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## GIS AND REMOTE SENSING-BASED EVALUATION OF NATURAL CONDITIONS FOR SUSTAINABLE AGRICULTURE IN THE KURA-ARAZ PLAIN, AZERBAIJAN

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### SUMMARY

Current research based on advanced technologies and innovative approaches can better save time and investment and appear more compatible with field studies. Based on remote sensing and ArcGIS technologies, the following research comprised the analysis of the natural and anthropogenic landscape variations in natural conditions. These were a result of the development of the agriculture sector in the 20-km buffer zone along the banks of the Kura and Araz rivers, Azerbaijan. In this regard, this study's main purpose sought to analyze the problems that arise during the intensive exploitation of the territory and provide information about the future forecast. Modern technology employment succeeded, processing the materials of Landsat 5, 8, and 9 satellites. The results revealed the rapid growth of population has caused soil salinization, drought of the water basins, expansion in construction areas, and an overall reduction in the agrolandscape area.

**Keywords:** Kur-Araz plain, climate action, remote sensing, agriculture, NDVI, NDMI, NDWI

**Key findings:** Studies integrating multi-temporal satellite-derived vegetation and moisture indices (normalized differences in vegetation, moisture, and water indices [NDVI, NDMI, and NDWI]) with GIS analysis revealed pronounced variations in the vegetation dynamics, soil moisture, and surface water availability in the Kura–Araz Plain, Azerbaijan. These explained spatial patterns of agricultural suitability and highlighted enhanced risks to sustainable land use under intensive exploitation.

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## INTRODUCTION

Over the past centuries, technological innovations have considerably increased agricultural production to feed the rapidly growing world population (Bendini *et al.*, 2024). Along with other partner advanced technologies—geographical information system (GIS), remote sensing, global positioning system (GPS), and artificial intelligence—computing systems and data analytics are crucial in monitoring products and implementing optimal and targeted management practices to further improve productivity (Moomen *et al.*, 2024). Past research has analyzed various applications of GIS in agriculture, covering the entire pipeline, from planned land use to crop-soil-productivity monitoring to post-crop operations (Mălinaş *et al.*, 2025). GIS and digital technologies, along with new and emerging application areas, further enable the goals of precision farming and sustainable food production (Coman *et al.*, 2025).

Previous innovative research on GIS application areas includes well-managed strategies about crop yield estimation, soil fertility assessment, cropping pattern monitoring, drought assessment, pest- and crop-disease detection and management, precision agriculture, fertilizer requirements, and weed management (Stamou and Stylianidis, 2025). GIS technology has the potential to enhance agricultural sustainability by integrating the spatial dimension of agriculture into agricultural policies (Bendini *et al.*, 2024; Ali and Kaul, 2025).

In this perspective, the modern technologies, especially GIS technologies, are greatly crucial in all areas, including the agriculture sector, with the concerned research work also associated with it. In the present era, the advances in geospatial technologies and the increasing availability of high-resolution satellite imagery have considerably strengthened the potential role of GIS in agricultural research. The integration of GIS with remote sensing data further enables continuous spatial and temporal monitoring of land use dynamics, crop growth conditions, and various soil characteristics. Such

integrated approaches significantly improve the accuracy of agricultural assessments and provide reliable decision-support tools for optimizing land management, reducing production costs and risks, and increasing overall efficiency at both local and regional scales.

Moreover, current studies emphasized that GIS-based agricultural analyses are essential for addressing emerging challenges related to climate change, land degradation, and sustainable resource utilization. Spatial modeling and scenario-based GIS applications allow researchers and policymakers to evaluate alternative management strategies and assess their potential environmental and economic impacts. Therefore, GIS has evolved from a supportive mapping tool into a core analytical framework for sustainable agricultural planning, reinforcing its importance in contemporary agricultural studies.

In this context, the application of GIS and remote sensing technologies becomes particularly significant for region-specific assessments, where environmental pressures directly influence agricultural productivity. Such spatially explicit evaluations provide a scientific basis for developing adaptive strategies tailored to local ecological and socioeconomic conditions.

## MATERIALS AND METHODS

This research conducted the preferred modern research methods along with field research activities carried out in the target area (Sharma *et al.*, 2024). Based on the modern methods, it was possible to proceed with multi-year dynamics (Nazim *et al.*, 2025). For this purpose, the processing of satellite images and the decoding of satellite images belonging to various study years took place. Landsat 5, 8, and 9 satellite images from 2010 and 2022 have succeeded in their downloading and processing. As a result, preparing the maps reflecting the vegetation, moisture, and water difference indices (NDVI, NDMI, and NDWI) of the research area was successful, with their further analysis carried out in the ArcGIS program. The results obtained from the data

analyses entailed recording. Infrared and near-infrared bands of the Landsat satellite sought to determine the NDVI index. Modern methods and ArcGIS technology employment proceeded during the research. The NDVI index calculation was according to the following formula.

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Where NDVI = the normalized differences in vegetation index (Jocea *et al.*, 2025), NIR = the intensity of the rays reflected in the near-infrared region of the spectrum (Lottering *et al.*, 2025), and RED = the intensity of the rays reflected in the red region of the spectrum.

In determining the normalized difference index of water (NDWI), the study used the green and near-infrared bands (Skilodimou *et al.*, 2025). The water, when completed, appears with positive values, and the objects, such as vegetation and soil, are with negative values or zero (Rabie *et al.*, 2025). The NDWI index calculation was as follows.

$$NDWI = (Green - NIR)/(Green + NIR)$$

The calculated indices (NDVI, NDMI, and NDWI) underwent subsequent analysis to assess the spatial and temporal dynamics of vegetation and water resources within the

study area. These results provided a comprehensive basis for evaluating environmental changes and informing sustainable agricultural management strategies.

## RESULT AND DISCUSSION

The considered study area includes a buffer zone of 20 km from the Kura River in the Kura-Araz plain (Figure 1). The relevant study selected such an area to monitor multi-year variations at the same distance on both banks of the river. Overall, the research area comprised 791,000 ha. The investigation area includes Aghgol (distinguished by its water supply), Sarisu Lake (the largest lake in terms of its area), Kura and Araz rivers (the first two choices in terms of length in Azerbaijan), and a part of the Kura-Araz plain (distinguished especially by agriculture, which has been used since ancient times). The Kura River shows measurable multi-year variations in water quality due to both natural hydrological cycles and anthropogenic activities, such as irrigation and industrial discharge. Similarly, lakes like Aghgol and Sarisu have experienced changes in water levels, highlighting the importance of continuous monitoring of water resources in the Kura-Araz plain (Mammadov *et al.*, 2022).



**Figure 1.** Study area.

In the studied region, farming mainly relied on irrigation, and it was an important agricultural region of the country. Cotton growing, dry subtropical fruit growing, and horticultural plants were the specialties in this arable area. Moreover, cultivation comprised cereals, grapes, potatoes, sugar beets, sunflowers, and fodder crops. Likewise, enough natural opportunities existed for the development of animal husbandry and raising cattle and sheep. The research area has its location on national and regional highways. Transportation routes connect Baku City with most of the country's administrative districts, and Georgia, Iran, and Turkey pass through its territory. The recent increase in international freight traffic has enhanced the importance of these roads. Earlier research has shown that in the Kura–Araz lowland, the intensive irrigated agriculture considerably shaped land-use patterns and increased the pressure on soil and water resources. Moreover, past studies have reported that proximity to major transportation corridors accelerates agricultural expansion and landscape transformation, which proved to be in a greater analogy with the spatial patterns observed in these study results (Meharet *et al.*, 2025).

In arid and irrigated areas of Azerbaijan, land reclamation and strengthening and expansion of arable land emerged as more favorable for agriculture, which also requires an intensive study of soil characteristics in this area. Moisture deficiency, erosion, salinization, hardening of the soil profile, the height of the humus layer, and insufficient humus appeared to be typical for the Kura-Araz plain, which has complex natural soil-ecological conditions. However, the soils in the Kura-Araz plain were intensively losing their fertility properties under natural and anthropogenic stress conditions. Therefore, it is critical to increase the investment in this direction to improve the reclamation activities of the irrigated areas and restore them to the highest productivity. Water leakage losses from rivers and irrigation canals cause negative impacts, such as salinization, by increasing the level of underground groundwater. The said process was more pronounced in the soils of the Kura-Araz plain, which eventually affects soil quality with

reduced productivity. Recent studies have shown improved irrigation management and modern soil reclamation techniques can mitigate soil salinization and erosion in the Kura-Araz plain. Implementing these measures is crucial to maintain soil fertility and sustain agricultural productivity under both natural and anthropogenic pressures (Aliyev *et al.*, 2020).

In low-lying areas, combating salinization has been a long-time problem. In the Kura-Araz plain soil, the varied salt content depends on the irrigation water, the drainage rate of the area, and the groundwater regime. The results showed the anthropogenic processes influence the groundwater close to the surface by expanding the salinized areas, which ultimately reduce cultivated areas. The salt content (according to dry residue) gradually increases toward the lower layers associated with intensive irrigation and agriculture activities. Studies showed that in the investigated irrigated grass-gray soils, a weak salinization process was evident in the crop and subcrop layers, with a considerable salinization process observed at the lower depths. Numerous studies enunciated that the inadequate drainage and rising level of groundwater occurred to be the primary drivers of secondary salinization in the Kura–Araz plain. Similar vertical salt distribution patterns, with robust salinization in deeper soil horizons, have gained documentation in irrigated grass-gray soils, authenticating the consistency of the latest results with established regional soil processes (Nazim *et al.*, 2025).

In the Kura-Araz plain, the improper management of surface water develops favorable conditions for the growth of marsh, marsh-meadow, and meadow ecosystems. The same situation was especially notable in the natural-anthropogenic processes that occurred around the Aghgol, located in the Mil plain. Based on satellite images, it was noteworthy that during the last 30–35 years, the area of swamp and swamp-meadow complexes forming in and around Aggol has increased by 2,000 ha (Amanova *et al.*, 2024). In the study area, salinity resulted in groundwater (Janga *et al.*, 2023). The mechanical composition of soil variations also rose above the ground. Water

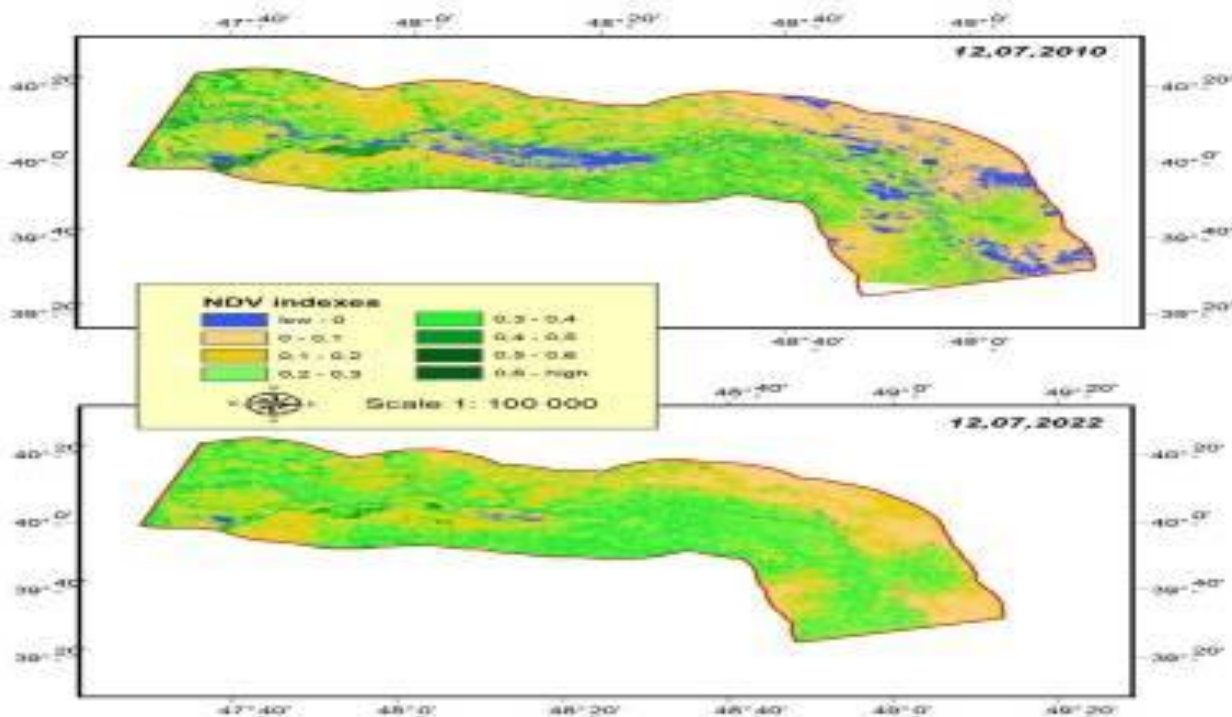
can rise to a height of 1.5–2.4 m. As the saltwater rises—and it dries up in the summer—the salt contents become trapped in the rising process; thus, the salinity process begins in those arable lands. As the soil salinization process begins, productivity decreases. In Azerbaijan, the building of drainage was not to drain swamps but to wash away the saline soil. There are two big collectors in Azerbaijan—Bash Mil-Mugan and Shirvan collectors. Saltwater discharged into the sea occurs through these collectors. The preparation of the drainage system helped wash the saline soils away. One should also note that on the right bank of the Kura River, the Main Mil-Mugan collector pours 100 m<sup>3</sup> of water into the sea per second (Ibrahimova *et al.*, 2024).

In total, the Kura-Araz plain has 0.8 million ha of arable land, with a collector drainage system on the territory of 0.6 million ha. The building of drainage and irrigation systems should be at the same time to work in parallel with each other. Hence, during watering, the drain should remove excess water, and the groundwater will not rise. In preventing this problem, reconstruction works should proceed immediately. The increased activities of agriculture affect natural conditions with different degrees. The topography and climatic elements of the area can change over a long period of time. However, a short period of time is enough to change soil cover, vegetation, and other various components. In studying these factors, the creation of maps of the absolute height with slope and inclination of the topography ensued. Typically, the main part of the research area was below sea level. Studies conducted in the buffer zone of 20 km from the Kura River in the Kura-Araz plain showed that 91.4% of the area sits below sea level, 6.1% has an altitude of 0–100 m, and 2.5% is over 100 m located above sea level. Previous geomorphological studies revealed that a large portion of the Kura–Araz lowland lies below the sea level, forming natural, favorable conditions for groundwater accumulation and poor drainage. Similar hypsometric distribution has successful documentation using GIS-based terrain analysis, confirming that the identified

elevation pattern was characteristic of the region (Meharet *et al.*, 2025).

According to topography aspects, most locations of the area were on the south and southwest (26%). The topography aspects affect the development of agriculture. Thus, south, southeast, and southwest-oriented slopes received more solar heat. Therefore, growing heat-demanding plants flourished there. In particular, the Kura-Araz plain differed from ancient times due to the developed activities of agriculture, to be more precise, cotton cultivation. Surely, the intensive development of cotton cultivation has caused the variation and degradation of the physico-chemical properties of water and soil. The low elevation has caused the inclination to be low in the research area, and 88.8% of the area has positions on slopes with an inclination of up to 5°. The inclination decrease has created favorable conditions for the development of agriculture. Low slopes lead to the enhancement of crop and animal husbandry. The Kura-Araz plain was the most important winter pasture of Azerbaijan, and its productivity was 5–6 s/ha on average. The combination of low slopes and favorable solar exposure has historically supported both intensive crop cultivation, including cotton, and extensive animal husbandry in the Kura-Araz plain. However, continuous agricultural activity has also contributed to soil and water degradation, emphasizing the need for sustainable land management practices to preserve long-term productivity (Huseynov and Mammadov, 2021).

The NDV index map entailed its creation within the buffer zone to assess plant growth in the cultivated areas and the effect of agriculture on vegetation in the study area (Figure 2). Processing of satellite images of 2010 and 2022 sought to assess the current situation. In 2010, the index was negative, and the water basins covered a wider area. As a result of the floods that occurred in the Kura and Araz rivers in that year, the areas covered by this index had widened. In 2022, even in the Kura River, the covering of a tiny area was clearly evident. Previous studies have shown slope aspects significantly influence the microclimatic conditions, especially solar



**Figure 2.** Statistical indicators of the NDV index in 2010 and 2022.

radiation and soil temperature, which directly affect crops' distribution and productivity in arid and semi-arid regions. Research focused on the Kura-Araz plain confirmed that long-term cotton cultivation has contributed to soil structure degradation and variations in soil-water chemical properties, supporting the patterns observed in the prevailing study (Ibrahimova and Imanov, 2025).

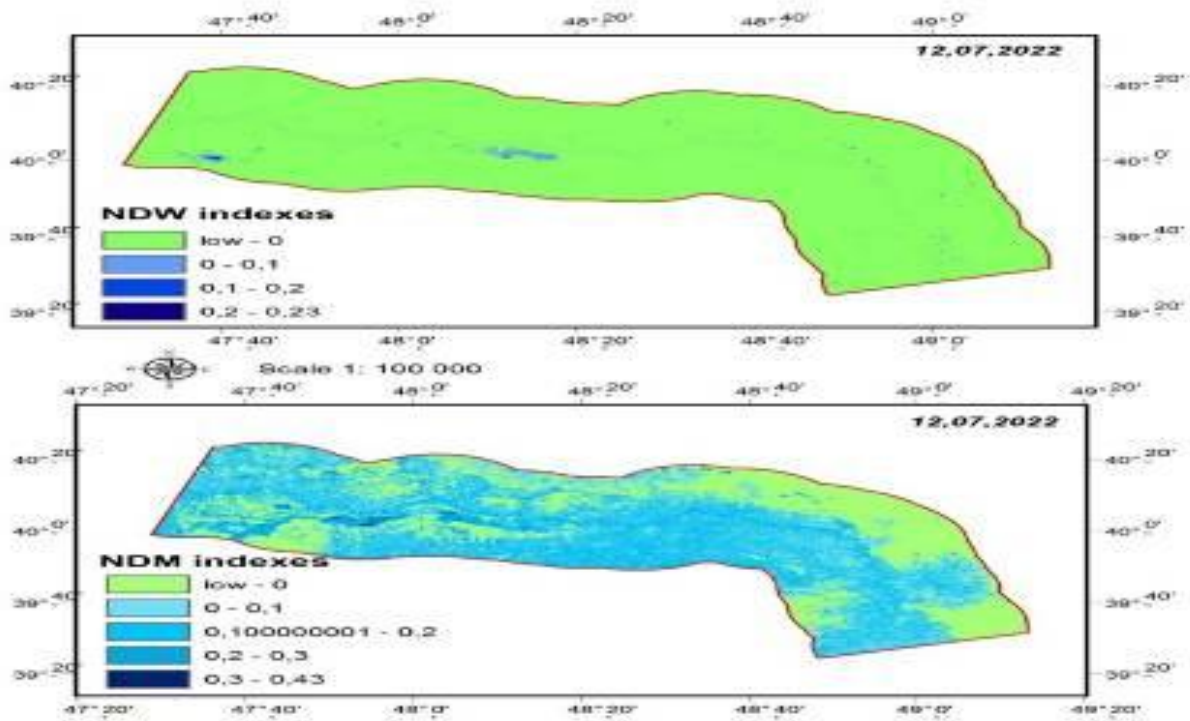
In 2010, areas with a negative index revealed water basins covered an area of 79,000 ha. However, in 2022, this area has lowered by more than 92%. Additionally, in 2010, the lowest index (-0.43) resulted in a further decrease to -0.24 in 2022. The results showed the water level has also decreased. Furthermore, a decline was evident in the research area where the index was high and vegetation cover was more intensive. On the left bank of the Kura River, drying and poor development of vegetation were more noticeable. It is possible to see that the area of the lake was shrinking in Aghgol and surrounding areas. Compared to 2010, the area where the index was 0.1–0.4 has

expanded significantly. Therefore, the research area has reached more intensive adoption by the population, and the cultivated areas have expanded (Table 1). The NDW and NDM indices also underwent analysis in the buffer zone of the area for precise research in the Kura-Araz plain, which has favorable conditions for agriculture. Previous studies have shown long-term reduction in surface water bodies clearly manifested in decreasing negative NDVI/NDWI values, particularly in arid and semi-arid river basins. Reports of similar trends of shrinking water-covered areas and declining minimum index values have surfaced for the Kura-Araz basin, confirming the variations identified in these study results were consistent with regional hydrological transformations (Nazim et al., 2025).

The normalized difference water index (NDWI) also proves the water level in the Kura and Araz Rivers was low in July 2022, and even the Kura River cannot deliver its water to the Caspian Sea. In Aghgol and surrounding water basins, the water level has decreased, and many oxbow lakes have dried up (Figure

**Table 1.** Statistical indicators of the NDV index on July 12, 2022.

No.	Area (ha)	NDV indices	
		MIN	MAX
1	5721	-0.24	0.0
2	121907	0.0	1.0
3	238164	0.1	0.19
4	227699	0.2	0.29
5	162682	0.3	0.39
6	32497	0.4	0.49
7	2330	0.5	0.57
Total	791000		



**Figure 3.** NDW and NDM indices in July 2022.

3). According to the normalized difference moisture index (NDMI), the highest index appeared in the flat areas between the Kura and Araz rivers. With nutritional conditions, in Kura, the rainy period starts from the end of March and lasts until June. The main share of the nutrition was snow (36%) and underground water (30%). Rainwater (20%) and water from melting glaciers (14%) together make up 1/3 of the Kura River's nutrition. In the study area, the groundwater level has sat at different depths depending on the topography. The soil's salt content and the

mineralization of the water increase as and when the groundwater approaches the earth's surface. The moisture index varies between - 0.46 and 0.2 in the main part of the area where the research took place (Table 2). These hydrological assessments indicate both surface and groundwater resources in the Kura-Araz plain are under increasing stress, which may negatively impact irrigation and agricultural productivity. Continuous monitoring using indices like NDWI and NDMI is therefore crucial to inform sustainable water management strategies in the region (Aliyev *et al.*, 2020).

**Table 2.** Statistical indicators of the NDM index in 2022 (ha).

No.	Area (ha)	NDM indices	
		MIN	MAX
1	249898	-0.46	0.0
2	245765	0.0	0.099
3	223028	0.1	0.19
4	68959	0.2	0.29
5	3350	0.3	0.43
Total	791000		

Overall, the integrated analysis of NDVI, NDWI, and NDMI indices provides a comprehensive understanding of the spatio-temporal dynamics of vegetation and water resources in the Kura-Araz plain. These findings offer valuable insights for developing targeted land and water management practices to support sustainable agriculture in the region.

## CONCLUSIONS

In the Kura-Araz plain, the intensive development of agriculture has caused considerable variations in natural conditions. The potential development of cotton crops has led to soil salinization. During irrigation, the ignoring of groundwater level was evident with the intensification of salinization. The dynamics of vegetation development showed the cultivated field area has significantly expanded, with the territory acquiring intensive exploitation. It showed a close relation to the relief and climatic conditions of the study area.

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