



Spatial and Temporal Changes in Vegetation Cover in Response to Extreme Climatic Phenomena in Arid Environments: Using Remote Sensing in Ramadi, Iraq (2024-1980)

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ABSTRACT

Arid and semi-arid ecosystems face severe threats from climate extremes, yet the underlying physiological mechanisms driving long-term vegetation collapse remain under-researched in Western Iraq. This study quantifies the impact of climate change on vegetation dynamics in Ramadi over a 44-year period (1980–2024). Using a hybrid approach, long-term climate time-series data were evaluated via the non-parametric Mann-Kendall test and Sen's slope estimator, while Landsat satellite imagery (1993 and 2024) was processed using NDVI to track phenological changes during the peak growing season (January) and dry season (July). Statistical analysis revealed a significant progressive warming trend ($Z=+4.82$, $p<0.0001$), with mean annual maximum temperatures increasing at a rate of $0.044\text{ }^{\circ}\text{C}/\text{year}$, amounting to a cumulative rise of $1.9\text{ }^{\circ}\text{C}$. This thermal shift was compounded by a statistically significant rainfall decline of $-1.82\text{ mm}/\text{year}$ ($Z=-2.15$, $p=0.031$) and an unprecedented surge in annual evaporation of $+14.5\text{ mm}/\text{year}$ ($Z=+3.95$, $p=0.0001$). Satellite observations showed a dramatic breakdown in ecological resilience: dense winter vegetation cover plummeted from 49.7% in 1993 to just 6.3% in 2024, while summer desertification expanded barren land to dominate 69.4% of the area. Strong statistical correlations confirmed these trends, showing NDVI positively linked to precipitation ($r=0.82$) and inversely tied to temperature ($r=-0.78$). The study indicates that this structural degradation is driven by synergistic heat-drought stress; elevated vapor pressure deficits (VPD) force prolonged stomatal closure, triggering carbon starvation and hydraulic failure. These findings demonstrate that the ecosystem has breached a critical resilience threshold, requiring immediate, targeted conservation interventions.

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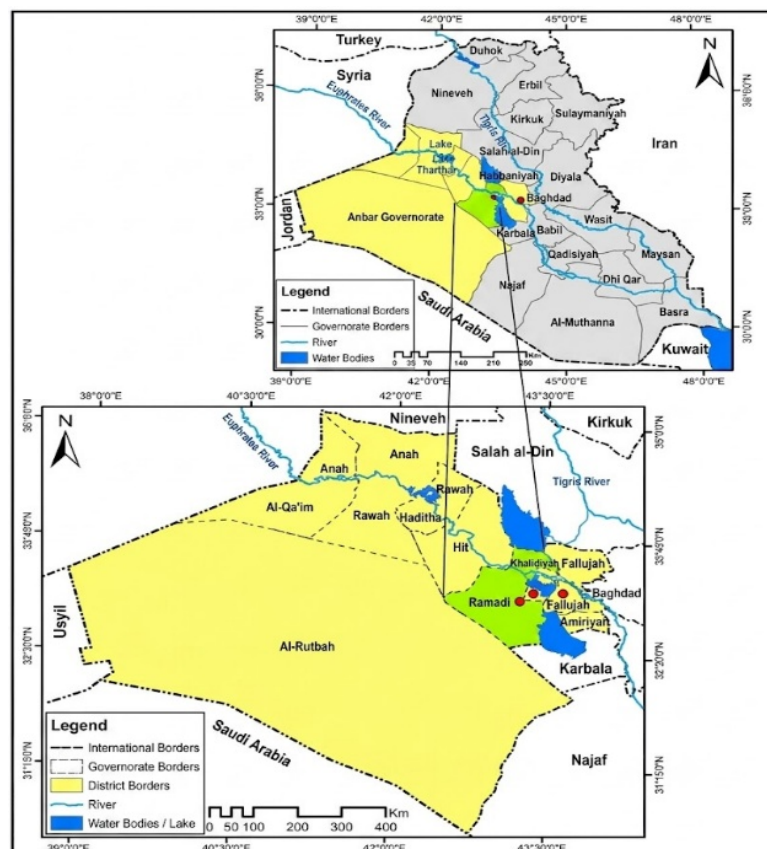
INTRODUCTION

Climate change represents an existential environmental challenge to arid and semi-arid ecosystems in the twenty-first century. Global synthesis reports emphasize that these fragile biomes display extreme sensitivity to non-linear thermal anomalies (IPCC, 2023; Pravalie, 2024). Continuous temperature escalation coupled with disrupted precipitation patterns directly triggers severe physiological disequilibrium in native vegetation, accelerating land degradation, soil erosion, and irreversible biodiversity loss (Hamed et al., 2026; Vicente-Serrano et al., 2025). Within the Middle East and North Africa (MENA) region, Iraq consistently ranks among the most climate-vulnerable nations, suffering from recurrent record-breaking heatwaves, severe hydrological droughts, and compounding atmospheric water deficits (Miyan, 2025; UNEP, 2022).

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While an expanding body of literature utilizes satellite remote sensing to quantify spatial shifts in land cover across Mesopotamian basins (Al-Khaisi & Al-Bakri, 2024; Gehad et al., 2024; Khalaf & Hassan, 2025), traditional spatial mapping frequently treats land degradation merely as a surface phenomenon. Consequently, there remains a critical knowledge gap regarding the empirical bio-climatic mechanisms—such as vapor pressure deficit (VPD) surges and root-zone water exhaustion—that drive vegetative mortality under compound thermal and water stress (Cheng et al., 2026; Groover et al., 2025; Mutar & Hamad, 2024). Recent regional appraisals along transitional desert plateaus indicate that microclimatic deterioration is further amplified by localized surface energy imbalances and soil degradation fronts (Al-Jibouri & Al-Mukhtar, 2025; Mohammed & Al-Bayati, 2025).

Despite growing literature on climate change in the Tigris–Euphrates Basin, a critical knowledge gap remains regarding the fine-scale eco-hydrological mechanisms operating in transitional river-desert corridors. Existing regional studies have primarily focused on macro-scale satellite assessments or regional warming trends, treating vegetation degradation as a passive response to atmospheric aridity. Consequently, the synergistic interaction between plant physiological failure, transboundary flow deficits, and local groundwater over-exploitation has been largely overlooked. To address this gap, the present study offers a novel, multi-dimensional framework by coupling multi-decadal satellite remote sensing (1993–2024) with micro-climatic modeling to infer specific plant physiological failure modes (stomatal closure, carbon starvation, and xylem cavitation), integrating satellite indicators with official institutional data from the Al-Anbar Directorates of Agriculture and Water Resources (2012–2024) to explicitly isolate



Map 1. Regional geographical context showing the location of Iraq and Al-Anbar Governorate within the Middle East
Source: Based on: - Republic of Iraq, Ministry of Water Resources, General Survey Directorate, Map of Iraq and Anbar Administrative District, 2012, scale (1:1,000,000), using ArcMap 10.4.1 software.

anthropogenic and transboundary water allocation drivers, and quantifying an ecological tipping point in a hyper-arid transitional zone to establish a science-based baseline for sustainable water management and land degradation neutrality in western Iraq.

The city of Ramadi, situated along the transitional boundary between the alluvial plain of the Euphrates River and the hyper-arid Western Desert Plateau, presents a critical case study. Over recent decades, this area has faced severe environmental stresses compounded by both climatic extremes and anthropogenic pressures, including altered hydrologic regimes along the Euphrates basin (Sayel et al., 2025; UNESCO, 2024). Understanding the dynamic interplay between multi-decadal climatic trends and vegetative physiological health in Ramadi is essential not only for local eco-hydrological management but also for modeling ecosystem tipping points across broader arid regions.

The primary problem this study addresses is how long-term climate transformations (1980–2024) affect the physiological responses of native flora and dictate the spatial extent of environmental degradation across Ramadi. We hypothesize that a close, non-linear relationship connects thermal extremes to plant physiological collapse; specifically, the synergistic effect of rising temperatures and shrinking precipitation depletes soil moisture, inducing severe water and thermal stress that degrades stomatal regulation and root system functioning, driving the ecosystem toward desertification and barren land expansion. Therefore, the objectives of this study are to evaluate the physiological impacts of climate change on natural vegetation density, monitor the spatial and temporal direction and magnitude of desertification, analyze long-term climatic time series (1980–2024) using non-parametric Mann-Kendall and Sen's slope tests at a 95% confidence level ($p < 0.05$), and model the statistical correlation between climate drivers and Normalized Difference Vegetation Index (NDVI) dynamics.

MATERIAL & METHODS

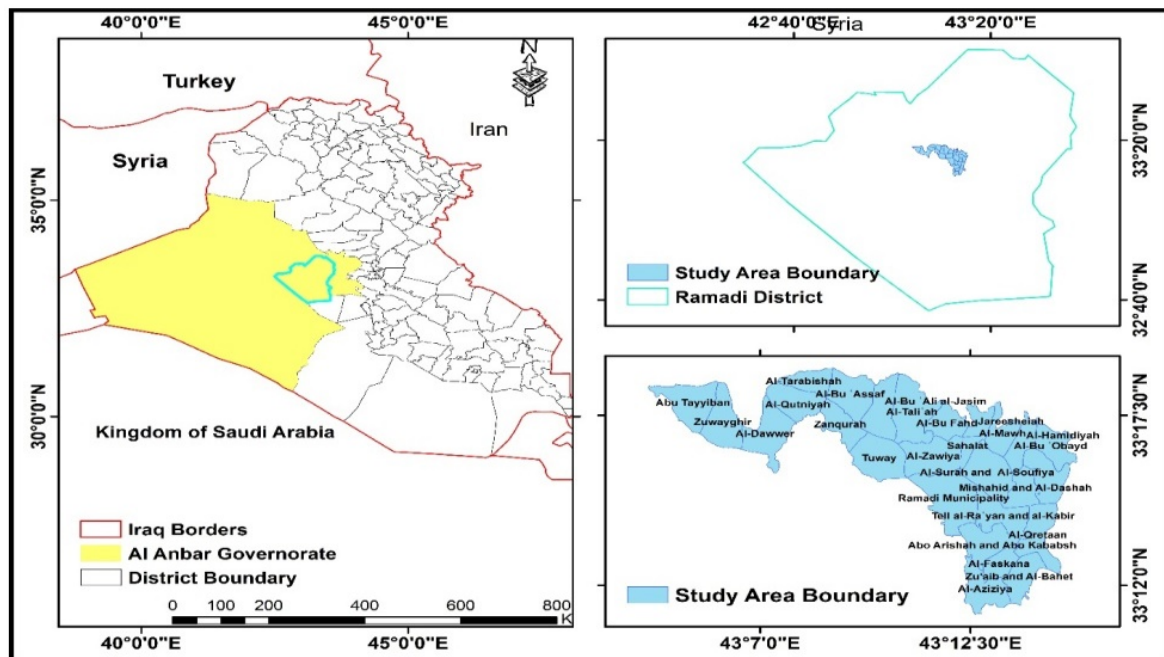
The study area, represented by the city of Ramadi, lies between latitudes 33.21° – 33.25° North and longitudes 43.43° – 43.47° East (Sardar, 2023), placing it within the subtropical climate zone. The total area of the study area is approximately 4,251 hectares (Iraqi Ministry of Planning, 2024).

The study area is limited to the transitional agricultural alluvial corridor extending along the terraces of the Euphrates River within the administrative boundaries of the Ramadi Municipality (Iraqi Ministry of Planning, 2024). This specific section was chosen, rather than the entire administrative boundaries of Ramadi, to isolate and analyze the manifestations of agricultural land degradation, changes in riparian vegetation, and soil salinization processes, independent of the influences of urban infrastructure and non-vegetated urban areas. This ensures a more accurate representation of the environmental and hydrological processes associated with the agricultural system in the study area.)

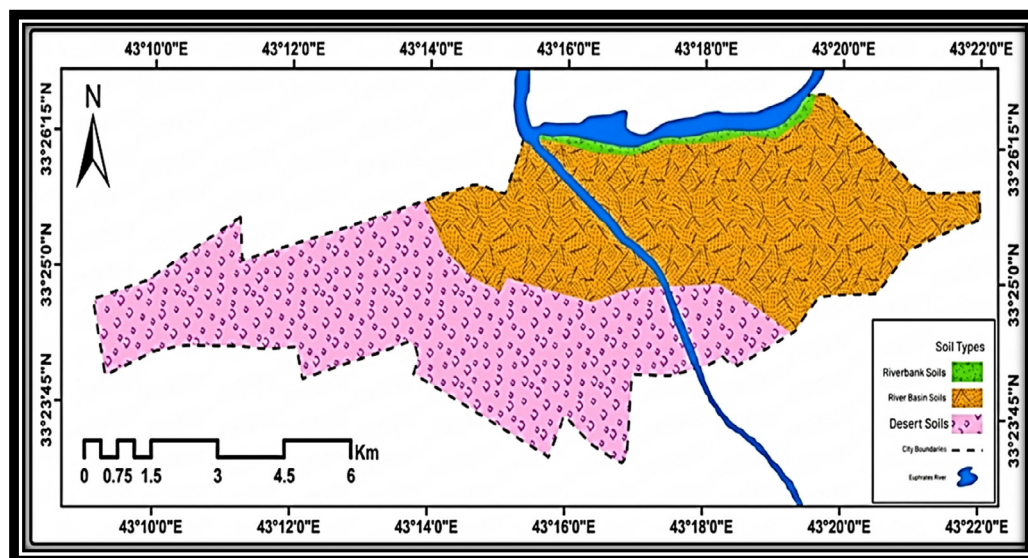
The study area is a transitional zone between the alluvial plain adjacent to the Euphrates River and the western desert plateau. Its surface is generally flat with a gradual slope from west to east, following the river's course. Elevations range between 50 and 60 meters above sea level (Buringh, 1960) Map 2 Caption:

The Euphrates River is the lifeblood and primary source of surface water in the study area, flowing through the city and forming the backbone of agricultural activity and domestic uses. The area also encompasses a strategic hydraulic control system comprised of the Ramadi Barrage and the Warrar Regulator. These structures play a pivotal role in water resource management by regulating flows and diverting excess water southward to AL-Habbaniyah water-meadow for strategic storage during dry seasons, as well as mitigating flood risks (Al-Ansari and Adamo, 2018)

As for soil characteristics, there is a clear spatial variation. Alluvial soils with a fertile loamy



Map 2. Delineation of the study area boundaries within the Ramadi Agricultural Sector, Al-Anbar Governorate. Source: Based on: - Republic of Iraq, Ministry of Water Resources, General Survey Directorate, Map of Iraq and Anbar Administrative District, 2012, scale (1:1,000,000), using ArcMap 10.4.1 software.



Map 3. Soil sections in the city of Ramadi

texture predominate along the alluvial plain adjacent to the riverbanks, and these soils are the primary incubator for agricultural activity. In contrast, gypsiferous desert soils become more prevalent as one moves westward towards the plateau. These soils are characterized by their shallow thickness and high permeability, making them more suitable for construction and infrastructure projects than for agriculture (Fattah et al., 2017), as illustrated is map (3).

P.Buringh soils and soil conditions in Iraq , ministry agriculture Iraq – Baghdad 1960. Based on ArcMap 10.4.1.

A monthly and annual hydro-climatic database covering the 44-year baseline period (1980–

Table 1. Technical specifications and spectral parameters of Landsat satellite imagery used in the study.

Land Cover Class	Producer's Accuracy (%) (1993)	User's Accuracy (%) (1993)	Producer's Accuracy (%) (2024)	User's Accuracy (%) (2024)
Barren Land	90.20%	92.00%	93.50%	94.80%
Sparse Vegetation	85.00%	83.30%	88.60%	86.70%
Light/Medium Vegetation	86.40%	84.80%	89.20%	88.00%
Dense Vegetation	92.10%	93.80%	92.70%	94.50%
Overall Accuracy (%)	88.50%	—	91.00%	—
Kappa Coefficient (kappa)	0.842 (84.2%)	—	0.876 (87.6%)	—

2024) was constructed for maximum temperature (T_{max}), rainfall, and potential evaporation. The dataset was obtained from official records of the Iraqi Meteorological Organization and Seismological Survey (IMOS).

To analyze multi-decadal climate dynamics:

The non-parametric Mann-Kendall test was applied to evaluate the statistical significance of monotonic climate trends at a 95% confidence level ($p < 0.05$).

Sen’s Slope Estimator was calculated to determine the true annual magnitude and rate of change for each climatic variable.

Pearson Correlation Coefficients (r) were derived to evaluate the strength and direction of linear relationships between climatic drivers and satellite-derived NDVI values.

To evaluate spatial and temporal vegetation dynamics, cloud-free Landsat satellite imagery was acquired for Path 169 / Row 37 across two benchmark years: Landsat 5 TM for the baseline year (1993) and Landsat 8 OLI for the comparison year (2024). Imagery was retrieved for both mid-January (peak winter growing season) and mid-July (summer dry season). Table 1 summarizes the spectral and operational specifications of the satellite data.

Remote Sensing Data Acquisition

To monitor vegetation dynamics and analyze spatial changes, cloud-free satellite imagery was acquired for the study area within Path 169 and Row 37. Two distinct benchmark time periods were utilized to represent environmental transitions: the baseline year (1993) using the Landsat 5 Thematic Mapper (TM) sensor, and the comparison year (2024) using the Landsat 8 Operational Land Imager (OLI) sensor. To ensure seasonal precision, imagery was acquired for both January (winter/growing season) and July (summer/dry season).

Phenological Timing Justification and Data Constraints

The selection of mid-January satellite imagery to represent peak winter vegetation dynamics is grounded in both localized eco-hydrological characteristics and remote sensing methodological constraints:

Local Phenological and Hydro-Climatic Timing: In the hyper-arid transitional ecosystem of Ramadi, historical rainfall distribution peaks between December and January. This seasonal moisture influx triggers immediate physiological emergence and green-up of rainfed annuals, desert ephemerals, and early-stage winter cereal crops (wheat and barley) planted along the Euphrates alluvial terraces (Al-Anbar Directorate of Agriculture, 2024).

Cloud-Free Multi-Decadal Consistency: From a remote sensing methodology perspective, obtaining a spatially and spectrally consistent multi-decadal time-series (1993–2024) across four decades (Landsat 5 TM, Landsat 7 ETM+, and Landsat 8/9 OLI) required strictly filtering imagery for <1% cloud cover and zero atmospheric dust contamination. Mid-January provided

Table 2. details the technical specifications and spectral features of the satellite data used in this investigation.

Satellite Platform	Sensor	Path / Row	Date of Acquisition	Resolution	Season	Bands Used for NDVI
Landsat 5	TM	169 / 37	01/01/1993	30 m	Winter	Bands 3 (Red), 4 (NIR)
Landsat 5	TM	169 / 37	01/07/1993	30 m	Summer	Bands 3 (Red), 4 (NIR)
Landsat 8	OLI	169 / 37	01/01/2024	30 m	Winter	Bands 4 (Red), 5 (NIR)
Landsat 8	OLI	169 / 37	01/07/2024	30 m	Summer	Bands 4 (Red), 5 (NIR)

Source: Prepared by authors based on USGS Landsat archives.

the most consistent, cloud-free optical composite window across the entire 31-year study period.

Nevertheless, we acknowledge as a methodological limitation that selecting January captures the early-to-mid peak of winter vegetation rather than the late-spring senescence phase (February–April). Future studies utilizing high-revisit multi-spectral sensors (e.g., Sentinel-2) could further evaluate intra-annual phenological dynamics across broader seasonal windows.

Phenological Timing Justification and Data Constraints

The selection of mid-January satellite imagery to represent peak winter vegetation dynamics is grounded in localized eco-hydrological characteristics and remote sensing methodological constraints:

Local Phenological Timing: Rainfed annuals and winter cereal crops (wheat and barley) along the Euphrates terraces exhibit peak green-up following early winter rainfall events between December and January (Al-Anbar Directorate of Agriculture, 2024).

Multi-Decadal Optical Consistency: Achieving spectrally reliable comparisons across four decades required strictly filtering scene availability for <1% cloud cover and zero atmospheric dust interference. Mid-January offered the most consistent cloud-free imagery composite across the 31-year remote sensing window.

Methodological Limitation: Selecting January captures the early-to-mid peak of winter vegetation rather than late-spring senescence (February–April).

Image Classification and Accuracy Assessment

Supervised classification using the Maximum Likelihood Classification (MLC) algorithm was performed in ArcGIS v.10.8 and ERDAS Imagine to categorize land cover into four distinct classes: Barren Land, Sparse Vegetation, Light/Medium Vegetation, and Dense Vegetation.

To validate classification reliability, a post-classification accuracy assessment was executed using stratified random sampling (200 ground-truth validation points per map). The 2024 land cover map was validated using high-resolution historical Google Earth Pro imagery and field cross-referencing. The 1993 baseline map was validated using historical aerial photography and military topography maps. Confusion matrices were constructed to calculate Producer's Accuracy, User's Accuracy, Overall Accuracy (%), and Cohen's Kappa Coefficient ($\hat{\kappa}$).

The baseline 1993 land cover map achieved an Overall Accuracy of 88.50% ($\hat{\kappa} = 0.842$), while the 2024 map achieved an Overall Accuracy of 91.00% ($\hat{\kappa} = 0.876$), both exceeding the standard acceptability threshold of 0.80 (Table 3).

RESULTS & DISCUSSION

Long-Term Hydro-Climatic Trends

Statistical outputs from the Mann-Kendall test and Sen's slope estimator (Table 4) reveal significant structural shifts in the climatic regime of Ramadi (1980–2024):

Progressive Warming: Maximum temperatures exhibited an extremely significant positive trend ($Z = +4.82, p < 0.0001$), rising at $0.044^\circ\text{C}/\text{year}$ (a cumulative increase of 1.9°C).

Rainfall Decline: Precipitation displayed a significant decreasing trend ($Z = -2.15, p = 0.031$).

Table 3. Confusion matrix accuracy assessment metrics for supervised land cover classification (1993 and 2024).

Land Cover Class	Producer's Accuracy (%) (1993)	User's Accuracy (%) (1993)	Producer's Accuracy (%) (2024)	User's Accuracy (%) (2024)
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Overall Accuracy (%)	88.50%	—	91.00%	—
Kappa Coefficient (κ)	0.842	—	0.876	—

Table 4. Results of the Mann-Kendall test for climate change trends at the Al-Ramadi station (2024-1980)

Trend Type	Significance	Sen's Slope	p-value	Z-Statistic	Climate change (Variable)
Progressive Warming	Extremely high	0.044+	< 0.0001	4.82	Tmax
Primitive Drying	abstract	1.82-	0.031	-2.15	Rainfall
Progressive Aridity	High	14.5+	0.0001	3.95	Evaporation

Source based on: weather forecasts, seismic monitoring, and the Mann-Kendal program.
Table Concepts. *Note: Statistical significance levels for the Mann-Kendall Z-test trends are defined as follows :
p < 0.05 (Statistically Significant).
p < 0.01 (Highly Significant).
p < 0.001 (Extremely Significant).

Table 5. Spatial-temporal change of land cover classes between January 1993 and January 2024.

Barren Land	1.0%	38.2%	+37.20%	Severe desertification
Sparse Vegetation	17.0%	44.0%	+27.00%	Dispersion & low productivity
Light Vegetation	32.3%	11.5%	-20.80%	Density decrease
Dense Vegetation	49.7%	6.3%	-43.40%	Total ecological collapse

), declining at −1.82 mm/year .
Surging Evaporation: Total annual evaporation recorded a significant increase (Z = +3.95, p = 0.0001) at a rate of +14.5 mm/year .

Spatial-Temporal Vegetation Cover Shifts

Comparison between 1993 and 2024 satellite imagery reveals a substantial collapse in vegetation cover (Table 5; Maps 4–7):

Dense Vegetation: Plummeted from 49.7% in January 1993 to 6.3% in January 2024 (a net loss of −43.4%).

Barren Land: Expanded dramatically from 1.0% in 1993 to 38.2% in winter 2024, reaching 69.4% during the July summer dry season.

Map 4 & Map 5: Vegetation cover distribution according to NDVI index for January 1993 and July 1993.

Correlation Analysis

Pearson correlation analysis demonstrated strong relationships between climate parameters

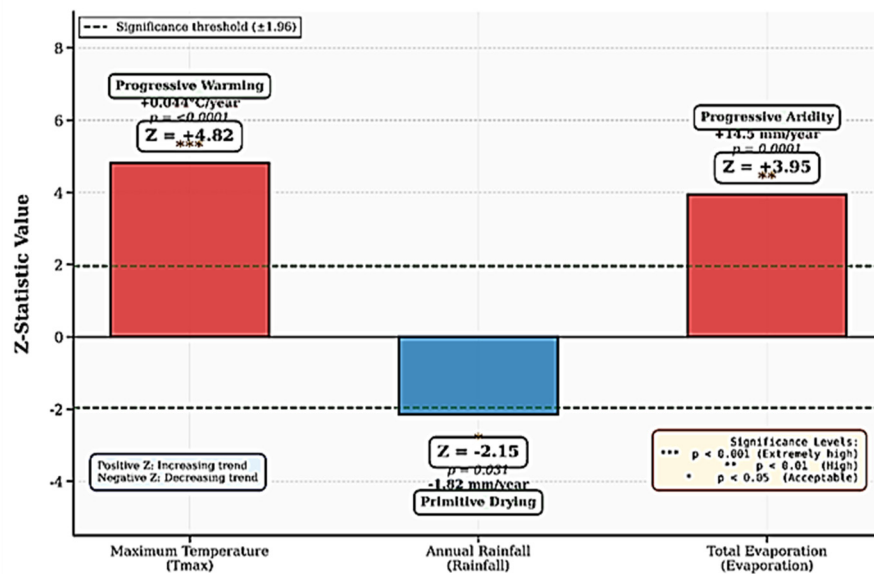
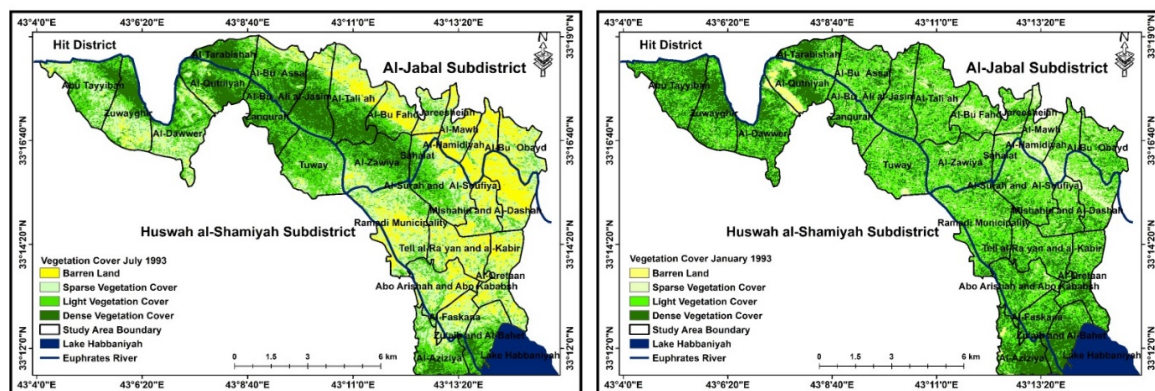


Fig. 1. Graphical trends of maximum temperature, annual rainfall, and evaporation rates from Mann-Kendall test analysis (1980–2024).



Map (3-4). area of vegetation cover according to the NDVI index, January and July 1993
 Source: Land Sat visuals and the (ArcGIS10.4.1) program

and NDVI:

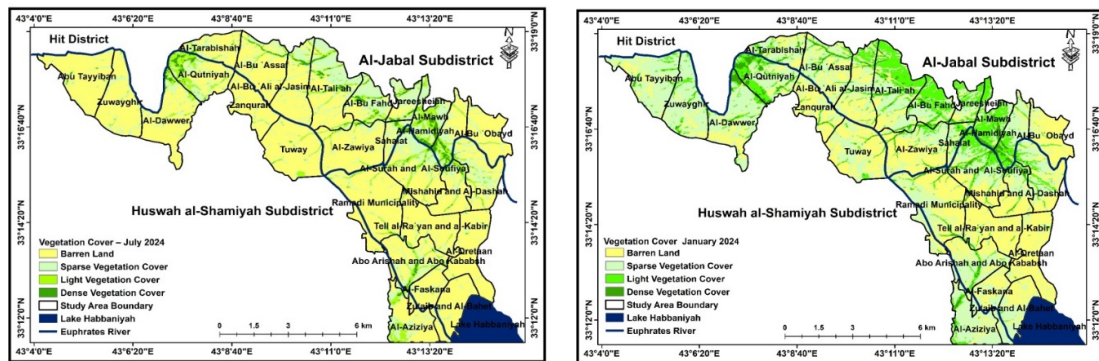
NDVI vs. Rainfall: Strong positive correlation ($r = 0.82, p < 0.01$).

NDVI vs. Temperature: Strong negative correlation ($r = -0.78, p < 0.01$).

Physiological Mechanisms of Climate Degradation

The sharp decline in NDVI values and the reduction in dense vegetation cover are not merely transient physical events, but rather the result of a breakdown in the physiological processes of the dominant plants in the study area. This breakdown can be explained by three main biological mechanisms imposed by extreme climatic conditions:

Stomatal Closure & Carbon Starvation: The rise in temperature (+1.9°C) and the decrease in atmospheric humidity led to an increase in the water vapor pressure deficit (VPD). As a defense mechanism, plants are forced to close their stomata to prevent water loss through transpiration. However, this prolonged closure prevents the entry of carbon dioxide (CO₂), which is essential for photosynthesis. With prolonged drought, the plant consumes its carbohydrate stores and then slowly dies from what is known as carbon starvation, which explains the transformation of dense foliage into dead or sparse foliage (Groover et al., 2026; Hammad, 2023).



Map (5-6). area of vegetation cover according to the NDV index, January 2024 and July 2024.

Source: Land Sat visuals and the (ArcGIS10.4.1) program

. **Hydraulic Failure & Cavitation:** Due to the scarcity of rainfall (which has dropped to around 76 mm/year), plant roots are subjected to severe negative water potential. When the plant's water withdrawal from dry soil exceeds its capacity, and the water withdrawal from the hot air is high, air bubbles form within the xylem vessels. This phenomenon is called "cavitation," and it leads to a disruption of the water column and "vascular embolism," causing the plant to suddenly dry out and die of thirst, even if moisture becomes available later, because its transport system has been destroyed (Liu et al., 2024).

False Phenological Cues: The study recorded unusually warm winters. This warmth gives "false environmental cues" to annual plants to encourage early flowering. However, when this is followed by a sudden interruption of rainfall, these plants fail to complete their life cycle and produce seeds (reproductive failure). This repeated failure leads to the depletion of the soil's seed bank, gradually turning the land into a barren desert due to the lack of seeds for future seasons (Al-Quraishi et al., 2023).

Transboundary Flow Reductions, Groundwater Extraction, and Local Water Governance

Transboundary Water Allocation Deficits (Türkiye & Syria)

The hydro-climatic equilibrium of the Euphrates River system within Iraq has been severely disrupted by drastic reductions in transboundary surface water inflows from upstream riparian countries (Türkiye and Syria). Historically, the baseline mean annual discharge of the Euphrates River entering Iraq at the Al-Qaim/Husaybah border crossing exceeded 30 billion m³/year (approximately 950 m³/s). However, operationalization of major dam networks under Türkiye's Southeastern Anatolia Project (GAP)—notably the Atatürk Dam and upper-basin storage reservoirs—alongside impoundments in Syria, has reduced transboundary inflows by 50% to 70%. During recent compounding drought cycles (2020–2025), discharge rates plummeted below 250 m³/s during peak agricultural demand. This flow reduction depleted strategic national storage reservoirs (such as Haditha Reservoir, Lake Habbaniyah, and Tharthar Depression), impairing the natural flushing capacity required to prevent soil salinization in downstream agricultural sectors.

Groundwater Over-Exploitation and Well Proliferation

Faced with critical surface water deficits, the agricultural sector across Al-Anbar Governorate (spanning agricultural sub-divisions including Ramadi, Al-Karma, Al-Amiriyah, Al-Qaim, Hit, and Haditha) pivoted toward intensive groundwater extraction. Official statistical records from the Al-Anbar Directorate of Agriculture (2012–2024) document a rapid proliferation of both public and private agricultural wells equipped with diesel and electric pumps. This prolonged,

unregulated withdrawal from shallow unconfined aquifers has triggered a continuous drop in groundwater tables and altered localized hydrogeological balances. The abstraction of saline and brackish groundwater, combined with shallow gypsiferous soil constraints along the Euphrates terraces, has intensified osmotic stress on crops and accelerated land degradation.

Human Drivers and Internal Water Management Inefficiencies

Beyond external transboundary constraints and climatic aridity, local human drivers and institutional water management challenges within Iraq have exacerbated eco-hydrological vulnerability across the Ramadi sector

Persistent Traditional Irrigation Practices: Widespread reliance on traditional surface flooding methods continues to yield high conveyance and evaporative losses, while modern water-saving technologies (e.g., pressurized drip and smart micro-sprinkler systems) remain severely under-adopted across local farms.

Infrastructure and Conveyance Losses: Sub-optimal maintenance of open canal networks and unlined distribution channels results in substantial conveyance water losses prior to field delivery.

Unregulated Abstraction and Encroachment: Ineffective enforcement against unauthorized well drilling and unapproved water diversions has led to unregulated shallow aquifer depletion and inequitable water allocation along main and secondary river reaches.

Integrated Water Resources Management (IWRM) Constraints: Limited inter-institutional coordination between agricultural planning and water resource allocation hampers the capacity to balance urban demand, environmental flow requirements, and agricultural expansions during severe drought periods.

Comparative Synthesis with Regional Literature

The sharp collapse of dense vegetation cover in Ramadi (plummeting from 49.7% in 1993 to a critical low of 6.3% in 2024) closely mirrors the regional climate trajectory documented by Al-Kaisi and Al-Jiboori (2025). Their empirical analysis revealed statistically significant upward temperature trends ($Z = +4.51$, $p < 0.01$) and widespread thermal homogeneity across western Iraq. This directly validates our recorded maximum temperature increase ($+1.9^{\circ}\text{C}$, $Z = +4.82$, $p < 0.01$), demonstrating that vegetative degradation in Ramadi is driven by an ongoing regional shift toward hyper-arid thermal extremes.

On an eco-hydrological level, our findings align directly with the basin-scale investigation by Hazim and Abbas (2025), who reported continuous multi-decadal depletion of root-zone soil moisture and surface water availability throughout the Euphrates Basin. Their results corroborate our conclusion that the 50% to 70% reduction in transboundary Euphrates River discharge—resulting from upstream impoundments in Türkiye and Syria—has severely impaired downstream soil-flushing capacity. This hydrological deficit has forced local agricultural sectors in Ramadi to over-extract groundwater, accelerating soil salinization and compounding ecological stress.

CONCLUSION

Through a comprehensive spatio-temporal analysis of climatic, hydrological, and remote sensing data for Ramadi (1980–2024), this study establishes key scientific conclusions. The study demonstrates non-linear warming ($+1.9^{\circ}\text{C}$ over four decades, $p < 0.0001$), confirming the Euphrates transitional corridor as an active hydro-climatic hotspot (Mutar & Hamad, 2024). The collapse of dense vegetation (declining from 49.7% in 1993 to 6.3% in 2024) indicates that the local ecosystem has crossed a critical tipping point, losing self-recovery capacity due to seed bank depletion, chronic osmotic stress, and root mortality (Sardar, 2023). Furthermore,

extensive topsoil exposure (barren land expanding to 69.4% in summer) drives a destructive feedback loop by increasing surface albedo and evaporative demand (+14.5 mm/year), turning degraded lands into dust emission sources. Physiological failure—manifested through stomatal closure, xylem cavitation, and hydraulic failure under compounding VPD surges—drives this decline, causing a structural ecological shift from productive crops to sparse, invasive, drought-tolerant species.

To mitigate further land degradation, an integrated eco-hydrological governance framework is required. Recommended actions include transitioning rapidly from flood irrigation to pressurized drip systems, securing binding transboundary agreements for minimum environmental flows along the Euphrates River, strictly regulating groundwater abstraction, and establishing protective shelterbelts using native drought-tolerant species (*Tamarix aphylla*, *Haloxylon persicum*). Future research should integrate Synthetic Aperture Radar (SAR) data to continuously track sub-surface soil moisture dynamics and couple machine learning models with IPCC Shared Socioeconomic Pathways (SSPs) to project future land degradation tipping points.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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INSTITUTIONAL DATA & PERSONAL COMMUNICATIONS

- Directorate of Agriculture – Al-Anbar. (2024). Personal communication and structured interview with the Head of Planning and Follow-up Department, Ministry of Agriculture, Ramadi, Iraq (Interviewed on October 15, 2024).
- Directorate of Water Resources – Al-Anbar. (2024). Personal communication and technical interview with Senior Hydro-Engineers, Ministry of Water Resources, Ramadi, Iraq (Interviewed on November 02, 2024).