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ASSESSMENT OF VEGETATION COVER DYNAMICS AND ECOSYSTEM DEGRADATION IN THE ARAL SEA REGION USING GIS AND SATELLITE DATA

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Abstract
This study assesses vegetation cover dynamics and ecosystem degradation in the Aral Sea region of the Republic of Karakalpakstan, Uzbekistan, during 2021–2025 using Geographic Information System (GIS) technologies and satellite remote sensing data. The main objective was to identify spatial and temporal changes in vegetation cover, map environmentally degraded areas, and identify zones with potential for ecological recovery. Landsat and Sentinel-2 satellite imagery were considered for the analysis, together with the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI). GIS-based thematic mapping and multi-year comparison were used to characterize changes in vegetation and surface-water conditions. NDVI provides an indicator of vegetation condition, while NDWI supports the assessment of water availability and surface moisture. The proposed approach is particularly relevant to the Aral Sea region, where water scarcity, soil salinization, climate variability, desertification, and anthropogenic pressure interact. The results and methodological framework can support environmental monitoring, sustainable land management, ecosystem restoration planning, and the identification of priority areas for ecological rehabilitation in the Aral Sea region.

Keywords: Aral Sea region, Karakalpakstan, GIS, satellite data, NDVI, NDWI, ecosystem degradation, vegetation cover, environmental monitoring, land degradation.

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1. Introduction

The Aral Sea basin is one of the most environmentally vulnerable regions of Central Asia. The long-term reduction of the Aral Sea, intensive use of water resources, climate change, soil salinization, desertification, and anthropogenic pressure have substantially affected natural ecosystems and landscape processes in the region.

The Aral Sea region of the Republic of Karakalpakstan represents one of the areas where these environmental changes are particularly pronounced. The region includes the lower reaches of the Amu Darya, delta ecosystems, riparian vegetation, agricultural lands, saline areas, natural desert vegetation, and landscapes formed on the exposed seabed of the former Aral Sea.

The retreat of the Aral Sea exposed extensive areas of the former seabed and contributed to the formation of the Aralkum desert. High soil salinity, wind erosion, and the transport of dust and salt aerosols affect the distribution, productivity, and natural regeneration of vegetation in these areas.

Under such conditions, continuous monitoring of vegetation cover is an important component of environmental assessment. Vegetation responds sensitively to changes in water availability, soil moisture, climatic conditions, anthropogenic pressure, and ecosystem degradation and can therefore serve as a useful ecological indicator.

Although conventional field surveys remain essential for detailed ecological assessment, their spatial coverage is limited. Satellite remote sensing provides an opportunity to monitor large areas repeatedly and consistently. The integration of remote sensing and GIS technologies enables environmental processes to be analyzed across both space and time.

One of the most widely used indicators for vegetation assessment is the Normalized Difference Vegetation Index (NDVI). NDVI uses the contrasting reflectance properties of vegetation in the red and near-infrared spectral regions to provide a relative measure of vegetation vigor and cover. The Normalized Difference Water Index (NDWI) can be used to assess surface water and moisture-related changes.

Therefore, assessment of vegetation cover dynamics in the Aral Sea region of Karakalpakstan over the 2021–2025 period is important for understanding recent environmental changes and for supporting evidence-based ecosystem management and restoration.

Research Objective

The main objective of this study is to assess vegetation cover dynamics and ecosystem degradation in the Aral Sea region of the Republic of Karakalpakstan during 2021–2025 using GIS technologies and satellite remote sensing data.

Research Objectives

to collect and preprocess satellite data for 2021–2025;
to assess vegetation cover using the NDVI;
to identify changes in surface water and moisture conditions using the NDWI;
to develop thematic environmental maps using GIS technologies;
to compare vegetation cover conditions between 2021 and 2025;
to identify degraded areas and areas showing signs of vegetation recovery;
to analyze the possible environmental drivers of the observed changes; and
to develop practical recommendations for monitoring and restoring Aral Sea region ecosystems.

2. Study Area

The study focuses on the Aral Sea region of the Republic of Karakalpakstan, Uzbekistan. The study area includes the lower Amu Darya, the remaining water bodies of the Aral Sea, the Aralkum desert formed on the exposed seabed, natural and artificial water bodies, and agricultural landscapes.

The region is characterized by a strongly continental climate. High summer temperatures and high evaporation, together with low and variable precipitation, create severe water constraints for natural and managed ecosystems.

The distribution of natural vegetation is closely associated with water availability, soil moisture, and salinity. Relatively moist ecosystems occur mainly in the Amu Darya delta and around water bodies, whereas xerophytic and halophytic vegetation is more characteristic of the Aralkum and other dry and saline landscapes.

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3. Materials and Methods

3.1. Satellite data

Satellite imagery from Landsat and Sentinel-2 was considered for the 2021–2025 period. Image selection should prioritize low cloud cover, comparable seasonal acquisition dates, complete spatial coverage of the study area, and atmospherically and radiometrically corrected surface-reflectance products. Image processing can be conducted in Google Earth Engine, QGIS, or ArcGIS.

3.2. NDVI

Vegetation cover is assessed using the Normalized Difference Vegetation Index:

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

where NIR is the near-infrared spectral band and RED is the red spectral band. Higher NDVI values generally indicate greater vegetation activity or density, whereas lower values may indicate sparse vegetation, vegetation stress, bare surfaces, or water. Thresholds should be calibrated and validated for the specific environmental conditions of the study area.

3.3. NDWI

Surface water and moisture conditions are assessed using the Normalized Difference Water Index:

$$\mathbf{NDWI = (GREEN - NIR) / (GREEN + NIR)}$$

where GREEN represents the green spectral band and NIR represents the near-infrared band. NDWI can be used to identify open-water features and changes in surface moisture. Joint analysis of NDVI and NDWI makes it possible to examine the relationship between vegetation dynamics and water availability.

3.4. GIS analysis

GIS analysis is used to produce vegetation-cover maps, water-body maps, land-cover maps, degradation maps, NDVI change maps, and NDWI change maps. The difference between NDVI values in 2021 and 2025 can be calculated as follows:

$$\mathbf{\Delta NDVI = NDVI2025 - NDVI2021}$$

Positive values indicate an increase in vegetation index values, while negative values indicate a decline. Interpretation should consider seasonality, precipitation, land use, and other environmental factors.

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4. Results

4.1. Vegetation cover dynamics

Vegetation cover in the Aral Sea region is expected to show substantial spatial heterogeneity during 2021–2025. Relatively higher vegetation indices are likely to occur in the Amu Darya delta, around water bodies, and on irrigated agricultural lands, where water availability is comparatively greater.

In contrast, the exposed seabed and strongly saline areas of the Aralkum are expected to exhibit relatively low NDVI values. Soil salinity, limited moisture, high evaporation, and wind erosion constrain vegetation establishment and productivity in these environments.

At the same time, some parts of the Aralkum may show increasing vegetation signals associated with the establishment of drought- and salt-tolerant plants, including saxaul communities. Such changes may provide useful evidence for evaluating natural succession and the effectiveness of ecological restoration measures.

Assessment of NDVI dynamics during 2021–2025 Table 1.

Year	Mean NDVI	Minimum	Maximum	Interpretation
2021	To be calculated	To be calculated	To be calculated	After GIS analysis
2022	To be calculated	To be calculated	To be calculated	After GIS analysis
2023	To be calculated	To be calculated	To be calculated	After GIS analysis
2024	To be calculated	To be calculated	To be calculated	After GIS analysis
2025	To be calculated	To be calculated	To be calculated	After GIS analysis

Note: Numerical values should be calculated from the actual Landsat/Sentinel-2 imagery and should not be replaced with unsupported estimates.

4.2. Spatial distribution of degradation

Analysis of NDVI changes can be used to classify the study area into zones of strong degradation, moderate degradation, relative stability, vegetation improvement, and stronger recovery trends. Degradation is expected to be more pronounced in areas with limited water availability, high soil salinity, severe climatic stress, and strong anthropogenic pressure.

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In agricultural areas, vegetation dynamics are also strongly influenced by irrigation regimes, crop type, and agricultural practices. Therefore, NDVI results should be interpreted together with land-use and land-cover information.

4.3. Dynamics of surface-water bodies

NDWI analysis provides an effective means of assessing year-to-year changes in surface-water bodies and moisture conditions. Expansion or contraction of water bodies can influence vegetation both directly and indirectly. Improved moisture conditions near water bodies can support vegetation development, whereas declining water availability and groundwater levels can increase water stress and accelerate ecosystem degradation.

NDWI-based assessment of surface-water dynamics Table 2.

Year	Water Area	Annual Change	Environmental Assessment
2021	To be calculated	To be calculated	To be assessed
2022	To be calculated	To be calculated	To be assessed
2023	To be calculated	To be calculated	To be assessed
2024	To be calculated	To be calculated	To be assessed
2025	To be calculated	To be calculated	To be assessed

5. Discussion

Vegetation dynamics in the Aral Sea region cannot be explained by a single environmental factor. Vegetation condition reflects the combined influence of water availability, precipitation, temperature, soil salinity, wind erosion, land use, and anthropogenic pressure.

A decline in NDVI does not necessarily indicate permanent degradation. Vegetation can temporarily decrease during dry years or under unfavorable seasonal conditions. Therefore, analysis of a multi-year time series is important for distinguishing short-term variability from persistent trends.

If NDVI shows a consistent decline in a particular area throughout 2021–2025, this provides stronger evidence of persistent vegetation deterioration. Conversely, increasing NDVI values may indicate vegetation recovery, improved moisture conditions, changes in land management, or successful restoration.

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Joint interpretation of NDVI and NDWI is particularly important. A simultaneous decrease in NDWI and NDVI may indicate that water limitation is an important driver of vegetation decline. In areas undergoing ecological restoration, a sustained increase in NDVI can serve as a useful indicator of vegetation establishment and recovery.

Planting saxaul and other drought- and salt-tolerant species on exposed parts of the former seabed may help reduce wind erosion, stabilize soils, limit the redistribution of salt and dust aerosols, and support the development of new plant communities. Remote sensing and GIS can therefore also be used to evaluate the spatial effectiveness of restoration measures.

6. Environmental Monitoring and Practical Significance

The proposed methodology can support the improvement of environmental monitoring in the Aral Sea region of Karakalpakstan. Annual NDVI maps can be used to monitor vegetation condition, while NDWI can support systematic monitoring of surface-water dynamics. GIS-based analysis can identify degraded areas and prioritize locations for ecological restoration. Establishing a geospatial database would also support an integrated digital environmental monitoring system for the Aral Sea region.

Such a system could be used to monitor desertification, soil salinization, vegetation decline, changes in water bodies, land-use dynamics, and ecological recovery. The approach is particularly valuable because satellite observations can be repeated consistently over large and difficult-to-access areas.

7. Conclusions

GIS and satellite remote sensing provide an effective methodological framework for monitoring environmental change in the Aral Sea region of Karakalpakstan. The combined use of NDVI and NDWI for the 2021–2025 period can provide spatially explicit information on vegetation dynamics and water-related changes. Vegetation conditions are expected to vary substantially across the region. The Amu Darya delta, areas surrounding water bodies, and irrigated lands generally provide more favorable conditions for vegetation, whereas the Aralkum and strongly saline areas are characterized by sparse vegetation and greater environmental stress.

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NDVI dynamics can serve as an important indicator of ecosystem degradation and recovery. However, NDVI should not be interpreted in isolation. Reliable assessment requires integration with NDWI, land-cover data, climate variables, soil salinity, groundwater information, and field observations.

Future studies should integrate satellite-derived vegetation and water indices with temperature, precipitation, soil salinity, groundwater levels, and biodiversity indicators. Such a multidisciplinary approach would improve the assessment of ecosystem resilience and degradation and provide a stronger scientific basis for restoration planning in the Aral Sea region.

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