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Research Article

Monitoring and Assessment of Agricultural Drought Using Satellite Data: A Comprehensive Case Study in the Afaj District, Al-Qadisiyah Governorate, Southern Iraq

Alsaidi K.

Independent Scholar

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ABSTRACT

Drought is one of the most severe environmental hazards affecting water resources, agriculture, and ecosystems, particularly in arid and semi-arid regions. Iraq is highly vulnerable to climate change and declining water inflows from the Tigris and Euphrates rivers, leading to increasing drought severity and land degradation. This study analyzes the spatiotemporal distribution of drought in Afaj District, Al-Qadisiyah Governorate, southern Iraq, using Sentinel-2 satellite data and remote sensing indices including the Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI), and Normalized Difference Drought Index (NDDI) for the years 2019 and 2025.

Satellite images with 10 m spatial resolution were processed to evaluate vegetation health, surface moisture, and drought intensity. Statistical analysis showed strong positive correlation between NDVI and NDWI ($r \approx 0.69$) and strong negative correlations between NDDI and both NDVI and NDWI, confirming the reliability of these indices for drought monitoring. Land cover analysis revealed significant environmental changes, with bare land expanding by about 28% between 2019 and 2025, while vegetation and water-covered areas declined.

The results indicate a substantial intensification of drought conditions, with areas experiencing moderate to high drought severity increasing from 48% in 2019 to 75% in 2025. These findings highlight the growing risks of land degradation, agricultural decline, and ecosystem loss in southern Iraq. Remote sensing techniques using integrated spectral indices provide an effective tool for monitoring drought dynamics and supporting sustainable water and land management strategies.

1. INTRODUCTION

Drought represents one of the most extensive, recurrent, and damaging natural hazards affecting human societies and natural ecosystems across the globe. Unlike sudden-onset disasters such as floods, earthquakes, or cyclones, which strike with little warning and produce immediate, visible destruction, droughts develop gradually and insidiously, often going unnoticed in their early stages until their impacts become severe and widespread. This gradual development makes drought particularly challenging to monitor, predict, and manage, as the absence of dramatic initial events can lead to delayed recognition and response, allowing impacts to accumulate and intensify before effective interventions are implemented. The consequences of drought are profound and multidimensional, extending far beyond the immediate experience of water scarcity to affect virtually every sector of the economy, disrupt ecosystem functioning, and undermine the livelihoods and well-being of millions of people across all continents and climate zones.

Agricultural production is the sector most directly and severely impacted by drought, given its fundamental dependence on reliable supplies of water through rainfall, soil moisture, and irrigation. When drought conditions develop, crop yields begin to decline as plants experience water stress during critical growth stages, affecting both the quantity and quality of harvests. Livestock productivity falls as pastures dry up and water sources for animals diminish. The entire food system comes under increasing stress, with reduced agricultural output leading to higher food prices, reduced availability of nutritious foods, and heightened food insecurity among vulnerable populations, particularly in rural areas where households depend directly on their own production for subsistence. In

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countries where agriculture represents a significant share of economic activity and employment, the impacts of drought ripple through the entire economy, reducing rural incomes, constraining demand for goods and services, and undermining economic growth and development.

Beyond its direct effects on agriculture, drought exerts pressure on domestic water supply systems as reservoirs, rivers, and groundwater sources decline, forcing water utilities to implement restrictions and rationing, and in extreme cases, leaving communities without adequate water for basic needs. Water-intensive industries, including manufacturing, mining, and food processing, face operational constraints as water becomes scarce and more expensive. The energy sector is also affected, particularly where hydropower generation depends on reservoir levels, but also where thermoelectric power plants require large volumes of water for cooling. When multiple sectors are simultaneously impacted by drought, the cumulative economic losses can be staggering, running into billions of dollars for major drought events and persisting for years after meteorological conditions have returned to normal.

The environmental consequences of drought are equally severe and often longer-lasting than the economic impacts. Prolonged water scarcity leads to land degradation as vegetation cover declines, soils become exposed to wind and water erosion, and organic matter levels fall. Desertification, the process by which productive land transforms into desert-like conditions, is often triggered or accelerated by recurrent drought, particularly in semi-arid and arid regions where ecosystems are already stressed by limited water availability. Biodiversity suffers as plant and animal species struggle to survive under increasingly harsh conditions, and ecosystem services, including carbon sequestration, water purification, and pollination, are degraded. The deterioration of ecological systems in turn reinforces the vulnerability of human communities that depend on these systems for their livelihoods and well-being, creating a vicious cycle of environmental degradation and human suffering that can be extremely difficult to reverse.

Given the complexity of drought phenomena and the need for systematic descriptions applicable to monitoring, early warning, and impact assessment, numerous indices have been developed to quantify different aspects of drought. Each of these indices addresses a specific dimension of drought and has its own strengths and limitations depending on the application context and data availability. The Standardized Precipitation Index, developed by McKee and colleagues in 1993, focuses on meteorological drought by quantifying precipitation deficits over multiple timescales, providing a flexible tool for assessing drought conditions from months to years. The Soil Moisture Drought Index, introduced by Hollinger and colleagues in 1993, addresses agricultural drought by directly assessing moisture conditions in the root zone. The Vegetation Condition Index, developed by Liu and Kogan in 1996, uses satellite data to assess vegetation health relative to historical conditions, providing an indicator of agricultural drought impacts on plant growth. Among the most widely applied satellite-based indices are the Normalized Difference Vegetation Index, first proposed by Rouse and colleagues in 1973, which measures vegetation greenness and density; the Normalized Difference Water Index, developed by McFeeters in 1996, which assesses surface water and vegetation moisture content; and the Normalized Difference Drought Index, introduced by Charat and colleagues in 2009, which combines information from NDVI and NDWI to provide a more comprehensive indicator of drought severity.

Vegetation is typically the earliest biophysical component to exhibit measurable stress under developing drought conditions, as plant growth and physiological processes are highly sensitive to even modest reductions in water availability. Long before water levels in reservoirs or groundwater show measurable declines, plants begin to experience water stress, with visible effects including reduced growth, wilting, changes in leaf color, and eventually, mortality. This sensitivity makes vegetation an ideal indicator for early detection and monitoring of drought, as changes in plant condition can provide advance warning of developing water scarcity before it reaches crisis proportions. Remote sensing technology, which enables the systematic observation of vegetation conditions over large areas at regular intervals, has revolutionized drought monitoring by providing the capability to detect and track vegetation stress across entire regions, including areas where ground-based observations are sparse or nonexistent.

A wide range of remote sensing-based indices has been developed to quantify drought severity through the analysis of land surface reflectance characteristics captured by satellite sensors. These indices exploit variations in the spectral reflectance of different land cover types across the visible, near-infrared, and shortwave infrared regions of the electromagnetic spectrum. The fundamental principle underlying these indices is that healthy, well-watered vegetation exhibits characteristic spectral signatures, with strong absorption of red light for photosynthesis and strong reflection of near-infrared radiation due to internal leaf structure. When plants experience water stress, these spectral characteristics change in predictable ways, with reduced near-infrared reflectance and changes in shortwave infrared absorption related to leaf water content. By capturing these spectral changes, remotely sensed indices provide an efficient, cost-effective, and spatially comprehensive means of monitoring drought dynamics, particularly valuable in regions where ground-based observations are limited by sparse networks of meteorological stations, difficult terrain, or resource constraints.

Iraq is exceptionally vulnerable to the impacts of climate change and drought, ranking as the fifth most vulnerable country in the world to climate breakdown according to United Nations assessments published in 2022. This extreme vulnerability stems from a combination of geographical, hydrological, and socio-economic factors that converge to create a perfect storm of water-related challenges. The country is located in an arid to semi-arid region characterized by high temperatures, high evaporation rates, and naturally variable and generally limited precipitation. Its two great rivers, the Tigris and Euphrates, which have sustained civilization in Mesopotamia for thousands of years, originate outside its borders, with the vast majority of their flow generated in Turkey, Syria, and Iran. This transboundary nature of Iraq's water resources makes the country acutely vulnerable to the water policies of its upstream neighbors, who have constructed numerous large dams and irrigation schemes over recent decades that have dramatically reduced the flow of freshwater entering Iraq.

For many decades, Iraq has suffered from progressively decreasing averages of rainfall and snowfall due to climate change consequences, a trend that has affected not only the traditionally drier middle and southern parts of the country but even the northern region, which historically received between four hundred and one thousand millimeters of rainfall annually. This decline in precipitation, combined with rising temperatures that increase evaporative demand, has steadily reduced the availability of water for agriculture, domestic use, and ecosystem maintenance. Compounding these climatic challenges are the water policies of neighboring countries, particularly Turkey and Iran, which have constructed numerous dams on the Tigris and Euphrates rivers and their tributaries. The Southeastern Anatolia Project in Turkey alone includes over twenty dams on the Euphrates and Tigris rivers, with massive storage capacity that allows Turkey to regulate the flow of these rivers largely independently of downstream conditions. Similar developments in Iran on rivers that feed the Tigris system have further reduced inflows. As a result of these combined pressures, the entire country has become increasingly prone to droughts, and the severity of drought events has increased markedly over the past two decades, with devastating consequences for water resources, ecosystem productivity, agricultural production, and rural livelihoods.

The people of Iraq have been profoundly affected by these developments. In the marshlands of southern Iraq, once the largest wetland ecosystem in the Middle East and a UNESCO World Heritage site, reduced water flows have led to widespread desiccation, with once-extensive permanent marshes transforming into seasonal wetlands or completely dry, salt-encrusted basins. Fishing communities that depended on the marshes for their livelihoods have seen their catches decline dramatically. Farmers who relied on river water for irrigation have watched their crops fail as water allocations have been cut and soil salinity has increased due to inadequate leaching. Entire communities have been displaced as their traditional livelihoods have become untenable, with many households forced to abandon their lands and migrate to cities in search of alternative means of survival, a phenomenon known as reverse migration that places additional strain on already overburdened urban infrastructure and services.

This study was therefore undertaken to analyze the spatiotemporal distribution of drought severity in the Afaj District of Al-Qadisiyah Governorate in Southern Iraq, using high-resolution satellite data and applying a suite of well-established remote sensing indices. The specific objectives of this research were to analyze the spatiotemporal distribution of drought severity classes in the study area using Sentinel-2 satellite data and applying NDVI, NDWI, and NDDI indices for the years 2019 and 2025; to document the impacts of drought severity on land cover and land use changes over this period; and to prepare detailed maps illustrating the temporal and spatial distribution of drought severity classes across the study area. The years 2019 and 2025 were specifically chosen to represent contrasting moisture conditions within the study period, with 2019 representing a relatively wetter year and 2025 representing the driest year during the last decade, allowing for a robust assessment of drought dynamics and their impacts on the landscape and its human communities. By providing a detailed, quantitative assessment of drought conditions and their evolution over time, this study aims to generate actionable scientific knowledge that can inform drought monitoring, early warning systems, agricultural policy, and adaptation planning in one of the regions most severely affected by climate change and water scarcity in the world.

2. MATERIALS AND METHODOLOGY

2.1 Location and Characteristics of the Study Area

The Afaj District is an administrative unit within Al-Qadisiyah Governorate, located in southern Iraq approximately three hundred seventy kilometers southeast of the national capital, Baghdad. The district is situated between latitudes thirty-one degrees fourteen minutes north and longitudes forty-six degrees nineteen minutes east, encompassing a total area of approximately four thousand two hundred one point nine six square kilometers. The region is characterized by flat to gently undulating topography typical of the Mesopotamian plain, with elevations gradually decreasing toward the southeast. The Euphrates River flows through the governorate, and the Al-Gharraf River, a major branch of the Tigris River, also traverses the region, providing the primary surface water resources for irrigation and domestic use. Historically, the area contained significant marshlands that formed part of the larger Mesopotamian marshland complex, providing critical wetland habitats and supporting local livelihoods through fishing, rice cultivation, and traditional water buffalo breeding.

The climate of the study area is classified as a subtropical desert climate according to the Köppen climate classification system, designated as BWh. This climate type is characterized by extremely hot summers, mild winters, and very low annual precipitation that is highly variable from year to year. Long, intensely hot summers dominate the annual cycle, with mean daily maximum temperatures frequently exceeding forty degrees Celsius during July and August, and mean annual temperature averaging twenty-nine point eight five degrees Celsius. Winters are short and relatively mild, with mean daily minimum temperatures rarely falling below freezing, though cold spells can occasionally bring temperatures close to zero. Rainfall is scarce and highly seasonal, falling primarily between November and April, with the months from May through October receiving virtually no precipitation. The mean annual rainfall is less than thirty millimeters, a value that places the region among the driest areas of Iraq and indeed of the entire Middle East. This extreme aridity means that agriculture is entirely dependent on irrigation, and even irrigated agriculture faces constant challenges from high evaporation rates, soil salinization, and the limited and increasingly unreliable water supplies from the river systems.

The dominant natural vegetation of the region is characteristic of desert and semi-desert environments, consisting of scattered drought-adapted shrubs, perennial herbs, and annual plants that complete their life cycles during the brief period when moisture is available following winter rains. However, decades of water development, agricultural expansion, and more recently, drought and water scarcity, have dramatically transformed the landscape. Much of the natural vegetation has been replaced by agricultural lands where irrigation water is available, or by barren, salt-encrusted wastelands where water has been withdrawn or where drainage is inadequate. The marshlands, once a dominant feature of the landscape in the northeastern part of the district, have been severely degraded by reduced water inflows, with large areas converting from permanent wetlands to seasonal marshes or completely dry land. These ecological changes have profound implications for biodiversity, ecosystem services, and the livelihoods of local communities that have historically depended on these resources.

2.2 Satellite Data Acquisition and Processing

The spatiotemporal variations of agricultural drought in the study area were analyzed using high-resolution satellite imagery from the European Space Agency's Sentinel-2 mission. Sentinel-2 is a constellation of two polar-orbiting satellites designed to provide high-resolution multispectral imagery for land monitoring applications, including agriculture, forestry, land cover mapping, and environmental monitoring. The satellites carry the MultiSpectral Instrument, which captures data in thirteen spectral bands ranging from the visible and near-infrared to the shortwave infrared, with spatial resolutions of ten meters, twenty meters, and sixty meters depending on the band. For this study, images with ten-meter spatial resolution were selected to provide the level of detail necessary for accurate discrimination of land cover types and detection of drought-related changes at the field scale.

Sentinel-2 images for the months of June in both 2019 and 2025 were obtained from the United States Geological Survey Earth Explorer platform, which provides free and open access to a vast archive of satellite data. June was specifically selected as the optimal month for drought assessment in this region because it represents the transition period at the end of the rainy season and the beginning of the dry summer, when vegetation conditions reflect the cumulative effects of the preceding winter's rainfall and the early impacts of summer drought stress. By using images from the same month in different years, the analysis controls for seasonal variations and focuses specifically on interannual differences in moisture conditions and vegetation response. The two years were carefully chosen to represent contrasting moisture conditions within the study period, with 2019 representing a relatively wetter year and 2025 representing the driest year during the last decade, based on analysis of meteorological data and preliminary assessment of vegetation conditions. This contrast allows for a robust assessment of drought dynamics and their impacts on land cover and land use over the six-year period.

All image processing and analysis were performed using Quantum GIS software, version 3.16.4, an open-source geographic information system that provides powerful tools for remote sensing data processing, spatial analysis, and map production. The raw satellite images were first subjected to atmospheric correction to remove the effects of atmospheric scattering and absorption that can distort spectral reflectance values. Cloud masking was applied to exclude any pixels affected by cloud cover, though June images in this arid region are typically cloud-free. The images were then subset to the study area boundaries, and all subsequent calculations and analyses were performed on these subset images.

2.3 Calculation of Spectral Indices

Three key spectral indices were calculated from the Sentinel-2 data to assess vegetation condition, surface moisture, and drought severity: the Normalized Difference Vegetation Index, the Normalized Difference Water Index, and the Normalized Difference Drought Index. Each of these indices provides complementary information about land surface conditions, and their combined use enables a comprehensive assessment of drought impacts.

The Normalized Difference Vegetation Index is the most widely used vegetation index in remote sensing applications and serves as a fundamental tool for assessing vegetation cover, density, and health. NDVI is based on the principle that healthy green vegetation strongly absorbs red light for photosynthesis while strongly reflecting near-infrared radiation due to the internal structure of leaves. By calculating the normalized difference between near-infrared and red reflectance, NDVI produces values that range from negative one to positive one, with higher values indicating denser, healthier vegetation. For this study, NDVI was calculated using the standard formula developed by Rouse and colleagues in 1973:

$$NDVI = (\rho NIR - \rho R) / (\rho NIR + \rho R)$$

where ρNIR represents the spectral reflectance in the near-infrared band, corresponding to Sentinel-2 band 8, and ρR represents the spectral reflectance in the red band, corresponding to Sentinel-2 band 4. NDVI values approaching positive one typically indicate dense, healthy, and photosynthetically active vegetation, reflecting strong absorption in the red band and high reflectance in the near-infrared region. Values near zero generally correspond to sparse or stressed vegetation, bare soil, or urban surfaces, while negative values are typically associated with water bodies, which absorb most incident radiation across both the red and near-infrared wavelengths.

The Normalized Difference Water Index was developed by McFeeters in 1996 to enhance the presence of open water features in satellite imagery and to assess vegetation water content. NDWI takes advantage of the fact that water bodies strongly absorb near-infrared radiation while reflecting green light, producing positive values for water surfaces. The index is calculated using the following formula:

$$NDWI = (\rho G - \rho SWIR) / (\rho G + \rho SWIR)$$

where ρG represents the spectral reflectance in the green band, corresponding to Sentinel-2 band 3, and $\rho SWIR$ represents the spectral reflectance in the shortwave infrared band, corresponding to Sentinel-2 band 8. NDWI theoretically ranges between negative one and positive one, with values greater than zero typically indicative of open water bodies. However, in practical applications, water bodies may occasionally exhibit NDWI values below zero, particularly where exposed sediments, suspended materials, or shallow conditions influence spectral reflectance. Under drought conditions, NDWI provides valuable information about vegetation water stress, as water-stressed plants show reduced NDWI values compared to healthy, well-watered vegetation.

The Normalized Difference Drought Index was developed by Gu and colleagues in 2007 and refined by Charat and colleagues in 2009 as an integrated indicator designed to provide a more robust and sensitive measure of drought severity than either NDVI or NDWI alone. NDDI combines information from both vegetation greenness and moisture content, recognizing that drought impacts both the vigor of vegetation and its water status. The index is calculated using the following formula:

NDDI = (NDVI - NDWI) / (NDVI + NDWI)

High NDDI values indicate drought conditions, in which both NDVI and NDWI are low, reflecting stressed vegetation and limited moisture availability. Low NDDI values indicate non-drought conditions, in which both NDVI and NDWI are higher, reflecting healthy vegetation with adequate moisture. Because NDDI incorporates information on both vegetation vitality and water content, it provides a more sensitive indicator of drought than NDVI or NDWI alone, capable of detecting developing drought stress earlier and discriminating drought severity more effectively across a range of environmental conditions. This enhanced sensitivity has been demonstrated in numerous studies across diverse climatic and geographical contexts, including grasslands in the United States, crop conditions in China, and various applications in Southeast Asia and the Middle East.

2.4 Classification of Drought Severity and Land Cover

Following the calculation of the three spectral indices, the study area was classified into meaningful categories for analysis and interpretation. For land cover classification based on NDVI values, five distinct land cover types were identified: weak vegetation, moderate vegetation, urban land, bare land, and water bodies. The NDVI thresholds for these classes were established based on examination of the NDVI value distribution across the study area and comparison with high-resolution imagery for reference. Areas with NDVI values indicating healthy, vigorous vegetation were classified as moderate vegetation, while areas with lower but still positive NDVI values indicating sparse or stressed vegetation were classified as weak vegetation. Areas with NDVI values near zero or slightly negative were classified as urban or bare land, distinguished based on spatial context and comparison with reference imagery. Areas with strongly negative NDVI values characteristic of water bodies were classified as such.

For drought severity classification based on NDDI values, five drought classes were similarly defined: very low drought severity, low drought severity, moderate drought severity, high drought severity, and very high drought severity. The classification thresholds were established based on the distribution of NDDI values across the study area and reference to established relationships between NDDI and observed drought conditions from previous studies. Areas with the lowest NDDI values, indicating minimal drought stress with healthy vegetation and adequate moisture, were classified as very low drought severity. Progressively higher NDDI value ranges were assigned to low, moderate, high, and very high drought severity classes, with the highest values indicating extreme drought conditions characterized by severely stressed or dead vegetation and minimal moisture availability.

Once the classifications were established, the area covered by each land cover class and each drought severity class was computed for both 2019 and 2025. These area calculations enable quantitative assessment of the changes that occurred over the six-year period and provide the basis for understanding the impacts of drought on the landscape. Thematic maps were created for each index and each year to provide visual representations of the spatial patterns of vegetation, moisture, and drought severity across the study area, facilitating interpretation and communication of the results.

2.5 Statistical Analysis

To quantitatively assess the relationships among the three spectral indices, statistical analysis was conducted using six hundred sample points distributed across the study area. These points were selected using a stratified random sampling approach to ensure representation of all land cover types and drought severity classes. For each sample point, the values of NDVI, NDWI, and NDDI were extracted from the respective raster layers for both 2019 and 2025, creating a dataset of paired observations.

Correlation analysis was performed to determine the strength and direction of relationships among the indices. Pearson correlation coefficients were calculated for the pairs NDVI-NDWI, NDVI-NDDI, and NDWI-NDDI, providing measures of the linear association between each pair of variables. The coefficients range from negative one to positive one, with values near zero indicating no linear relationship, positive values indicating a direct relationship, and negative values indicating an inverse relationship. The statistical significance of the correlations was assessed using standard significance tests, with p-values less than zero point zero five considered statistically significant. Additionally, linear regression analysis was performed for each pair of indices, with the coefficient of determination providing a measure of the proportion of variance in one index that can be explained by its linear relationship with the other.

3. RESULTS AND DISCUSSION

3.1 Spatial Distribution of Land Cover and Land Use Based on NDVI Analysis

The Normalized Difference Vegetation Index analysis provided a detailed picture of vegetation conditions and land cover distribution across the Afaj District for both 2019 and 2025. The NDVI values across the study area ranged from a minimum of negative zero point two four in the water body area located in the northeastern part of the study area, to a maximum of zero point five zero, representing the most densely vegetated agricultural lands distributed across various locations. This range of values reflects the diverse land surface conditions present in the study area, from open water surfaces with strongly negative NDVI through barren desert soils with NDVI values near zero, to irrigated agricultural fields with moderate to high NDVI values.

Based on the NDVI value distribution, the study area was classified into five distinct land cover categories that capture the dominant surface types present. Weak vegetation areas, characterized by sparse or stressed vegetation cover, occupied significant portions of the landscape, particularly in areas where irrigation water is limited or where soil salinity constrains plant growth. Moderate vegetation areas, representing healthier and denser vegetation, were concentrated in the agricultural zones along the river courses and in areas with better water access. Urban land, including built-up areas with impervious surfaces, was distributed across the district, with the main population centers clearly visible in the imagery. Bare land, consisting of exposed soil with minimal or no vegetation cover, dominated large portions of the landscape, particularly in areas away from the rivers and irrigation infrastructure. Water bodies, including rivers, canals, and the remaining marshland areas, occupied the smallest proportion of the study area, reflecting the extreme water scarcity characteristic of the region.

The dominance of urban and bare land as the most prevalent land cover types, and the minimal extent of water bodies, powerfully reflect the impacts of drought conditions and the ongoing water crisis in the region. In a landscape where water is the primary limiting factor for vegetation growth, the extent of bare land serves as a direct indicator of the severity of water scarcity. The fact that bare land occupies such a large proportion of the study area, and that this proportion increased dramatically between 2019 and 2025, provides stark evidence of the intensifying drought stress affecting this region.

3.2 Temporal Changes in Land Cover between 2019 and 2025

The comparison of land cover distributions between 2019 and 2025 revealed dramatic and highly significant changes that occurred over this relatively short six-year period. Table 1 presents the quantitative changes in area for each land cover class, while Figure 2 provides a visual representation of these changes.

Figure 2. Temporal and Spatial Land Cover Changes (2019–2025) Based on NDVI Classification

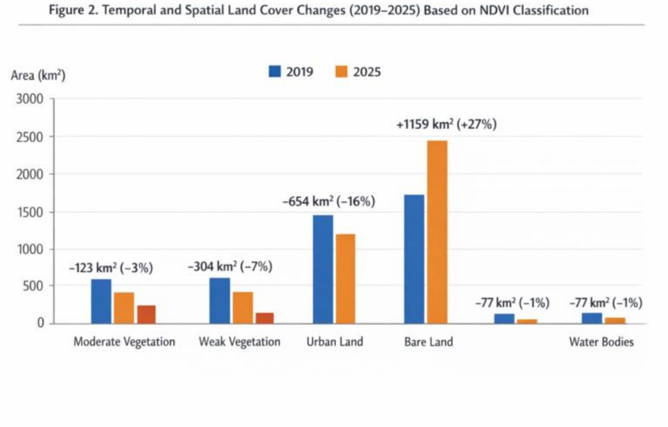


Table 1. Temporal and Spatial Land Cover Changes between 2019 and 2025 Based on NDVI Analysis

Land Cover Class	Area 2019 (km²)	Area 2019 (%)	Area 2025 (km²)	Area 2025 (%)	Change (km²)	Change (%)
Moderate Vegetation	209.22	5	85.95	2	-123.27	-3
Weak Vegetation	486.58	12	182.93	5	-303.65	-7
Urban Land	1792.65	43	1138.21	27	-654.44	-16
Bare Land	1523.80	36	2682.34	63	+1158.54	+27
Water Bodies	189.71	4	112.54	3	-77.17	-1
Total Area	**4201.96**	**100**	**4201.96**	**100**		

The most striking change evident from these data is the dramatic expansion of bare land, which increased by over one thousand one hundred fifty-eight square kilometers, representing a twenty-seven percent increase in its share of the total study area. In 2019, bare land occupied thirty-six percent of the district, but by 2025, it had expanded to cover an overwhelming sixty-three percent of the landscape. This massive expansion of bare land occurred at the expense of virtually all other land cover classes. Moderate vegetation areas declined by three percent, weak vegetation areas declined by seven percent, urban land declined by sixteen percent, and even water bodies, already a minor component of the landscape, declined by one percent.

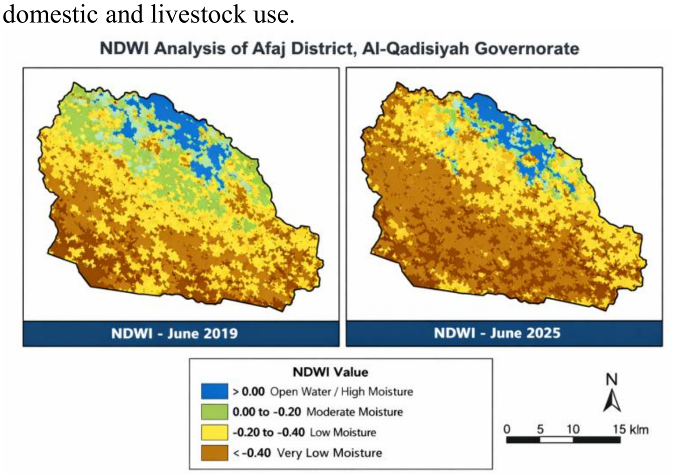
The decline in vegetated areas, totaling a ten percent reduction in combined moderate and weak vegetation cover, directly reflects the impacts of intensifying drought on plant growth and survival. As water availability has decreased, whether through reduced rainfall, diminished river flows, or falling groundwater levels, vegetation has become increasingly stressed, with many areas that previously supported at least sparse plant cover converting to completely bare soil. This loss of vegetation cover has profound implications for ecosystem function, soil stability, and the provision of ecosystem services. Bare soils are highly vulnerable to wind and water erosion, leading to loss of nutrient-rich topsoil and further degradation of land productivity. The loss of vegetation also reduces carbon sequestration, diminishes habitat for wildlife, and degrades the aesthetic and recreational value of the landscape.

The seventeen percent decline in urban land area is particularly noteworthy and requires careful interpretation. Unlike vegetation loss, which can be directly attributed to drought stress, the decline in urban land area likely reflects a combination of factors including population movement, economic changes, and the impacts of drought on rural livelihoods. As agricultural productivity has declined due to water scarcity and soil salinization, farming communities have faced increasing difficulty in sustaining their livelihoods. Many households have responded by abandoning their lands and migrating to cities in search of alternative sources of income, a phenomenon known as reverse migration. This rural-to-urban movement would be expected to increase urban populations and expand urban areas, not decrease them. The observed decline in urban land area therefore suggests that the classification may be capturing not just built-up areas but also peri-urban vegetation and other surfaces associated with human settlements that have been affected by drought. Alternatively, it may reflect the abandonment of rural settlements as populations have moved away, with formerly inhabited areas reverting to bare land and being classified as such. This interpretation is consistent with reports of widespread rural depopulation in southern Iraq as communities have been displaced by drought and water scarcity.

The decline in water body area, while relatively small in percentage terms, is nonetheless significant given the already minimal extent of surface water in this arid region. The reduction in water bodies reflects the ongoing shrinkage of the marshlands in the northeastern part of the study area, a trend that has been documented by numerous studies and reports over recent decades. As inflows from the Tigris and Euphrates rivers have declined due to upstream dam construction and reduced precipitation, the marshes have progressively dried out, transforming from permanent wetlands to seasonal marshes or completely dry basins. This loss of wetland habitat has devastating consequences for the unique biodiversity of the Mesopotamian marshlands, including numerous species of fish, birds, and other wildlife that are adapted to these environments. It also undermines the traditional livelihoods of Marsh Arab communities who have depended on the marshes for fishing, water buffalo breeding, and rice cultivation for millennia.

3.3 Analysis of NDWI and Its Relationship to Drought

The Normalized Difference Water Index analysis provided complementary information on surface moisture conditions across the study area. NDWI values for the study area ranged from negative zero point five one to positive zero point one four, with the spatial distribution of these values shown in Figure 3. Areas with positive NDWI values, indicating the presence of surface water or high moisture content, were primarily concentrated in the northeastern part of the study area corresponding to the remaining marshland areas and along the main river channels. These positive NDWI areas represent the last refuges of surface water in an otherwise arid landscape and are critically important for maintaining wetland ecosystems, supporting irrigation, and providing water for domestic and livestock use.

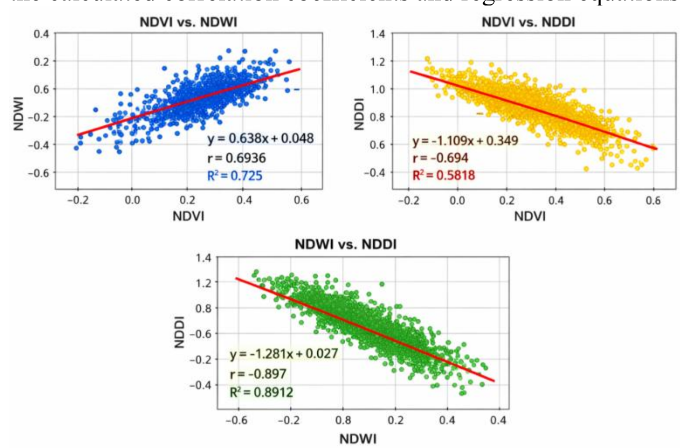


Areas with negative NDWI values, indicating surfaces with low moisture content, dominated the vast majority of the study area. The most negative values, approaching negative zero point five, were associated with bare desert soils with extremely low moisture content. Intermediate negative values characterized urban areas and areas with sparse vegetation, where some moisture is present but insufficient to produce positive NDWI signals. The spatial patterns of NDWI closely mirrored those of NDVI, with higher NDWI values generally corresponding to areas of healthier vegetation, reflecting the fundamental relationship between vegetation vigor and moisture availability.

Comparison of NDWI between 2019 and 2025 revealed a general decline in values across much of the study area, consistent with the intensifying drought conditions indicated by the land cover changes. Areas that showed positive NDWI values in 2019 often showed reduced values in 2025, indicating declining moisture levels, and in some cases, areas that were previously moist enough to register positive values in 2019 had become dry enough to register negative values by 2025. This decline in NDWI values provides quantitative confirmation of the progressive drying of the landscape that is evident from the land cover changes and from field observations of marshland shrinkage and agricultural decline.

3.4 Statistical Relationships among NDVI, NDWI, and NDDI

The statistical analysis conducted on six hundred sample points distributed across the study area revealed highly significant correlations among the three spectral indices, confirming their utility as integrated tools for drought assessment and providing quantitative insights into the relationships between vegetation condition, moisture availability, and drought severity. Figure 4 presents scatter plots illustrating these relationships along with the calculated correlation coefficients and regression equations.



The relationship between NDVI and NDWI showed a strong positive correlation, with a Pearson correlation coefficient of zero point six nine three six and an R-squared value of zero point seven two five. This strong positive relationship indicates that areas with healthier, denser vegetation tend to have higher moisture content, a finding that is intuitively obvious but nonetheless important to document quantitatively. The relationship is not perfect, however, as indicated by the R-squared value of zero point seven two five, meaning that approximately seventy-two percent of the variation in NDWI can be explained by its linear relationship with NDVI. The remaining variation reflects the influence of other factors, including differences in soil moisture not directly reflected in vegetation condition, the presence of open water surfaces that produce high NDWI values independently of vegetation, and differences in plant water use efficiency and drought tolerance among species.

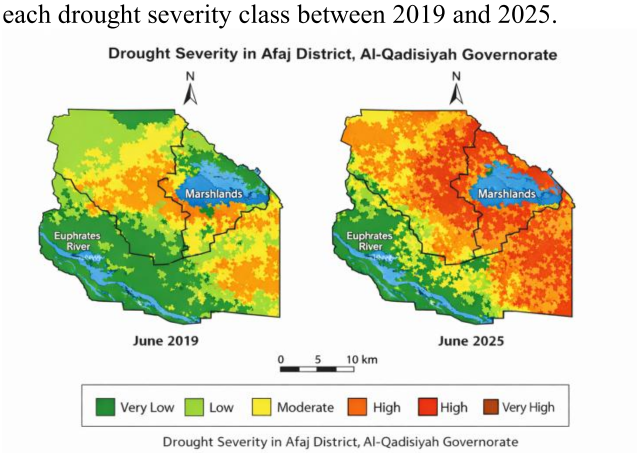
The relationships between NDDI and the two component indices were both strongly negative, as expected given the construction of NDDI as a ratio that increases when both NDVI and NDWI are low. The correlation between NDVI and NDDI was negative zero point six nine four, with an R-squared value of zero point five eight one eight, indicating that approximately fifty-eight percent of the variation in NDDI can be explained by its inverse relationship with NDVI. The correlation between NDWI and NDDI was even stronger, at negative zero point eight nine seven, with an R-squared value of zero point eight nine one two, indicating that nearly ninety percent of the variation in NDDI is explained by its inverse relationship with NDWI. This stronger correlation with NDWI suggests that

NDDI is particularly sensitive to variations in moisture availability, consistent with its design as a drought index.

These statistical relationships confirm that NDDI effectively integrates information from both NDVI and NDWI to provide a comprehensive measure of drought severity. When NDVI and NDWI are both low, indicating stressed vegetation and limited moisture, NDDI values are high, signaling drought conditions. When NDVI and NDWI are both high, indicating healthy vegetation with adequate moisture, NDDI values are low, indicating non-drought conditions. The strong correlations also validate the use of NDDI as a sensitive and reliable indicator for drought monitoring in this region, as it captures the combined effects of vegetation stress and moisture deficit that characterize drought conditions more effectively than either index alone.

3.5 Spatial and Temporal Patterns of Drought Severity Based on NDDI Analysis

The Normalized Difference Drought Index analysis provided the most comprehensive assessment of drought severity across the study area and enabled the classification of the landscape into five distinct drought severity classes: very low, low, moderate, high, and very high. Table 2 presents the classification thresholds for these classes, while Table 3 and Figures 5 and 6 present the quantitative changes in area for each drought severity class between 2019 and 2025.



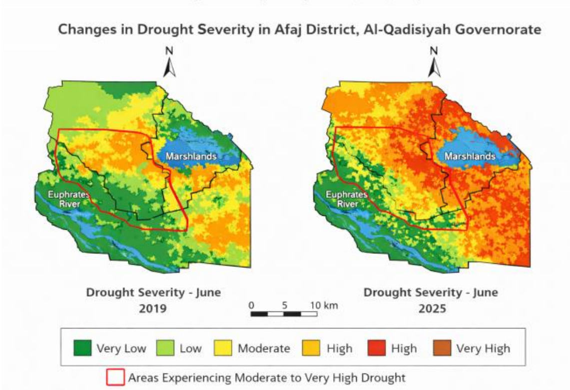
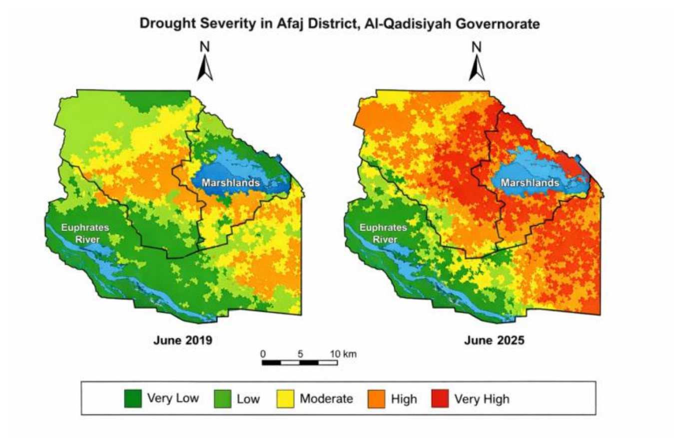


Table 2. Classification of Drought Severity Classes Based on NDDI Values

Drought Severity Class	NDDI Value Range
Very Low	< -0.5
Low	-0.5 to 0.0
Moderate	0.0 to 0.5
High	0.5 to 1.0
Very High	> 1.0

Table 3. Changes in Drought Severity Class Areas between 2019 and 2025

Drought Severity Class	Area 2019 (km²)	Area 2019 (%)	Area 2025 (km²)	Area 2025 (%)	Change (km²)	Change (%)
Very Low	465.77	11	411.65	10	-54.12	-1
Low	1734.41	41	648.42	16	-1085.99	-25
Moderate	1183.64	28	2509.79	60	+1326.15	+32
High	584.10	14	177.37	4	-406.73	-10
Very High	233.10	6	454.71	11	+221.61	+5
Total Area	**4201.96**	**100**	**4201.96**	**100**		



The spatial distribution of drought severity classes, as illustrated in Figure 1, shows a clear pattern with the highest drought severity classes concentrated in and around the marshland areas located in the northeastern part of the study area. This pattern reflects the particular vulnerability of these wetland areas to drought, as they depend on sustained inflows of freshwater from the river systems. When these inflows are reduced, whether due to upstream dam operations, reduced precipitation, or increased evaporation, the marshes rapidly dry out, converting from moist, vegetated wetlands to dry, salt-encrusted basins. The areas immediately surrounding the marshes also show elevated drought severity, as declining water tables and reduced soil moisture affect vegetation even outside the wetland areas proper.

The temporal comparison between 2019 and 2025 reveals a dramatic intensification of drought severity across the study area over this six-year period. In 2019, the largest proportion of the study area, forty-one percent, was classified as experiencing low drought severity, with moderate drought severity covering twenty-eight percent, high drought severity covering fourteen percent, and very high drought severity covering six percent. By 2025, this distribution had shifted dramatically, with moderate drought severity expanding to cover sixty percent of the study area, becoming the dominant class by a wide margin. The area classified as experiencing very high drought severity increased from six percent to eleven percent, while the areas experiencing low and high drought severity both declined substantially. Overall, the proportion of the study area experiencing moderate to high drought severity increased from forty-eight percent in 2019 to seventy-five percent in 2025, a dramatic increase that reflects the rapid pace of landscape drying.

The expansion of severely drought-affected land has direct and measurable impacts on land cover and land use, as documented in the NDVI analysis. The conversion of vegetated and urban land to bare land is the most visible manifestation of this drought intensification, but the impacts extend far beyond simple land cover change. The decline in agricultural productivity that accompanies increasing drought severity undermines rural livelihoods, reduces food security, and drives population displacement. The degradation of wetland ecosystems reduces biodiversity, diminishes ecosystem services, and destroys cultural heritage. The expansion of bare land increases the vulnerability of the landscape to wind erosion, generating dust storms that affect air quality and human health across large areas.

The intensification of drought severity documented in this study is consistent with the broader trends affecting southern Iraq and indeed the entire Middle East region. Climate change projections for this region consistently indicate increasing temperatures, decreasing precipitation, and greater variability in both, all of which contribute to increased drought risk. The water policies of upstream countries, particularly Turkey and Iran, have dramatically reduced the flows of the Tigris and Euphrates rivers, the lifeblood of Iraqi agriculture and ecosystems. Groundwater resources, already under stress from over-extraction, are being further depleted as surface water supplies dwindle. The combination of these factors creates a perfect storm of water scarcity that is transforming the landscape and challenging the resilience of human communities and ecosystems alike.

3.6 Interpretation and Implications of Findings

The results of this study have profound implications for understanding the dynamics of drought and land degradation in southern Iraq and for developing effective strategies to address these challenges. The dramatic expansion of bare land at the expense of vegetated and urban areas, coupled with the intensification of drought severity across the study area, provides quantitative evidence of the rapid pace of environmental change in this region. These changes are not subtle or gradual but are occurring on timescales of years to decades, with detectable and significant transformations evident even over the relatively short six-year period from 2019 to 2025.

The decline in agricultural land is particularly concerning given the fundamental importance of agriculture for local livelihoods and food security. Agriculture in this region has been practiced for millennia, sustained by the waters of the Tigris and Euphrates rivers and the ingenuity of farmers who developed sophisticated irrigation systems adapted to the arid environment. Today, that millennia-old agricultural tradition is under threat as water becomes increasingly scarce and soils become increasingly saline. The loss of agricultural land documented in this study represents not just an economic loss but a cultural and social loss, as farming communities that have inhabited these lands for generations are forced to abandon them in search of viable livelihoods elsewhere.

The expansion of bare land and the intensification of drought severity also have important implications for the regional and global climate. Bare, dry surfaces have higher albedo than vegetated surfaces, reflecting more solar radiation back to space, which can affect local and regional climate patterns. They also produce more dust when winds blow, contributing to the dust storms that have become increasingly frequent and severe in Iraq and neighboring countries. These dust storms have documented impacts on human health, contributing to respiratory illnesses and other health problems, as well as disrupting transportation, energy production, and other economic activities. The dust also carries nutrients that, when deposited in other areas, can affect ecosystem productivity, and when deposited on snow and ice in mountain regions, can accelerate melting by reducing surface albedo.

The loss of wetland habitats in the marshland areas has particularly severe consequences for biodiversity. The Mesopotamian marshlands are recognized as one of the most important wetland ecosystems in the Middle East, supporting numerous species of migratory birds, fish, and other wildlife. Many of these species are adapted specifically to these wetland environments and cannot survive elsewhere. As the marshes shrink and degrade, populations of these species decline, and some may face extinction. The loss of wetland habitat also affects the traditional Marsh Arab communities who have depended on the marshes for their livelihoods and cultural identity for millennia. These communities have already been devastated by the drainage of the marshes in the 1990s and the ongoing water scarcity of recent decades, and their continued survival as distinct cultural groups is increasingly uncertain.

The findings of this study also have important implications for drought monitoring and early warning systems. The strong correlations observed among NDVI, NDWI, and NDDI, and the sensitivity of these indices to drought conditions, confirm that satellite-based remote sensing can provide reliable, timely, and cost-effective information for tracking drought development and assessing its impacts. The ten-meter spatial resolution of Sentinel-2 data enables detection of drought effects at the field scale, providing information that can be used by farmers, water managers, and policymakers to target interventions to the most severely affected areas. The availability of free, open-access satellite data means that this monitoring capability can be implemented even in resource-constrained settings, without the need for expensive ground-based monitoring networks.

The results also highlight the need for urgent and comprehensive action to address the root causes of drought and water scarcity in Iraq. Climate change is a global problem that requires global solutions, but local and regional actions can also make a difference. Improved water management practices, including more efficient irrigation, water harvesting, and groundwater management, can help stretch limited water supplies further. Investments in drought-resistant crops and improved agricultural practices can help farmers cope with reduced water availability. Restoration of degraded lands through revegetation and soil conservation measures can help reverse the process of desertification and improve the resilience of ecosystems to drought. Regional cooperation on water resources management, including agreements on water sharing and joint management of transboundary river basins, is essential for ensuring that all riparian countries have access to the water they need for sustainable development.

4. CONCLUSIONS

This comprehensive study has demonstrated the power and utility of satellite-based remote sensing for monitoring and assessing agricultural drought in the arid environments of southern Iraq. Through the application of Sentinel-2 satellite data and three well-established spectral indices—the Normalized Difference Vegetation Index, the Normalized Difference Water Index, and the Normalized Difference Drought Index—the research has provided a detailed quantitative assessment of drought severity and its impacts on land cover and land use in the Afaj District of Al-Qadisiyah Governorate over the period from 2019 to 2025.

The results have revealed a landscape under severe and intensifying stress from drought and water scarcity. Over the six-year study period, bare land expanded by a staggering twenty-seven percent, coming to dominate an overwhelming sixty-three percent of the study area by 2025. This expansion of bare land occurred at the expense of virtually all other land cover classes, with moderate vegetation declining by three percent, weak vegetation declining by seven percent, urban land declining by sixteen percent, and water bodies declining by one percent. These changes reflect the cumulative impacts of reduced precipitation, increased temperatures, heightened evapotranspiration, and dramatically reduced inflows from the Tigris and Euphrates river systems due to upstream dam construction and water withdrawals.

The analysis of drought severity using the Normalized Difference Drought Index revealed a dramatic intensification of drought conditions over the study period. In 2019, forty-eight percent of the study area experienced moderate to high drought severity, but by 2025, this proportion had increased to seventy-five percent. The moderate drought severity class expanded from covering twenty-eight percent of the area in 2019 to sixty percent in 2025, while the very high drought severity class expanded from six percent to eleven percent. This intensification of drought severity is directly linked to the observed land cover changes, with the expansion of severely affected areas driving the conversion of vegetated and urban land to bare land.

The statistical analysis confirmed strong and significant correlations among the three spectral indices, validating their use as integrated tools for drought assessment. The strong positive correlation between NDVI and NDWI, with an R-squared value of zero point seven two five, confirms that areas with healthier vegetation tend to have higher moisture availability. The strong negative correlations between NDDI and both NDVI and NDWI, with R-squared values of zero point five eight one eight and zero point eight nine one two respectively, confirm that NDDI effectively captures the combined effects of vegetation stress and moisture deficit that characterize drought conditions. These statistical relationships provide quantitative confirmation of the utility of these indices for drought monitoring and assessment.

The decline in agricultural land documented in this study has profound implications for the livelihoods and food security of local communities. As water has become scarcer and soils have become more saline, agricultural productivity has declined, and farmers have been forced to abandon their lands. This loss of agricultural livelihoods has driven reverse migration from rural areas to cities, as displaced farmers seek alternative means of securing a livelihood. The social and economic consequences of this displacement are far-reaching, placing additional strain on already overburdened urban infrastructure and services, disrupting traditional communities and ways of life, and contributing to social and economic instability.

The degradation of wetland habitats in the marshland areas documented in this study has severe consequences for biodiversity and for the unique Marsh Arab communities that have depended on these wetlands for millennia. The Mesopotamian marshlands, once the largest wetland ecosystem in the Middle East, are shrinking rapidly as inflows decline, threatening numerous species of migratory birds, fish, and other wildlife that are adapted to these environments. The traditional livelihoods of Marsh Arab communities, including fishing, water buffalo breeding, and rice cultivation, are becoming increasingly untenable, and these communities face an uncertain future.

The findings of this study have important implications for policy and practice. They underscore the urgent need for comprehensive action to address the root causes of drought and water scarcity in Iraq, including improved water management practices, investments in drought-resistant agriculture, restoration of degraded lands, and regional cooperation on transboundary water resources. They demonstrate the value of satellite-based remote sensing for drought monitoring and early warning, providing a tool that can inform decision-making at multiple levels, from individual farmers to national policymakers. They highlight the importance of integrating scientific research with local knowledge and community engagement to develop effective and sustainable solutions to the challenges of drought and water scarcity.

The study also points to important directions for future research. Longer-term monitoring is needed to assess trends over decadal timescales and to distinguish short-term fluctuations from long-term directional change. Finer-resolution analysis could provide more detailed information about drought impacts at the field and farm scales, supporting more targeted interventions. Integration of satellite data with ground-based observations of soil moisture, crop yields, and socioeconomic conditions could provide a more complete picture of drought impacts and support more accurate forecasting and early warning. Assessment of the effectiveness of different adaptation strategies, including changes in crop varieties, irrigation techniques, and land management practices, could provide evidence-based guidance for farmers and policymakers seeking to enhance resilience to drought.

In conclusion, this study has provided compelling evidence of the severe and intensifying drought conditions affecting southern Iraq and of the profound impacts of these conditions on land cover, land use, and human communities. The findings underscore the urgent need for action to address water scarcity, to support affected communities, and to build resilience to drought in the face of ongoing climate change. They also demonstrate the power of satellite-based remote sensing as a tool for monitoring drought and informing decision-making, providing hope that with better information and more effective action, the challenges of drought and water scarcity can be met.

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