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ASSESSMENT OF THE SYNERGISTIC IMPACT OF CLIMATE CHANGE AND HUMAN ACTIVITIES ON LANDSCAPE ECOZONES

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SUMMARY

The ensuing study aimed to assess the variations in land-vegetation cover caused by the influence of climate change and human activities. The use of an integrative relationship of various factors helped determine the boundaries of natural and anthropogenic impacts, assessing their pressure level on the ecosystem. In a study from 1999 to 2024, observations on the negative impact of climatic factors progressed on the soil cover of the Nakhchivanchay River basin. Against this background, the temperature increased (approximately 0.19 °C–0.22 °C), precipitation decreased (9.15–9.75 mm), soil moisture decreased (4.95–5.35 mm), degraded soils' area rose by 2.85%–3.05%, and the area with dense vegetation incurred depletion by 1.75%–1.95%. These climate-based variations can help in the selection of crop types and natural fodder for livestock. On the soil-vegetation cover, human activities have also occurred in negative and positive directions. With positive human activities, it was possible to mitigate the negative impact of climate change and maintain soil fertility and biomass balance. The results showed climate change has consistently degraded soil and vegetation, while human activities can either intensify or alleviate these effects in the Nakhchivanchay River basin. The results highlighted that well-managed land use practices are crucial for reducing climate-driven degradation and enhancing sustainable productivity.

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Keywords: Climate change, human activities, synergistic approach, vegetation density, soil degradation

Key findings: The study delineates the respective boundaries of climatic and anthropogenic influences on soil fertility and biomass dynamics. The results highlighted that well-managed land use practices are crucial for reducing climate-driven degradation and enhancing sustainable productivity.

INTRODUCTION

The natural resource depletion and impact of climate change are forcing the socioeconomic and eco-geographical landscape of the modern world to change more rapidly. The most important aspect is the continuous increase in the interest of the 'green' economy and renewable natural resources. Renewable natural resources (water and soil resources and biomass) play a crucial role for both the existence of humanity and the main guarantor of the world economy in the present era with the rapid depletion of natural resources. Renewable natural resources also develop the basis for regenerative agriculture and emphasize the sustainability of overall agribusiness activities. Currently, sustainable development concepts are mainly reliant on the 'green economy' worldwide. The fact that renewable natural resources are vital and economically crucial, which necessitates their use on a larger scale, weakens their ability to regenerate. However, in several regions—particularly parts of Africa and Northwestern South America—the transition toward a green economy remains limited, with integrated water resource management insufficiently implemented. This challenge is especially evident in areas dominated by extensive agricultural practices, where inefficient water use continues to constrain sustainable development (Amiri and Brewer, 2020).

Continuous monitoring of variation in natural complexes, including renewable natural resources, against the backdrop of global variations should be a priority direction of modern science. Therefore, it is necessary to choose a balanced scientific direction that serves global variations, the dynamic pace of economic development, and the efficient use of natural resources. In mitigating and eliminating the consequences of emerging

ecogeographical problems, scientific methods are essential based on the combination of applicability, operation, interactivity, and forecasting. However, in conflict-affected regions, widespread exploitation of natural resources and severe degradation of ecosystems are prevalent, making systematic environmental monitoring both critical and indispensable. (Mustafayev *et al.*, 2025).

On ensuring flexibility and interactivity in research, the most important means is to obtain the necessary information on the research area without physical contact. Modern operational-interactive methods include the main principles as mentioned above. Such methods often attained their development through internal modification of leading basic methods, based on integration and synthesis of several methodologies. Such synergistic approaches, while combining the advantages of basic methods, develop more advanced features by eliminating their shortcomings. These methods and integrative approaches first succeeded in their implementation globally in countries such as the United States, China, and Japan. In these contexts, advances in industrial digitalization and the deployment of unmanned technologies have significantly contributed to enhanced interactivity and operational efficiency across multiple sectors (Sadigov *et al.*, 2024).

Based on trends observed in world practice, the serious necessity of continuous assessment of renewable resources received a proposed novel scientific approach. The new approach with main principles provides a faster and more reliable assessment of natural resources, without observational data and spatial-temporal restrictions, as well as investigates the scope of climate and anthropogenic effects. In the renewable energy sector, Azerbaijan has undertaken significant initiatives, including the establishment of

designated “Green Energy Zones” and the signing of agreements with international companies, such as TEPSCO, Nobel Energy, TotalEnergies, and A-Z Czech Engineering. These frameworks, supported by public-private partnerships and tax exemptions for imported equipment, encompass the deployment of solar energy systems in liberated territories, the operation of hydropower facilities, and the development of large-scale green energy (Sadigov and Mustafayev, 2024).

The effect of natural and anthropogenic factors may be evident with negative and positive aspects, which can sustain assessment by their visible impact on the ecosystem and socioeconomic development. Recently, in the ecosystem, global climate change and uncontrolled human activity have caused serious negative manifestations. Therefore, it is almost impossible to manage and eliminate the consequences of natural and anthropogenic effects based on objective and subjective reasons. Objective aspects are due to climate effects and human intervention in nature for survival and are an eternal process. The subjective aspect is that of the community playing a primary role in the destruction of the ecosystem by exerting greater pressure on nature.

Except for some areas, the current climate change mainly has a negative impact on nature. The chief indicators of climate change are increasing air temperature and decreasing precipitation, which, in turn, weaken moisture balance and intensify the

depletion of soil and vegetation cover. Moreover, it is difficult to prevent the negative effects of human activities because the rapid growth of the economy and population pressure dictates the appropriation of new territories, which inevitably affects the soil and vegetation cover. Combined negative effects of natural and anthropogenic factors cause more serious and irreversible consequences for soil and vegetation resources. The largest blow of the unpleasant variations occurring in nature falls on the vital resources, such as water, soil, and crop plants. However, the advantage in solving these issues is that the mentioned natural resources are also renewable resources.

Thus, the community should not only participate in the destruction of the ecosystem but must also focus on reducing the negative manifestations of climate change and protecting vital natural resources. Therefore, the people must choose suitable and rational areas of activity, considering local conditions. The scientific research should also contribute consistently in this area. Preference should point to scientific methods that serve to assess the impact of global climate change and continuously increasing socioeconomic activities on the ecosystem and renewable natural resources.

The Nakhchivanchay River basin, Azerbaijan, as the chosen study area, is a region distinct with its complex and specific physical and geographical conditions (Figure 1). The total area of the Nakhchivanchay River



Figure 1. Study area (Nakhchivanchay River Basin).

basin is 1624.1 km². The river basin is one of the regions characterized by arid and sharply continental climate conditions, with a more serious impact of climate change in this region. The crucial study aimed to assess the variations in land-vegetation cover caused by the influence of climate change and human activities.

MATERIALS AND METHODS

Satellite images, digital elevation models (DEM), and hydrometeorological observation data during the period of 1999–2024 were successful in their uses to collect primary research materials. Hypsometric indicators of the area (height, slope degree, and aspects) entailed studies using a DEM. Using fragments of Landsat-7 ETM+ and Landsat-8 OLI/TIRS multispectral satellite images obtained various landscape types (LULC), soil and vegetation cover, and existing moisture conditions. Vegetation (NDVI and SAVI), build-up (normalized difference built-up index, or NDBI), and urban (UI) indices were applicable in distinguishing the prevalent landscape types of the river basin and investigating the density of vegetation cover (Amanova *et al.*, 2024b).

In land cover analysis, the following soil indices became a priority, such as bare lands (BSI), salinized soils (normalized difference salinity index, or NDSI), soil erosion (EI), and NDBal. Likewise, the combination and reclassification of soil indices proceeded in ArcGIS, with their examination giving equal influence in the weighted overlay program. Hydrometeorological parameters (runoff and climate data) came from the database of existing observation stations. In areas where no observations occurred, climate and runoff data underwent reconstruction using modern interpolation and analog terrain methods and the counter-approach technology (Sadigov and Mustafayev, 2024).

Determining the heat-moisture state of the study area, water (NDWI), moisture (NDMI), drought (NDDI), and land surface temperature (LCT) indices sustained analysis. The estimation of moisture and hydrological

conditions (surface runoff, infiltration, and soil moisture levels) of the Nakhchivanchay River basin employed the scientific principles of the world's leading water balance methods as the basis (Ponce and Shetty, 2016).

The association between land-vegetation cover and forming components succeeded in their detection via both graphical, trend, and functional relationships. The process of verifying the reliability of inter-component relationships continued entirely in Esri ArcGIS version 10.8 using various multifunctional calculation, comparison, and probability programs.

RESULTS AND DISCUSSION

Although the dynamic development in climate change and human activity affects the ecosystem as a whole, it was the primary manifestation in the area's land cover. In the ecosystem, the main source of critical positive and negative variations depended on fluctuations in the temperature and humidity regime of the area. During the study period of 1999–2024, the factors, such as climate change, rapid growth of the economy, and population, led to serious transformations of geographical components in the Nakhchivanchay River basin in space and time. During this period, the role of both natural factors (climate and landscape variations) and anthropogenic (related to human activities) impacts attained investigations. Given the highest combined impact of natural and anthropogenic factors in the plain and foothill regions, more serious variations were evident in the soil cover and vegetation density. In the high mountainous areas, the variations mainly resulted from natural-oriented impacts. However, the positive trend was visible in some parameters of soil and vegetation, with a negative trend in some others. In the field of soil-pedological relations, it was considerably a difficult issue to separately assess the impact of natural and anthropogenic factors on the variations in landscapes, soil-vegetation cover, and water resources. However, current scientific innovations, space information, and

GIS technologies now allow determining the boundaries of natural and anthropogenic impacts (Mao *et al.*, 2018).

It is typical that numerous landscape variations materialize from various human activities. These include settlements and urbanization, crops, backyard gardens, the mining industry and technogenic landscapes, built-up objects, roads, water reservoirs, and canals. Landscapes' identification can easily ensue using space information and remote sensing. However, it is difficult to determine whether the variations occurring in some landscapes are of natural or anthropogenic origin. These include forests, meadows, pastures, deserts and semi-deserts, steppes, and badlands. However, in such cases, the differentiation between natural and anthropogenic influences usually appears through the following ways:

- a) Based on variations in climatic indicators and water balance of the territory. This method determines the possible criteria for variations occurring naturally against the background of variations in climatic and humidification parameters, with the assumption of external influences related to human activities.
- b) Given the proximity of settlements and the dynamics of their growth. Human interference with nature was higher in areas around settlements than in remote areas, and it was also possible to follow them using space information (Shukurov *et al.*, 2025).

All components in nature have a close and regular relationship with each other. During the assessment of soil and vegetation cover of the study area (Nakhchivanchay basin), applying a synergistic approach took place, exploring the influence of complex factors. The synergistic scientific approach sought to transform the natural regularities between components into a quantitative form and, thus, achieve an operational and interactive assessment of the variations occurring in the ecosystem. In this study, the data on the majority of factors that influence their formation to the maximum extent gained considerations during the assessment of soil resources and biomass of the area. The said formulation proceeded more efficiently and

reliably based on the space information and fast GIS technologies. However, dependence on observation data, time and space limitations, and difficulties associated with physical contact with the area became minimal (Amiri and Brewer, 2020; Sadigov and Mustafayev, 2024).

The division of factors that shape and manage the soil and vegetation cover can be into four groups (Al-Ghobari *et al.*, 2020):

- a) Indicators of surface cover of the territory: These indicators include LULC (land use and land cover) and HSG (hydrological soil groups). LULC is the sum of natural and anthropogenic landscapes that characterize the general appearance of the surface cover of the territory. The LULC concept is acceptable for both natural landscapes and their purpose in arable lands. HSG is an indicator that reflects the ability of soils to create surface runoff and infiltration. Four different HSGs were distinctive according to their granulometric composition (A, B, C, and D). From group A to D, a tendency for infiltration to weaken and runoff to increase was evident in soils. Indicators of surface cover include LULC and HSG, which together provide an integrated understanding of surface characteristics and hydrological behavior. The observed dominance of lower-infiltration HSG classes (C–D) in certain LULC categories suggests a higher propensity for surface runoff, consistent with established hydrological theory and previous studies, thereby supporting the reliability of our results (Anderson *et al.*, 1976; USDA–SCS, 1986) (Amanova *et al.*, 2024a; Sadigov *et al.*, 2024).
- b) Hypsometric and morphometric components: These factors include the elevation, slope degree, aspects, basin area, surface horizontal and vertical fragmentation, and river network density.
- c) Climate and humidity factors. These factors comprised air temperature, atmospheric precipitation, actual and potential evaporation, factual soil moisture, maximum soil water retention, hydrological losses, and initial abstraction.
- d) Anthropogenic factors: These factors include the effect of various human activities, such as settlement, agriculture, mining, construction,

Table 1. Variations in hydrometeorological and land-vegetation indicators during 1999–2024.

Study spheres	1999	2024	Difference (%)
Air temperature (°C)	9.31	10.36	+10.1
Atmospheric precipitation (mm)	513.9	467.5	-9.03
Potential evaporation (mm)	691.4	731.4	+5.47
Humidity coefficient	0.743	0.639	-13.9
Area of sparse vegetation cover (km ²)	432.0	513.2	+15.8
Area of highly degraded soils (km ²)	222.6	279.3	+20.3
Area of fertile soils (km ²)	165.7	141.5	-14.6
Area of settlements (km ²)	168.1	314.6	+87.2
Build-up areas (km ²)	29.72	48.41	+38.6
Surface runoff layer (mm)	172.7	156.1	-9.61
Maximum soil water retention (mm)	602.3	651.7	+7.58

communication infrastructure, afforestation and greening measures, grazing, canals, and reservoirs.

The results revealed close relationships existed between the soil-cover state and the climate, landscape, and hypsometric-morphometric parameters. A close correlation was between the state of the soil-vegetation cover and the components that form them, both separately and together. The determination coefficients of the obtained relationships fluctuated in the range of $R^2 = 0.65-0.94$ separately and in the range of $R^2 = 0.47-0.87$ with several components together (Anderson *et al.*, 1976).

Variations in climate and runoff quantities, LULC types, soil, and vegetation cover during the period of 1999–2024 in the Nakhchivanchay River basin appear in Table 1. During this time, climate change was unfavorable for land and vegetation cover in all indicators. Against the background of an increase in average temperature by 1.04 °C and a decrease in precipitation by 46.4 mm, the actual air and soil-water capacity decreased, while the maximum water retention accelerated significantly. Thus, the maximum air-water capacity increased by 40.1 mm and the maximum soil-water capacity by 49.4 mm. This revealed a total water volume of 145.3 million m³ per year. The said trend manifested as a whole with a considerable decrease in the overall moisture level of the river basin, including the quality of the soil and vegetation cover. As a result, the actual soil moisture (11.3%), fertility soil area (14.6%), and

vegetation density (15.8%) lowered, while the area of highly degraded soils (20.3%) rose. A comparable process resulted in the Kur-Araz lowland; however, unlike Nakhchivan, the region does not exhibit a sharply continental climate, as evidenced by relatively higher precipitation levels. Consequently, actual soil moisture reaches 18.7%; fertile soils account for 22.6% of the area, while degraded soils comprise 28.3%, reflecting moderate but spatially significant land degradation patterns (Khalilov *et al.*, 2023; Gumbatov *et al.*, 2024; Ayubov *et al.*, 2025).

Variations in vegetation cover density, general moisture level, and soil degradation of the Nakhchivanchay River basin during the study period of 1999–2024 are available in Figure 2. Using intercomponent relationships, it was possible to obtain specific numerical expressions of variations in the actual soil moisture and soil-vegetation cover with the influence of variations in different climatic parameters. It also sought to determine the distinction between the natural and anthropogenic impacts. The study also determined that against the background of an increase in the average annual temperature by 0.19 °C–0.22 °C, a decrease in precipitation by 9.15–9.55 mm, and the humidity coefficient by 0.018–0.021, the actual soil moisture decreased by 4.95–5.35 mm. Similarly, the density of vegetation decreased by 1.75%–1.95%, and the area of highly degraded soils rose by 2.85%–3.05% in the Nakhchivanchay basin (Gumbatov *et al.*, 2024; Mammadov and Teymurov, 2024; Mammadov *et al.*, 2025).

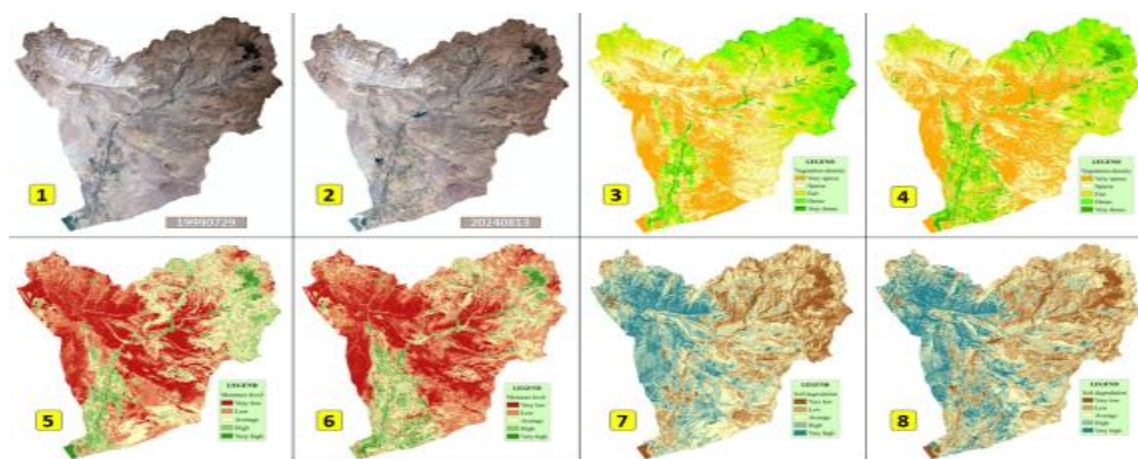


Figure 2. Variations during the preiod of 1999–2024: 1–2–Satellite images, 3–4–Vegetation cover density, 5–6–Moisture level, and 7–8–Soil degradation.

Table 2. Indicators of climate-moisture factors in different ecozones.

Research subject	Landscape ecozones						
	I	II	III	IV	V	VI	VII
Area (km ²)	218.8	150.6	308.7	258.9	108.0	305.9	273.2
Average elevation (m)	735.9	1006	1326	1516	1607	1638	1687
Slope degree (%)	9.25	13.46	23.28	27.69	30.59	30.71	31.25
Temperature (°C)	13.6	12.7	11.9	10.2	9.43	8.61	7.23
Precipitation (mm)	291.5	347.7	403.2	474.1	503.1	545.4	639.3
Humidity coefficient	0.239	0.318	0.413	0.563	0.729	0.907	1.135
Surface runoff coefficient	0.021	0.043	0.071	0.112	0.217	0.324	0.461
Actual evaporation (mm)	281.2	322.9	357.3	384.6	320.2	273.5	246.5
Maximum water retention (mm)	940.1	919.6	875.8	794.9	491.5	352.9	282.2
Actual soil moisture (mm)	17.39	84.65	142.7	214.2	268.7	275.6	256.9

The Nakhchivanchay basin incurred division into seven landscape ecozones based on the extent of variations with the influence of natural and anthropogenic factors during 1999–2024. Figure 3 showed the LULC types and differentiated ecozones of the river basin. The results of natural and anthropogenic impacts can also be evident in the seven ecozones, as mentioned above (Table 2). In the study area, the main areas of human activity were agricultural activities (especially expansion of arable land and pastures), urbanization, mining industry, construction of new reservoirs, and afforestation measures in some areas. The intensive human activities have also considerably altered the destination of arable lands. This was also clearly notable in the LULC variations that occurred during the

period of 1999–2024 in the Nakhchivanchay basin (Figure 4). Similar processes are evident on the southern slopes of both the Lesser and Greater Caucasus, where deforestation, varying degrees of soil erosion, and improper or inefficient grazing practices have intensified anthropogenic pressure. These factors have collectively disrupted the natural equilibrium and ecological stability of the region (Sadigov and Macnunlu, 2023; Mikayilov *et al.*, 2025; Huseynov *et al.*, 2026).

The combined negative effects of both natural and anthropogenic influences have led to a sharper depletion of the ecosystem, including the soil and vegetation cover. The soil and vegetation cover quality has reached significant reduction against the background of the increase in build-up areas with the

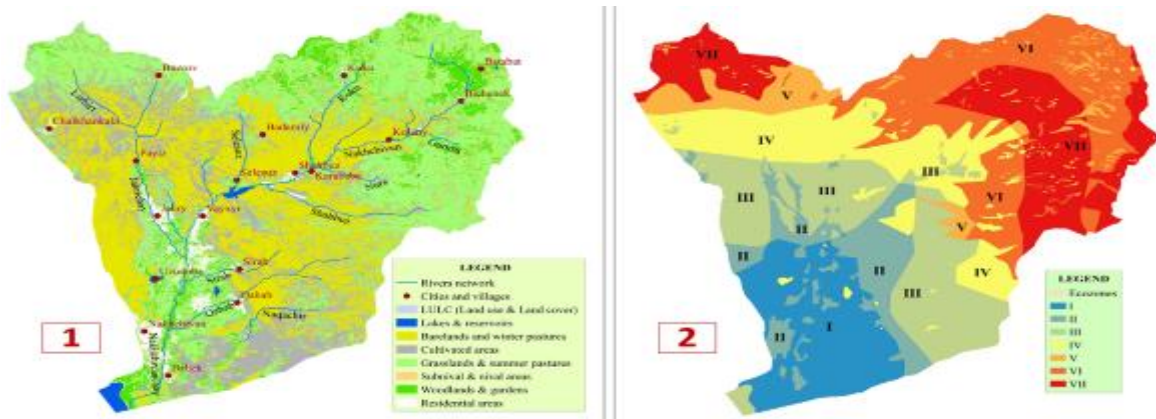


Figure 3. 1 – LULC (Land use and Land cover) types (2024), and 2 – Landscape ecozones.

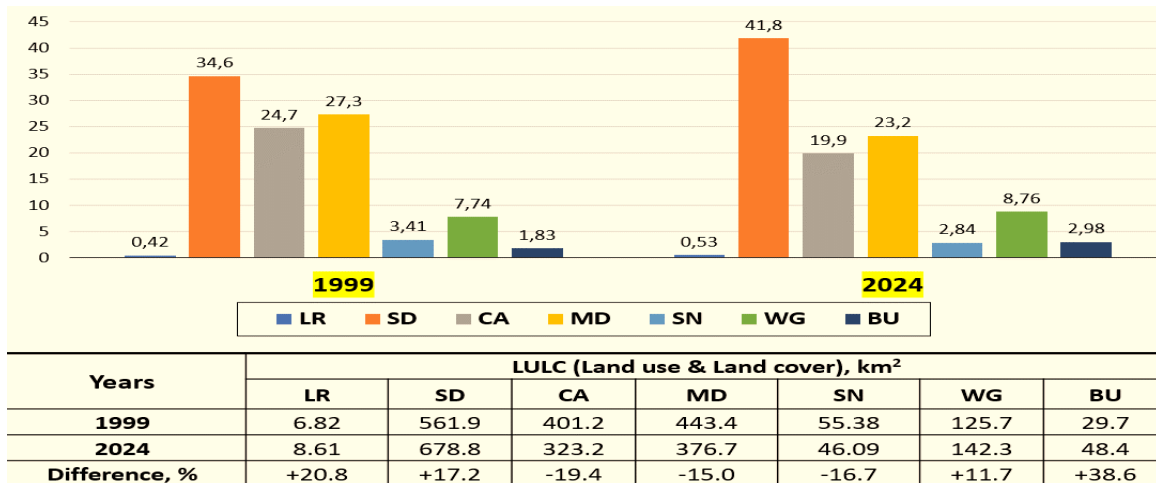


Figure 4. LULC variations during the period of 1999–2024 in the Nakhchivanchay basin (%): LR-lakes and reservoirs, SD-rangelands (semi-deserts), CA-croplands, MD-meadows, SN-subnival and nival areas, WG-woodlands and gardens, and BU-build-up areas.

expansion of the mining industry, pastures, and meadows. However, in some parts of the Nakhchivanchay basin, the urbanization process has led to an increase in moisture conditions, which locally manifested itself in the enrichment of soil and vegetation cover. The establishment of backyard gardens, arable areas, reservoir construction, afforestation, greening measures in some areas, and other cultural landscapes has resulted in a partial increase in the soil moisture level. In such circumstances, human activity often compensates for the negative effects of climatic factors up to some extent. The same

pattern can be obvious in the analysis of the ecozones in the study area (Sadigov *et al.*, 2024; Mammadov *et al.*, 2025).

In the study area, ecozones 1 and 2 were the heavily populated, comprising the largest cities of Nakhchivan and Babek located in the Nakhchivanchay basin. During the study period, both the suburban areas and the population have increased twice. In 1999, the actual soil moisture in ecozones 1 and 2 was 12.53 and 71.45 mm, respectively. If the anthropogenic effects did not occur, the actual moisture in these zones should have been 9.87 and 60.18 mm due to severe drought.

However, in fact, the current quantities were approximately 76.2% (17.39 mm) and 15.7% (82.6 mm) higher than the expected values, which is precisely a positive manifestation of human activities. As a result of anthropogenic impacts, the soil moisture in ecozone 1 gained 1.645 million m³ of additional water mass. The said water volume played a significant role in enriching the soil-vegetation cover within ecozone 1. However, since the water loss in the soils of ecozone 1 as a whole was 3.85% of the overall moisture content of the Nakhchivanchay River basin, it did not have a serious impact on the total moisture level of the study area. The establishment of reserves and sanctuaries in the region has played a remarkable role in conserving natural ecosystems and mitigating drought impacts. Studies conducted within protected areas indicate that the efficient management of available water resources has contributed to the preservation of vegetation cover and a measurable increase in biodiversity (Al-Ghobari *et al.*, 2024; Huseynov *et al.*, 2026; Sadigov *et al.*, 2026).

For the soil and vegetation cover, ecozones 3, 4, and 5 appeared to be the poorest parts of the study area. Except for a few riverside and suburban meadow-forest landscapes, fertile soils and vegetation were not available in these zones. During the study period, the combined action of both climatic and anthropogenic factors developed highly negative manifestations in the study area. Unfavorable climatic indicators and unsuccessful economic measures (expansion of rangelands and transhumance, felling of existing trees and shrubs, and improper observance of agrotechnical rules) led to a sharp depletion of soil resources and biomass. In ecozone 3, except for an increase in the greenery around the newly built reservoir, and in ecozone 4, around the city of Shahbuz, a sharp depletion (25%–35%) of soil and vegetation occurred (Mustafayev *et al.*, 2025).

In the upper reaches of the Nakhchivanchay River (sixth and seventh ecozones), anthropogenic impacts were relatively weak, and the climatic factors played the primary role in the variations. However, in these ecozones, weakness and depletion of soil

and vegetation cover were evident. Here, in terms of landscape in the reduction forests and meadow areas, the main influencing factor was climatic variations. With the influence of climatic factors, the area of some lakes has decreased, and a slight thinning of the forest cover and an increase in the area of meadows have been noteworthy. The occurrence of these phenomena shows a primary association with the high mountainous terrain, where approximately 60% of the area has slopes exceeding 15 degrees. In regions with sparse vegetation, such as subalpine and alpine meadows, the influence of anthropogenic activities is minimal or virtually negligible (Sadigov *et al.*, 2025; Sadigov *et al.*, 2026).

CONCLUSIONS

The impact of climate and anthropogenic factors on soil-vegetation cover during 1999–2024 was unfavorable for the ecosystem of the Nakhchivanchay River basin. However, in some areas, the expansion of arable and pasture areas, afforestation and gardening measures, reservoir construction, and backyard greenery resulted in the enrichment of soil and plant cover. In most areas of the Nakhchivanchay River basin, climatic and anthropogenic factors together caused a sharp decrease in soil cover and biomass. However, with their combined effect, no areas have been distinct in enrichment of soil and plant cover.

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