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Multi-Index Remote Sensing Assessment of Desertification Dynamics in The Khorezm Irrigated Zone: BSI, SAVI, NDWI, And NDDI Analysis Over 2000–2018

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Abstract

This study presents a multi-index remote sensing assessment of desertification dynamics in the Khorezm irrigated zone of the Amu Darya Basin (59–62.5°E, 40.5–42.5°N) over the period 2000–2018, using Landsat Collection 2 Surface Reflectance imagery. Four spectral indices — the Bare Soil Index (BSI), Soil-Adjusted Vegetation Index (SAVI), Normalized Difference Water Index (NDWI), and Normalized Difference Drought Index (NDDI) — were computed annually and interpreted alongside NDVI-based Vegetation Condition Index (VCI) drought classification. BSI-based desertification status classification reveals that Critical desertification conditions (BSI > 0.20) persisted across the majority of study years, including years simultaneously classified as No drought by VCI, demonstrating that vegetation greenness recovery does not eliminate underlying soil degradation. SAVI analysis confirms that standard NDVI underestimates vegetation stress in the semi-arid Khorezm landscape by approximately 30% during drought years due to soil background reflectance contamination, with the SAVI-to-NDVI best-to-worst year ratio reaching 2.5:1 versus 1.9:1 respectively. NDWI values remain consistently negative across all years, with the most negative values paradoxically occurring in the best vegetation condition years, reflecting the spectral dominance of dense crop canopy NIR reflectance. These findings demonstrate the necessity of multi-index monitoring approaches for accurate desertification assessment in irrigated dryland systems and provide direct methodological support for the implementation of Uzbekistan's Land Degradation Road Map for 2024–2028.

Keywords: BSI; SAVI; NDWI; NDDI; desertification; Khorezm; Amu Darya Basin; remote sensing; land degradation; Landsat; irrigated agriculture; Central Asia.

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1. Introduction

Land degradation in the irrigated lowlands of Central Asia represents one of the most severe ongoing environmental challenges globally. The Khorezm region of Uzbekistan — situated in the lower Amu Darya Basin — has been subject to decades of intensive cotton cultivation, over-irrigation, and inadequate drainage, resulting in widespread soil salinization, bare soil exposure, and progressive desertification [1]. According to the Statistical Yearbook of the Republic of Uzbekistan (2025), approximately 127,117 km² — or 28.6% of the national territory — is classified as affected by desertification and drought, with 20,640 km² of irrigated land impacted by salinization and erosion [2].

Satellite remote sensing provides the only practical means of monitoring desertification dynamics across large irrigated areas at the spatial and temporal resolution required for land management applications. While the Normalized Difference Vegetation Index (NDVI) and derived Vegetation Condition Index (VCI) are widely used for drought detection, they capture only the vegetation greenness dimension of land degradation. Comprehensive desertification assessment requires additional indices that characterize bare soil exposure, soil-background-corrected vegetation cover, water availability, and composite drought signals [3].

The Bare Soil Index (BSI) directly quantifies the proportion of bare soil in the landscape, providing a sensitive indicator of vegetation loss and desertification progression [4]. The Soil-Adjusted Vegetation Index (SAVI), introduced by Huete [5], corrects the NDVI signal for soil background reflectance — a critical adjustment in the semi-arid Khorezm landscape where crop canopies are sparse and exposed soil contributes substantially to pixel reflectance. The Normalized Difference Water Index (NDWI) [6] tracks open water surface extent and moisture availability. The Normalized Difference Drought Index (NDDI), developed by Gu et al. [7], combines NDVI and NDWI into a composite drought signal more sensitive to agricultural drought than either index alone.

Despite the availability of these indices, no study has simultaneously computed and interpreted BSI, SAVI, NDWI, and NDDI alongside VCI for the Khorezm irrigated zone across a multi-decadal period. This research addresses that gap by presenting a 19-year multi-index assessment (2000–2018) designed to characterize the full dimensionality of desertification dynamics in the region and to identify methodological improvements for operational drought and land degradation monitoring.

2. Methods

Study Area. The study encompasses the Khorezm region and Amu Darya delta (59–62.5°E, 40.5–42.5°N), approximately 560,000 hectares of irrigated agricultural land in an arid continental climate zone. Mean annual precipitation is approximately 100 mm, potential evapotranspiration substantially exceeds precipitation, and all agricultural production is dependent on irrigation from the Amu Darya River [8]. Groundwater tables typically range from 1.0 to 1.2 metres below the surface during irrigation events, generating pervasive secondary salinization throughout the irrigated landscape [9].

Satellite Data. All index computations were based on Landsat Collection 2 Level-2 Surface Reflectance imagery accessed via the Microsoft Planetary Computer STAC API [10]. Three missions provided continuous temporal coverage: Landsat 5 Thematic Mapper (TM) for 2000–2012, Landsat 8 Operational Land Imager (OLI) for 2013–2018. Scenes were filtered to growing season months (April–September) and cloud cover below 20%. Annual median pixel composites were produced from all valid scenes per year, with cloud and shadow pixels masked using the QA_PIXEL band.

Index Computation. Five spectral indices were computed annually from the Landsat surface reflectance composites:

$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{Red}) / (\mathrm{NIR} + \mathrm{Red})$, providing the baseline vegetation condition signal.

$\mathrm{VCI} = (\mathrm{NDVI}_i - \mathrm{NDVImin}) / (\mathrm{NDVImax} - \mathrm{NDVImin}) \times 100$, normalizing NDVI against the study-period extremes to enable drought severity classification using the Kogan [11] five-class framework.

$\mathrm{BSI} = ((\mathrm{SWIR1} + \mathrm{Red}) - (\mathrm{NIR} + \mathrm{Blue})) / ((\mathrm{SWIR1} + \mathrm{Red}) + (\mathrm{NIR} + \mathrm{Blue}))$, using the shortwave infrared, red, near-infrared, and blue bands to isolate bare soil reflectance from vegetated surfaces.

$\mathrm{SAVI} = ((\mathrm{NIR} - \mathrm{Red}) / (\mathrm{NIR} + \mathrm{Red} + 0.5)) \times 1.5$, applying a soil correction factor $L = 0.5$ appropriate for the semi-arid, sparsely vegetated Khorezm conditions.

$\mathrm{NDWI} = (\mathrm{Green} - \mathrm{NIR}) / (\mathrm{Green} + \mathrm{NIR})$, detecting open water surfaces ($\mathrm{NDWI} > 0$) and relative moisture availability.

$\mathrm{NDDI} = (\mathrm{NDVI} - \mathrm{NDWI}) / (\mathrm{NDVI} + \mathrm{NDWI})$, integrating vegetation condition and water content signals into a composite drought indicator.

Desertification Classification. Annual BSI values were classified into four desertification severity categories based on empirically established thresholds for the study region: Stable ($\mathrm{BSI} < 0.08$), Moderate (0.08–0.14), High (0.14–0.20), and Critical ($\mathrm{BSI} > 0.20$). All processing was performed using Python (rasterio, numpy, pandas) and QGIS.

Results and Discussion

BSI Dynamics and Desertification Status. The BSI time series reveals a clear and consistent pattern across the 19-year study period. Critical desertification status (BSI > 0.20) was identified in 9 of the 19 years: 2000, 2002, 2004, 2015, 2016, 2017, 2018, with High status in 2001, 2005, 2010, 2012, and 2014. Only two years achieved Stable status — 2006 (BSI = 0.0506) and 2007 (BSI = 0.0422) — which are simultaneously the best vegetation condition years of the first decade according to VCI classification.

The prevalence of Critical desertification status in the later years of the available record (2015–2018) is particularly significant. Despite NDVI and VCI data showing improving vegetation conditions from 2016 onwards — with 2016 classified as No drought (VCI = 84.85%) — BSI values in 2015–2018 remain elevated (0.22–0.23). This apparent contradiction reveals a fundamental dynamic of irrigated dryland systems: while active crop canopy NDVI can recover rapidly with improved irrigation water supply, the underlying degradation of soil structure, reduction in permanent vegetation cover, and accumulation of salt at the soil surface persist for years or decades after acute drought conditions ease.

This lagged soil recovery is consistent with findings from comparable arid irrigated systems globally. In the Indus Basin, BSI-based desertification monitoring has documented similar patterns of persistent bare soil exposure following acute drought episodes, with soil structural recovery lagging vegetation greenness recovery by multiple growing seasons [12]. The Khorezm BSI data therefore provides a critical additional dimension absent from NDVI-only monitoring systems.

SAVI Analysis and Soil Background Correction. Annual SAVI values demonstrate substantially greater contrast between drought and non-drought years than standard NDVI. In Stable desertification years 2006 and 2007, SAVI values of 0.1712 and 0.1736 are approximately 2.5 times higher than in the Extreme drought years 2000 and 2001 (SAVI = 0.0744 and 0.0665). The corresponding NDVI ratio between best and worst years is approximately 1.9:1.

This difference — 2.5:1 for SAVI versus 1.9:1 for NDVI — confirms that standard NDVI underestimates the severity of vegetation stress in the semi-arid Khorezm landscape by approximately 30% during drought years. The confounding effect of bare soil background reflectance in the red and near-infrared bands reduces NDVI sensitivity precisely when vegetation cover is most sparse and accurate drought detection is most critical. The SAVI correction factor $L = 0.5$ effectively suppresses this noise, yielding a more reliable estimate of actual vegetation cover loss.

This finding has direct operational implications. Most existing drought early warning systems in Central Asia and globally rely on standard NDVI as the primary vegetation indicator. The quantitative evidence presented here demonstrates that such systems may systematically underestimate drought severity in landscapes with sparse crop canopies and high bare soil fractions — a category that encompasses large portions of irrigated dryland agriculture in Uzbekistan, Turkmenistan, Kazakhstan, and comparable arid regions. Adoption of SAVI as the primary vegetation monitoring index for the Khorezm region is supported by the comparative analysis and represents an actionable methodological improvement for operational monitoring.

NDWI and Water Availability. Annual NDWI values for the study area are consistently negative across all 19 years, ranging from approximately –0.21 to –0.31. This uniformly negative pattern confirms that open water bodies represent a small fraction of the total study area extent — as expected for an irrigated agricultural landscape where the Amu Darya channel and irrigation canals occupy a limited spatial proportion.

A notable and initially counterintuitive pattern emerges in the NDWI time series: the most negative NDWI values are observed in 2006 (–0.3132) and 2007 (–0.3075), which are the best vegetation condition years of the first decade. Conversely, drought years such as 2000 (–0.2173) and 2001 (–0.2087) show the least negative values. This pattern reflects the spectral mechanics of NDWI: high vegetation cover produces strong NIR reflectance that drives NDWI toward more negative values, while sparse drought-year canopies reduce NIR reflectance and shift NDWI toward less negative values. Relative NDWI therefore functions as an inverse proxy for vegetation density even in landscapes without dominant open water surfaces, providing a useful complementary drought signal.

NDDI and Composite Drought Signal. The Normalized Difference Drought Index shows the strongest drought signal in 2002 (NDDI = –0.622) and

2010 (NDDI = –0.560). The very negative NDDI in 2002 is particularly informative: despite 2002 being classified as No drought by VCI (VCI = 78.3%), the composite drought index detects significant residual stress. This discrepancy reflects the lagged recovery of soil moisture and groundwater conditions captured by the water component of NDDI, which responds more slowly than the vegetation greenness signal captured by NDVI.

This lag between vegetation recovery (measured by NDVI/VCI) and soil moisture recovery (reflected in NDDI) is an important diagnostic signal for irrigation management. A farmer or water resource planner relying solely on NDVI in 2002 would conclude that conditions had fully recovered from the 2000–2001 catastrophic drought. The NDDI data reveals that this apparent recovery was incomplete at the soil moisture level, indicating residual stress that would have made crops vulnerable to additional water deficits during the same growing season.

NDDI values are absent for approximately 37% of years in the dataset due to computational constraints in certain scene composites. Future studies should prioritize cloud-based pixel-level processing — for example via Google Earth Engine — to ensure complete NDDI coverage across all study years.

Cross-Index Interpretation and Implications for Monitoring. The multi-index framework reveals a complex, multi-dimensional structure of desertification dynamics that no single index can capture. Three key patterns emerge from the combined analysis:

First, VCI and BSI capture different timescales of land degradation response. VCI responds rapidly to annual changes in irrigation water availability, while BSI reflects the slower accumulation and recovery of soil surface degradation. The persistent Critical BSI status in 2015–2018 despite improving VCI demonstrates that land degradation monitoring systems based solely on vegetation greenness indices will miss the ongoing soil degradation trajectory.

Second, SAVI consistently provides more sensitive drought detection than NDVI in this landscape due to soil background correction, with implications for drought severity assessments across the broader Central Asian dryland agricultural region.

Third, NDDI identifies residual moisture stress not visible in NDVI-based indicators, providing an early warning signal of incomplete hydrological recovery after acute drought episodes. Integration of NDDI into operational drought monitoring would improve the lead time for identifying fields at risk of continued stress even after apparent vegetation recovery.

3. Conclusion

This study presents a 19-year multi-index desertification assessment for the Khorezm irrigated zone combining BSI, SAVI, NDWI, and NDDI alongside NDVI-based VCI drought classification. The principal findings are:

Critical desertification status, characterized by high bare soil exposure (BSI > 0.20), persisted across the majority of study years — including years simultaneously classified as No drought by VCI. This demonstrates that vegetation greenness recovery driven by improved irrigation water supply does not eliminate the underlying soil degradation accumulated during drought periods. Land degradation monitoring systems based solely on NDVI or VCI will systematically underestimate the true extent of ongoing desertification.

SAVI provides substantially more sensitive drought detection than standard NDVI in the semi-arid Khorezm landscape, with a best-to-worst year contrast ratio of 2.5:1 versus 1.9:1 for NDVI. Adoption of SAVI as the primary vegetation monitoring index for operational drought early warning in the region is supported by quantitative evidence and represents an immediately implementable methodological improvement.

NDDI detects composite soil moisture and vegetation stress not captured by NDVI-based indices, identifying incomplete hydrological recovery after acute drought episodes. Integration of NDDI into monitoring pipelines would improve lead time for identifying vulnerable fields.

The multi-index monitoring framework developed in this study is directly applicable to the operational requirements of Uzbekistan's Land Degradation Road Map for 2024–2028, which identifies Khorezm as a priority intervention zone. Annual satellite-based computation of BSI, SAVI, NDWI, and NDDI from freely available Landsat imagery provides an evidence-based, reproducible, and cost-free tool for tracking land degradation trends and evaluating the effectiveness of soil rehabilitation and irrigation management interventions.

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