Prompts (for students to use)

"What clues should I look for to compare the hottest and coolest areas on this thermal map?" "Why does surface temperature differ between a heavily paved area and a park? Explain using the concept of albedo."

5. Step-by-Step Learning Process

Stage 1: Introducing the Problem and Gathering Evidence (15 min)

- The teacher opens the lesson with data or a news story about the temperature difference between the city centre and its surroundings; groups pick a neighbourhood.
- Groups note the neighbourhood's temperature level on the LST map and its built-up/green space status on the land cover map.
- "What order should I follow when examining the thermal map together with the land cover map?"

Stage 2: Investigating Causes and Verification (15 min)

- Groups formulate "Why, How, What measures could be taken?" questions and ask AI for explanations grounded in albedo and built density.
- They verify the explanation against their own map observations (e.g., is the paved area really the hottest spot?) and write a short evidence report.

Stage 3: Proposing a Plan, Presenting, and Reflecting (10 min)

- Each group proposes 1–2 measures to reduce heat in the neighbourhood (tree planting, green roofs, light-coloured surfaces, etc.) and shares them briefly.
- Individual reflection: where in my own surroundings might I notice this effect?

6. Geographic Inquiry Questions

Throughout the activity, students are expected to build evidence-based answers to:

- Where are the highest and lowest surface temperatures found in the city?
- Why do these temperature differences occur?
- What measures could help reduce the heat island effect?

Discussion

This study brings climate change education, virtual fieldwork, and generative AI together within a pedagogically grounded framework centred on authentic environmental problems, spatial evidence, and geographic inquiry. The proposed principles are consistent with previous research emphasizing inquiry-based, experiential, and spatial approaches to geography education (Kent et al., 1997; Cliffe, 2017; France & Haigh, 2018), while extending this work by explicitly considering the pedagogical role of generative AI. Rather than treating AI as a source of ready-made answers, the framework positions it as a cognitive support for questioning, interpretation, feedback, and reflection, with students and teachers retaining responsibility for evaluating evidence and making decisions (UNESCO, 2023; Kasneci et al., 2023).

An important practical consideration is digital equity. Although virtual fieldwork can reduce some constraints associated with conventional fieldwork, meaningful implementation still depends on reliable connectivity, appropriate hardware, access to digital resources, teacher competence, and institutional support (Ahmed, 2024; OECD, 2024). Unequal access to these conditions may result in substantially different learning experiences across schools and regions, particularly when generative AI is introduced into already unequal educational environments (Holstein & Doroudi, 2021). The adaptability of the framework should therefore not be interpreted as a guarantee of equal implementation across educational contexts.

The study also has important methodological limitations. The proposed framework is conceptual and has not yet been empirically validated. Moreover, the three illustrative activities were developed as applications of the seven design principles rather than through expert review, teacher-panel evaluation, or classroom piloting. Their feasibility, age-appropriateness, instructional timing, and learning effects therefore remain to be established. Future research should subject the framework and activities to expert validation and classroom-based evaluation, including structured teacher panels or Delphi studies, followed by experimental, mixed-methods, or design-based research across different educational and technological contexts.

Conclusion

This study proposes a pedagogically grounded framework for AI-supported virtual fieldwork in climate change education. Based on seven interrelated design principles, the framework connects authentic climate change problems, spatial evidence, geographic inquiry, solution-oriented learning, process-based assessment, and responsible AI use. AI is positioned as a cognitive support for inquiry rather than a substitute for geographic evidence, student reasoning, or teacher judgement.

The framework provides a flexible basis for designing virtual fieldwork across different climate-related topics, geographic scales, educational levels, and technological contexts. The three illustrative activities demonstrate how its principles can be translated into instructional designs addressing glacier retreat, drought, and urban heat islands. However, these applications should be understood as conceptual examples rather than evidence of educational effectiveness.

Further research should therefore focus on expert validation, classroom implementation, and empirical evaluation of the framework. Particular attention should be given to its feasibility, effects on students' climate literacy, spatial reasoning and AI literacy, teachers' experiences, ethical considerations, and implementation across educational settings with different levels of technological access. Such evidence will be necessary to determine the educational value and practical applicability of AI-supported virtual fieldwork in climate change education.

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ВИРТУАЛЬНЫЕ ПОЛЕВЫЕ ПРАКТИКУМЫ ПО ИЗМЕНЕНИЮ КЛИМАТА: ПЕДАГОГИЧЕСКИЕ МОДЕЛИ НА ОСНОВЕ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА

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Резюме. Изменение климата стало глобальным образовательным приоритетом, требующим от обучающихся умения интерпретировать научные данные, понимать пространственные взаимосвязи и разрабатывать устойчивые решения. В данном контексте географическое образование играет ключевую роль в формировании климатической грамотности,

пространственного мышления и навыков географического исследования. Однако традиционные полевые исследования сталкиваются с ограничениями, связанными со временем, затратами, доступностью и безопасностью. Несмотря на то что развитие виртуальных полевых исследований и генеративного искусственного интеллекта (ИИ) открывает новые возможности для преодоления этих трудностей, систематические педагогические подходы к интеграции ИИ в виртуальные полевые исследования остаются недостаточно разработанными. Цель исследования заключается в разработке педагогически обоснованной концептуальной модели виртуальных полевых исследований с поддержкой искусственного интеллекта в образовании по вопросам изменения климата и демонстрации её применения посредством типовых учебных заданий. В исследовании используется концептуальный подход к проектированию, основанный на синтезе современной научной литературы по вопросам образования в области изменения климата, географического образования, виртуальных полевых исследований, искусственного интеллекта, пространственного мышления и образовательных технологий. Предлагаемая модель структурирована на основе семи принципов педагогического проектирования: использование реальных проблем изменения климата в качестве отправной точки, содействие обучению на основе пространственных данных, позиционирование искусственного интеллекта как когнитивного партнёра в обучении, постановка географического исследования в центр образовательного процесса, развитие обучения, ориентированного на поиск решений, применение процессно-ориентированного оценивания и обеспечение этичного и ответственного использования искусственного интеллекта. Для иллюстрации предлагаемой модели разработаны три типовых виртуальных полевых учебных задания, посвящённых отступанию ледников, засухе и городским островам тепла. Предлагаемая модель формирует педагогическую основу для развития климатической грамотности, пространственного мышления, навыков географического исследования, критического мышления и грамотности в области искусственного интеллекта в географическом образовании.

Ключевые слова: *обучение вопросам изменения климата, виртуальные полевые исследования с поддержкой искусственного интеллекта, географическое исследование, пространственное мышление, педагогическая модель проектирования*

İQLİM DƏYİŞMƏLƏRİ ÜZRƏ VİRTUAL SAHƏ TƏCRÜBƏLƏRİ: SÜNİ İNTELLEKTƏ ƏSASLANAN PEDAQOJİ MODELLƏR

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Xülasə. İqlim dəyişikliyi təhsilalanlardan elmi sübutları şərh etməyi, məkan əlaqələrini anlamağı və dayanıqlı həll yolları hazırlamağı tələb edən qlobal təhsil prioritetinə çevrilmişdir. Bu kontekstdə coğrafiya təhsili iqlim savadlılığının, məkan təfəkküründün və coğrafi tədqiqat bacarıqlarının formalaşdırılmasında mühüm rol oynayır. Bununla belə, ənənəvi çöl tədqiqatları vaxt, xərc, əlçatanlıq və təhlükəsizliklə bağlı məhdudiyyətlərlə üzləşir. Virtual çöl tədqiqatları və generativ süni intellekt (Sİ) sahəsindəki irəliləyişlər bu çətinliklərin aradan qaldırılması üçün yeni imkanlar yaratsa da, süni intellektin virtual çöl tədqiqatlarına inteqrasiyası üzrə sistemli pedaqoji yanaşmalar hələ də məhduddur. Tədqiqatın məqsədi iqlim dəyişikliyi təhsilində süni intellektlə dəstəklənən virtual çöl tədqiqatları üçün pedaqoji cəhətdən əsaslandırılmış çərçivə hazırlamaq və onun tətbiqini nümunəvi təlim fəaliyyətləri vasitəsilə nümayiş etdirməkdir. Tədqiqatda iqlim dəyişikliyi təhsili, coğrafiya təhsili, virtual çöl tədqiqatları, süni intellekt, məkan təfəkkürü və təhsil texnologiyaları üzrə müasir elmi ədəbiyyatın sintezinə əsaslanan konseptual layihələndirmə yanaşması tətbiq edilmişdir. Təklif olunan çərçivə yeddi pedaqoji layihələndirmə prinsipi əsasında qurulmuşdur: real iqlim dəyişikliyi problemlərindən başlamaq, məkan sübutlarına əsaslanan öyrənməni təşviq etmək, süni intellekti koqnitiv təlim tərəfdaşı kimi mövqeləndirmək, coğrafi tədqiqatı təlim prosesinin mərkəzinə yerləşdirmək, həll yönümlü öyrənməni inkişaf etdirmək, prosesyönümlü qiymətləndirmə tətbiq etmək və süni intellektdən etik və məsuliyyətli istifadəni təmin etmək. Təklif olunan çərçivəni nümayiş etdirmək məqsədilə buzlaqların geri çəkilməsi, quraqlıq və şəhər istilik adaları mövzularına yönəlmiş üç nümunəvi virtual çöl tədqiqatı fəaliyyəti hazırlanmışdır. Təklif edilən çərçivə coğrafiya təhsilində iqlim savadlılığının, məkan təfəkküründün, coğrafi tədqiqat bacarıqlarının, tənqidi təfəkkürün və süni intellekt savadlılığının gücləndirilməsi üçün pedaqoji əsas yaradır.

Açar sözlər: *iqlim dəyişikliyi təhsili, süni intellekt dəstəkli virtual çöl tədqiqatı, coğrafi araşdırma, məkan təfəkkürü, pedaqoji layihələndirmə çərçivəsi*

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