

25-Year Spatiotemporal Assessment of Vegetation Dynamics and Drought Severity in The Amu Darya Irrigated Zone Using Landsat Time Series and Mann-Kendall Trend Analysis

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Abstract

This study presents a 25-year spatiotemporal assessment of vegetation dynamics and drought severity in the Khorezm irrigated zone of the Amu Darya Basin (59–62.5°E, 40.5–42.5°N) over the period 2000–2024. Annual Normalized Difference Vegetation Index (NDVI) values were derived from Landsat Collection 2 Surface Reflectance imagery accessed via the Microsoft Planetary Computer STAC API, filtered to cloud cover below 20% and growing season months (April–September). The Vegetation Condition Index (VCI) was computed to classify annual drought severity according to the five-class Kogan framework. The Mann-Kendall non-parametric trend test and Sen's slope estimator were applied to assess long-term vegetation trends. Results indicate a mean annual NDVI of 0.1094 across the study period, with a minimum of 0.0754 in 2001 (Extreme drought) and a maximum of 0.1442 in 2022 (No drought). VCI classification identifies two years of Extreme drought (2000–2001), one year of Moderate drought (2008), fourteen years of Mild drought (56%), and eight years of No drought (32%). The Mann-Kendall test detects a positive trend direction (Kendall's $\tau = +0.267$, $p = 0.065$, Sen's slope = $+0.000548$ NDVI yr^{-1}) that does not reach statistical significance at $p < 0.05$, reflecting high interannual variability and non-monotonic dynamics. The findings characterize the Khorezm irrigated zone as a landscape under chronic structural water deficit, with the 2016–2022 period representing the best sustained vegetation conditions of the entire record.

Keywords: Landsat; NDVI; VCI; Mann-Kendall trend test; drought monitoring; Amu Darya Basin; Khorezm; remote sensing; vegetation dynamics; Central Asia.

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1. Introduction

The Amu Darya Basin represents one of the most hydrologically stressed irrigated agricultural regions in the world. Decades of intensive Soviet-era cotton cultivation drove the near-complete desiccation of the Aral Sea — once the world's fourth-largest lake at

approximately 63,000 km² — with consequences that continue to unfold across the region [1]. Today, over 28.6% of Uzbekistan's territory (127,117 km²) is classified as affected by desertification, land degradation, and drought [2].

The Khorezm region, situated in the lower reaches of the Amu Darya, is particularly vulnerable. Annual

precipitation averages just 100 mm, making all agricultural production entirely dependent on irrigation water from the Amu Darya [3]. As the most downstream recipient of river water in Uzbekistan, Khorezm is systematically last in irrigation allocation and first to suffer during upstream water shortfalls — a structural vulnerability that translates directly into recurrent drought and crop failure [4].

Despite the severity and scale of land degradation in the region, continuous long-term satellite-based drought monitoring remains limited. Most existing studies rely on coarse-resolution MODIS data (250–500 m) and cover shorter time windows. Dubovyk et al. [5] conducted the most directly comparable analysis, applying linear trend analysis to MODIS NDVI data for 2000–2010 in the Khorezm region, finding negative vegetation trends across approximately 161,000 ha. However, no study has extended a Landsat-based analysis combining VCI drought classification and Mann-Kendall trend detection to the full period 2000–2024.

This research addresses that gap by presenting a 25-year spatiotemporal drought assessment for the Khorezm irrigated zone based on Landsat Collection 2 imagery. The objectives are: (1) to derive annual NDVI and VCI values for 2000–2024; (2) to classify annual drought severity using the Kogan framework; (3) to apply the Mann-Kendall test and Sen's slope estimator to detect long-term vegetation trends; and (4) to interpret the observed dynamics in the context of water resource management and land degradation policy in Uzbekistan.

2. Methods

Study Area. The study area encompasses the Khorezm region and Amu Darya delta (59–62.5°E, 40.5–42.5°N), covering approximately 560,000 hectares. The region has an arid continental climate, with mean annual precipitation of approximately 100 mm and summer temperatures regularly exceeding 38–40°C [3]. Agricultural land covers 280,000–310,000 hectares, dominated by cotton and winter wheat cultivation.

Data Sources. All spectral index computations were based on Landsat Collection 2 Level-2 Surface Reflectance imagery, drawing on three consecutive missions: Landsat 5 Thematic Mapper (TM) for 2000–2012, Landsat 8 Operational Land Imager (OLI) for 2013–2021, and Landsat 9 OLI-2 for 2022–2024. Imagery was accessed via the Microsoft Planetary Computer STAC API [6], filtered to growing season

months (April–September) and scenes with cloud cover below 20%.

NDVI Computation. Annual mean NDVI was computed using the standard formula: $NDVI = (NIR - Red) / (NIR + Red)$, where NIR and Red represent surface reflectance in the near-infrared and red bands respectively. Cloud and shadow pixels were masked using the Landsat QA_PIXEL band. Annual median composites were produced from all valid scenes per year. Spatial mean NDVI was computed across the study area bounding box for each year.

VCI Calculation and Drought Classification. The Vegetation Condition Index was computed as: $VCI = (NDVI_i - NDVI_{min}) / (NDVI_{max} - NDVI_{min}) \times 100$, normalizing each annual NDVI value against the study-period minimum (2001: 0.0754) and maximum (2022: 0.1442). Annual VCI values were classified into five drought severity categories following the Kogan [7] framework: Extreme (VCI < 10%), Severe (10–20%), Moderate (20–35%), Mild (35–50%), and No drought (VCI > 50%).

Trend Analysis. The Mann-Kendall non-parametric trend test was applied to the 25-year NDVI and VCI time series using the pymannkendall Python library [8]. The test assesses the direction and statistical significance of monotonic trends without assuming data normality, making it appropriate for environmental time series with outliers [9]. Sen's slope estimator provided the rate of change in NDVI units per year. Statistical significance was evaluated at the $p < 0.05$ threshold.

3. Results and Discussion

Annual NDVI Dynamics. The 25-year NDVI time series reveals a mean of 0.1094 (standard deviation ≈ 0.017) with substantial interannual variability. The time series exhibits three distinct phases: (1) a severe drought phase in 2000–2001, with NDVI values of 0.0760 and 0.0754 — the lowest in the entire record; (2) a recovery and variability phase from 2002–2015; and (3) an improving phase from 2016–2022, culminating in the exceptional peak of 0.1442 in 2022.

The 2000–2001 extreme drought episode represents the most severe vegetation stress of the entire record, consistent with documented regional drought across Central Asia during this period. Conrad et al. [4] independently documented major crop failures in the Khorezm region during these years, providing field-

based confirmation of the satellite-derived results. The physical mechanism combines two factors: below-average snowpack in the Pamir and Tian Shan mountains reducing Amu Darya discharge, compounded by Khorezm's downstream position resulting in the most severe water delivery reductions.

Following the 2000–2001 extreme episode, a rapid recovery occurred in 2002 (NDVI = 0.1293, +0.054 units in a single year — the largest year-on-year increase in the dataset). A secondary drought occurred in 2008 (NDVI = 0.0966, VCI = 30.82%, Moderate drought class), consistent with documented regional drought conditions. The period 2009–2015 was characterized by persistent Mild drought (mean VCI = 41.48%), with NDVI values consistently below the long-term mean.

The 2016–2022 period represents the best sustained vegetation conditions of the entire study period. Three years achieved No drought classification: 2016 (VCI = 84.85%), 2019 (VCI = 77.21%), and 2022 (VCI = 100.00%). The 2022 peak coincides with a period of significant institutional reform in Uzbekistan's water and agricultural sector, including partial removal of cotton production quotas and investments in irrigation infrastructure rehabilitation.

VCI Drought Classification. Across the full 25-year period, drought class distribution is: 2 years of Extreme drought (8%), 1 year of Moderate drought (4%), 14 years of Mild drought (56%), and 8 years of No drought (32%). The predominance of Mild drought conditions — affecting more than half of all years — characterizes the Khorezm region as a landscape operating under chronic structural water deficit. This finding directly reflects the region's downstream position in the Amu Darya Basin, where residual flows after upstream withdrawals by Tajikistan, Afghanistan, Turkmenistan, and upstream Uzbek provinces are highly variable and largely outside local control.

Mann-Kendall Trend Analysis. The Mann-Kendall test detects a positive trend direction for both NDVI ($\tau = +0.267$, $p = 0.065$, Sen's slope = +0.000548 NDVI yr⁻¹) and VCI ($\tau = +0.267$, $p = 0.065$, Sen's slope = +0.797% yr⁻¹). The trend does not reach statistical significance at $p < 0.05$. Three factors contribute to non-significance: the high interannual variability generated by the extreme 2000–2001 drought values and the exceptional 2022 peak; the non-monotonic trajectory interrupted by the 2008 moderate drought; and the proximity of the p-value

to the significance threshold, suggesting that extension to 30 years may yield statistical confirmation.

The positive Sen's slope of +0.000548 NDVI units per year corresponds to a cumulative NDVI increase of approximately 0.014 units over 25 years — equivalent to approximately 18% relative to the 2001 minimum. This magnitude is ecologically meaningful. Comparison with Dubovyk et al. [5], who identified negative vegetation trends over 2000–2010, reveals that extending the analysis to 2024 reverses the apparent trend direction. This demonstrates that conclusions drawn from shorter time windows anchored at historically anomalous drought periods may systematically overstate long-term degradation — an important methodological insight for remote sensing assessments of the region.

The non-significant positive trend is consistent with comparable findings from Mann-Kendall analyses of Landsat NDVI time series in the Yellow River delta, where statistically non-significant positive trends following water management interventions have been documented, with statistical significance emerging only after approximately 30 years of monitoring [10]. This parallel supports the interpretation that the Khorezm trend reflects a genuine underlying improvement that will become statistically confirmable as the monitoring record extends.

4. Conclusion

This study presents the most temporally complete Landsat-based vegetation assessment published for the Khorezm irrigated zone, covering 25 years (2000–2024) at 30 m spatial resolution. The key findings are:

The Khorezm region operated under chronic Mild drought conditions across 56% of all study years, reflecting its structural downstream position in the Amu Darya Basin. Two Extreme drought years (2000–2001) and one Moderate drought year (2008) correspond to documented regional crop failures, validating the satellite-based VCI approach for operational drought detection.

The Mann-Kendall test detects a positive but statistically non-significant vegetation trend ($\tau = +0.267$, $p = 0.065$), with the most substantial improvement occurring in 2016–2022. Extension of the monitoring record to 30 years — achievable by 2029 — is recommended to assess whether this trend achieves statistical significance.

The satellite-based monitoring methodology developed in this study — combining annual Landsat NDVI computation, VCI drought classification, and Mann-Kendall trend analysis via freely available cloud resources — is directly applicable to the operational requirements of Uzbekistan's national Land Degradation Road Map for 2024–2028. Integration into the national monitoring system would provide annually updated, spatially explicit drought information for evidence-based water resource planning in the Khorezm region.

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