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Assessing the Impact of Climate Change Using the Modified Normalized Difference Vegetation and Water Index in the Eastern Euphrates Wetlands: Evidence from Hoor Al-Huwaizah, Iraq

Narmean Ali Kadhum [1*], Alaa Salih Ati [2]

[1*] College of Agricultural Engineering Sciences, University of Baghdad, Iraq.
E-mail: neriman.ali2207p@coagri.uobaghdad.edu.iq

[2] College of Agricultural Engineering Sciences, University of Baghdad, Iraq.
E-mail: alaa.salih@coagri.uobaghdad.edu.iq

Abstract

Using Soil-Adjusted Vegetation Index (SAVI) and Modified Normalized Difference Water Index (MNDWI) from Landsat 7 and 8, this research examines the effects of climate change on vegetation and water in the Eastern Euphrates Project in the Hoor Al-Huwaizah wetlands and southern Iraq from 2002 to 2025 within a GIS environment. Preliminary findings suggest significant 2002-2025 changes, predominantly the increased diversity (spreading from a weak 96.3% cover) of the vegetation to a more balanced distribution of moderate and dense growth cover, indicative of the first stages of ecological recovery, probably resultant from regional climate changes and anthropogenic alterations of land cover near the wetlands. MNDWI also displayed a further positive trend of surface water availability recovery over time from 0.45% (2002) to 39.7% (2025) and despite the recovery of water surface within the wetlands, increasing unpredictability levels of dynamic/extreme climate change on near real time hydrology (i.e. >7 day to seasonal range uncertainty) and/or temperature (related wicked problems) dramatically increases the vulnerability of the region. Further research should focus on the need for effective adaptive frameworks to support wetland ecosystem stability. This study highlights the necessity of holistic ecological observations, based on methods such as the use of SAVI and MNDWI remote sensing indices, which are fundamental for the formulation of rationally founded climate change adaptation policy and the establishment of sustainable land and water management in semiarid regions.

Keywords:

Climate change, remote sensing, SAVI, MNDWI, surface water dynamics, vegetation recovery, wetland rehabilitation, sustainable water management.

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Corresponding Author: Narmean Ali Kadhum, E-mail: neriman.ali2207p@coagri.uobaghdad.edu.iq

Introduction

Climate change is the long-term change in temperature and precipitation, and its variance in weather patterns, caused by natural and anthropogenic influences (IPCC, 2021). The anthropogenic emissions of greenhouse gases worsen global warming, and since the beginning of industrialization, the Earth's average temperature has increased by 1.0 °C, with a predicted increase of 1.5 °C by 2030-2052 (Fawzy et al., 2020; Hans-Otto et al., 2021; Sharipov et al., 2024). Changes that occur in addition to an increase in global mean temperature include disruptions in atmospheric and oceanic circulation, increased temperatures and humidity, and changes in rainfall and global evaporation rates (Ibraheem, 2022). The most severe impacts occur in the already arid and semiarid regions with fragile ecosystems, limited water resources, and low adaptive capacity (Piranj et al., 2024; Ayada et al., 2024; Alwazzan & Ati, 2024; AlWazzan & Atti, 2022; Shah & Bansalm, 2023). Southern Iraq, lying in the lower Mesopotamian plain, is among the most climate-sensitive areas in the Middle East (Al-Majdi et al., 2025).

Covering an area of around 35,000 km², the marshes, including the Hoor Al-Huwaizah wetlands, act as an essential ecological buffer, provide habitat diversity, store water, and regulate microclimate (Al-Hilli, 1977). However, over decades of anthropogenic drainage, recurring droughts, and temperature increases, there have been changes in bogs (veg + water systems). The Eastern Euphrates Project, a constituent of the Hoor Al-Huwaizah complex, has experienced changes in soil moisture and water productivity. In contrast, climate change has had a significant, indirect impact due to poor water allocation (Khasi et al., 2024). These shifts need to be understood to craft an adaptive management and restoration plan for climate change. This study analyzes spatio-temporal changes in climate on the Vegetation and water systems of the Eastern Euphrates Project using satellite-based climatic indices (Suresh Kumar & Rajan, 2025). The soil-adjusted Vegetation Index (SAVI) and the 'water changed' (MNDWI) for the years 2002 to 2025. The objectives of the study are (1) the identification of shifts of the focus climate parameters (precip, temp, moisture), (2) vegetation and surface water, and (3) sustained land and water use management. This work provides scientific evidence of climate-driven transformations in southern Iraq by integrating remote sensing and GIS tools (Kulkarni & Jain, 2023). There is a nexus of scientific evidence on regional adaptations and insights from policy developments on climate change. It also provides wetland rehabilitation and usable evidence from environmental policies drafted (Zhang et al., 2021; Giorgi et al., 2019).

Materials and Methods

Study Area Selection

The Eastern Euphrates Project in Al-Suwaira, Southern Iraq, has recently become the subject of research due to the National Center for Water Resources Management's (NCWRM) large-scale land drainage (wetland)-agricultural conversions that began in 2002. These drainage schemes have caused extensive landscape changes, making the area ideal for studying the interactions of climate change and human actions.

In 2002, 25 soil pedons were excavated to collect field data and their soil properties measured, including salinity, soil moisture, organic matter, texture, and a range of properties measured in the laboratory to understand the soil water dynamics and vegetation health response to the actions of drainage, and to focus on the soils after the drainage.

In a follow-up to the previous work, the present study (2025) aims to determine the equilibrium achieved after a prolonged period of climate change and restoration in the area. The study also included morphological examination of 20 soil pedons and collection of 50 soil surface samples from the field. Salinity, saturation, acidity, and organic matter composition are being evaluated in a laboratory to assess the soil's agricultural and hydrological potential.

The Eastern Euphrates Project is situated in Al-Madina District, Basra Governorate, on the eastern bank of the Euphrates River. It extends northwest of Al-Madina and is bordered to the south by the Euphrates River, to the west by the Al-Sabbaghiyah River and Al-Chibayish District in Dhi Qar Governorate, and to the northeast by the administrative boundaries of Maysan Governorate. The entire project area is about 140 km² Figure 1 shows the study areais location in Iraq.

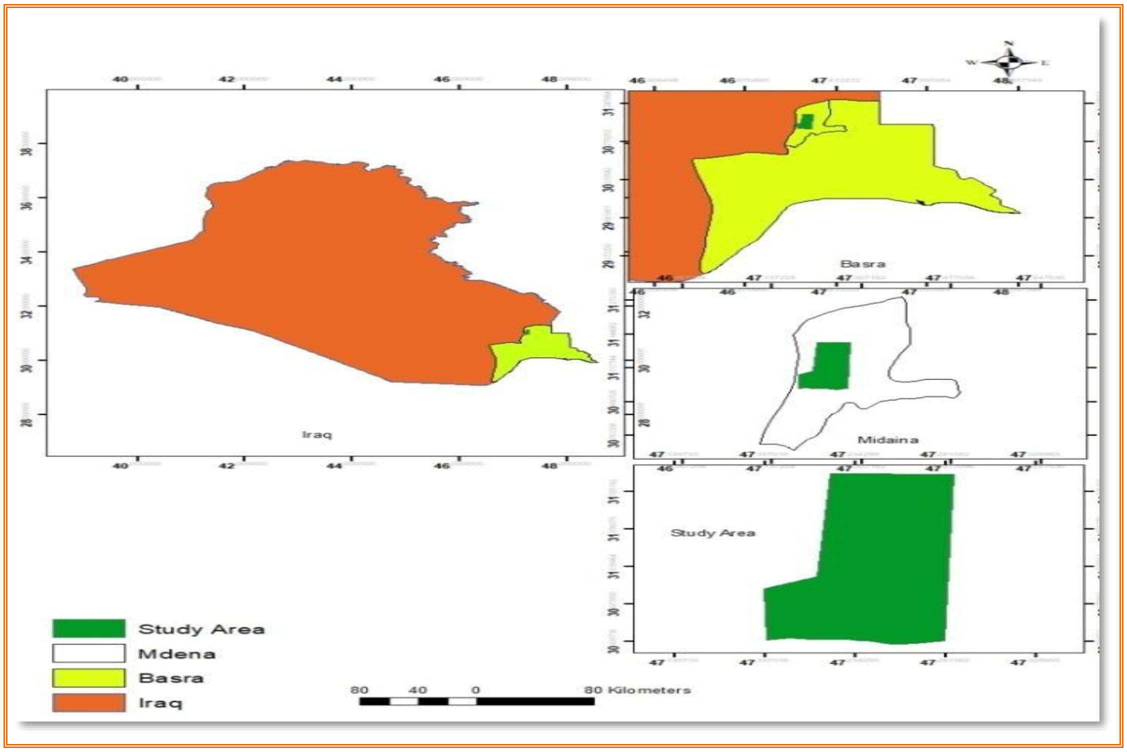

Figure 1. Map of Iraq showing Basra governorate and the study area

Integration of Climatic Data

Aside from soil data, the study also incorporated climatic data to determine the effects of climatic variability on vegetation changes and water resource availability. Changes in atmospheric temperature, precipitation, and evaporation will determine changes in vegetation and in surface and subsurface water over time. Thus, the vegetation and the available water resources.

The study acquired the climatic data from the two official institutions in Iraq:

1.General Authority for Meteorology and Seismology, the Ministry of Transport. (2002-2009)

This dataset offered temperature extremes (maximum and minimum), annual rainfall, and relative humidity for the period of 2002-2009. These data are helpful in determining the climatic conditions of the area in the earlier years of the study period when significant changes in temperature and precipitation occurred. These data are essential in determining the climatic trends for the first two decades of the 21st century, lifting the climate of the study area ecosystem.

2. Agricultural Meteorology Center, Ministry of Agriculture. (2009-2025)

The more recent climatic data from 2009-2025, provided by The Agricultural Meteorology Center, also contain records of temperature extremes, rainfall, evaporation, and relative humidity. The available datasets offered new information on climate anomalies, climate impacts on vegetation, and the availability of surface water, and the time frame of the datasets coincided with the climate anomalies and climate restoration efforts in the area, which made it optimal for assessing climate restoration efforts. \safeclimate \ restoration effort varied with the climate.

The combination of climate datasets provided us with an understanding of the study area's vegetation and water availability. Changes in annual rainfall, temperature, and evaporation rates, and the extremes were incorporated in the vegetation dynamics of the region. These variables help in understanding the climate changes and the ecological changes in the area, the changes in vegetation cover, and the surface water availability. These, with the integration of soil data, remotely sensed satellite data, and climatic data, provided an integrated approach in understanding the ecological changes in the area and how far climate variables and human interactions pushed the ecosystem to its current condition.

Geology Context

The region in study, bound by the Eastern Euphrates Project, presents as a flat and even landform, exhibiting no contours or steep elevations, and in direct contradiction to this uniformity, a few small and even dry river beds exist, like Al-Mishmash, Al-Subaiyah, and Al-Sabaghiyah Rivers, as documented by the Ministry of Water Resources (2002). The area is inclined towards the river of the Euphrates in the south and is, in totality, 1.5 meters to 2 meters above sea level. At the same altitude as the river, a number of small depressions exist, and some of these depressions, basins as we can call them, are a few meters below sea level.

Acquisition of Satellite Data

The Eastern Euphrates region is obtained from satellite pictures and their study during a defined time range, more precisely: the years 2002 and 2025. Using ArcGIS 10.8, within a GIS structure, we created soil trait maps and land cover class maps. Calculating time-differentiated changes in the region of the Eastern Euphrates Project demanded using the satellite pictures, taken during the relevant years of study, as displayed in Table 1, which have been selected.

Table 1. Satellite imagery for the years 2002 and 2025

Satellite	Satellite Sensor	Image Acquisition Date	Spectral Band
LANDSAT_7	ETM+	2002 /1 /15	Bands 3,2,1
LANDSAT_8	OLI/TIRS	2025 /1 /13	Bands 4,3,2

Calculation of Land Cover Indices

Land cover indices for the years 2002 and 2025 were calculated within the Geographic Information System (GIS) environment using ArcGIS Desktop 10.8. The analysis included a set of indices, among which:

1. Soil Adjusted Vegetation Index (SAVI): The SAVI was computed for the study area for both 2002 and 2025 based on the formulation proposed by Huete (1988) (Equation 1).

$$SAVI = \frac{(NIR - RED) \times (1 + L)}{(NIR + RED + L)} \quad (1)$$

Where:

- **NIR** = Near-Infrared band, represented by Band 6 (B6) in *Landsat 8 and 9*, and by Band 4 (B4) in *Landsat 7 and 5*.
- **RED** = Red band, represented by Band 5 (B5) in *Landsat 8 and 9*, and by Band 3 (B3) in *Landsat 7 and 5*.
- **L** = Soil adjustment factor, commonly set at 0.5 for semiarid regions.

2.Modified Normalized Difference Water Index (MNDWI):

The MNDWI was calculated for the study area following the formulation proposed by Chen et al. (2020) (Equation 2).

$$MNDWI = \frac{GREEN - SWIR}{GREEN + SWIR} \quad (2)$$

Where:

- **SWIR** = Short-Wave Infrared band, represented by Band 7 (B7) in *Landsat 8 and 9*, and by Band 5 (B5) in *Landsat 7 and 5*.
- **GREEN** = Green band, represented by Band 3 (B3) in *Landsat 8 and 9*, and by Band 2 (B2) in *Landsat 7 and 5*.

Research Design and Data Analysis

This analysis examined the satellite images for their distinction across various land cover classifications, such as bare land, weak, moderate, and dense growth. For vegetation and water coverage for the years 2002 and 2025, the SAVI and MNDWI indices were utilized for generating vegetation and water coverage maps. These maps provided a better understanding of the interspatial vegetation recovery and the distribution of surface water as affected by weather changes and restoration activities.

A satellite data and indices collaboration of soil, soil samples, and soil morphological description field data was examined to determine the soil characteristics, the vegetation health, and the available water at a given time. The combination of satellite data, field data, and climate data provided a synthesized characterization of the study area ecosystem and the impact of human activities and climate change.

Implications for restoration and climate adaptation

The regional history of environmental changes due to the extensive drainage activities and the recent climatic changes has provided the area as a prime target for wetland restoration and climate adaptation (Naji &Ati, 2019). The current study, vegetation recovery, and surface water investigation were and continue to be of prime interest in the Eastern Euphrates, focusing on the impact of natural and anthropogenic processes on the aforementioned.

The changes in the vegetation and the increase in the surface water show the successful impact of the restorative efforts that can positively influence the ecological equilibrium. Yet, the hydrological imbalance still persists, meaning that the consequences of climate change must be considered, even when climate-adaptive restorative efforts are undertaken.

The effects of the study on vegetation rehabilitation and the availability of water on the surface enhance and contribute to the eradication of the gray line of the water and land management and the equilibrium of the ecosystem. This study demonstrates the potential of improving the restorative activities in the geographical region to achieve equilibrium of water and the ecosystem. Sustainable management of the wetlands, climate adaptive infrastructures, and advanced irrigation techniques, and other water conserving agricultural practices can also be critical. All in all, the study focuses on the collaborative efforts of the restoration that are primary, not only in the restoration of the water and vegetation, but also in the restoration activities that center on the climate adaptive efforts.

Results and Discussion

Climate: Rainfall

The annual climate averages for the period between 2002 and 2025 are depicted in Table 2. The yearly climate averages for the period between 2002 and 2025 are shown in Table 2. There is extreme fluctuation in annual rainfall amounts, ranging from 245.8 mm in 2006, one of the study's wet years, to 1.54 mm in 2016, a year of extreme drought. Some other high rainfall years are 2005 (105.7 mm) and 2019 (103.6 mm). The years of 2012 and 2013 had a consecutive 2-7 mm of rain for the year, which are recorded as dry years.

Table 2. Annual climate averages for the period (2002 - 2025)

Date	Rain	AT Max	AT Min	AT Avg	RH Max	RH Min	RH Avg	SLR Total	WS Avg	WS Max	ET
	mm	C°	C°	C°	%	%	%	Mj/m2	m/s	m/s	mm
2002	151	33.6	18.36	25.98	72.95	19.85	46.4	222.23	12.54	26.58	305.59
2003	61.2	32.81	19.21	26.008	77.8	21.025	49.413	219.37	12.86	28.55	337.6
2004	98.6	33.44	18.01	25.725	76.81	21.45	49.13	241.8	11.075	23.38	268.06
2005	105.7	33.33	18.46	25.89	80.54	15.28	47.913	208.59	11.91	27.38	253.87
2006	245.8	33.18	19.12	26.15	80.77	19.9	50.33	195.29	11.86	21	316.92
2007	112.5	33.4	18.93	26.17	73.93	19.13	46.53	240.325	11.23	28.22	299.26
2008	65.5	33.58	19.23	26.404	80.93	21.41	51.17	192.18	12.43	27.73	303.36
2009	56.91	33.29	19.23	26.26	76.58	22.15	49.37	183.67	12.08	26.96	327.93
2010	57.6	35.85	20.33	28.09	79.37	22.31	50.84	211.09	11.78	24.225	349.11
2011	91.31	34.8	19.43	27.12	78.15	21.175	49.66	217.375	14.175	24.78	329.87
2012	2.11	32.98	20.12	26.55	71.92	21.123	46.52	18.65	2.46	9.103	6.09917
2013	5.46	35.88	21.99	28.93	74.52	23.07	48.79	19.58	2.5025	9.26	6.46
2014	7.09	32.74	18.6	25.67	81.39	24.58	52.98	19.25	2.27	8.75	5.61
2015	4	34.23	18.61	26.42	73.09	19.39	46.25	18.18	2.23	9.16	5.98
2016	1.54	33.65	18.74	26.19	76.43	21.29	48.86	19.69	2.09	8.57	5.78
2017	5.72	32.64	17.52	25.08	72.76	20.065	46.41	18.66	2.01	8.21	5.48
2018	5.23	33.58	18.03	25.804	70.81	25.83	48.32	17.68	2.12	9.06	5.73
2019	103.6	31.15	18.13	24.64	70.89	27.23	49.06	17.67	2.26	8.57	5.51
2020	162.2	33.47	18.62	26.05	68.801	18.66	43.733	17.53	2.66	9.56	6.47
2021	33.6	33.93	18.3	26.12	75.25	23.91	49.58	16.91	2.86	10.22	6.44
2022	79.71	31.8	17.39	24.59	71.55	19.37	45.46	18.16	2.35	7.42	5.92
2023	209	34.16	20.8	27.49	82.42	21.43	51.93	183.18	13.48	23.45	294.06
2024	100.4	34.72	20.7	27.71	80.73	20.92	50.82	193.67	12.5	19.81	289.56

This rainfall trend highlights the instability of the rainfall regime in Southern Iraq, which depends mainly on Mediterranean depressions of irregular time and space. Furthermore, the variability of the rainfall has been attributed to the ecosystem becoming more unpredictable due to climate change, specifically, more frequent droughts and lower amounts of rain in a shorter time. Rainfall can no longer be predicted.

Considered a stable water resource, but rather an intermittent climatic event lacking sustainability, thereby exacerbating environmental risks associated with Desertification, soil degradation, and water scarcity in southern Iraq.

There are some noticeable fluctuations in the time series chart, especially the period of extreme dryness from 2012 to 2018, after which the rainfall increases, as shown in Figure 2. On average, there were 77.08mm of rainfall per year, but with a coefficient of variation of 87.22%, which is exceptionally high, indicating there was significant variability year over year. The figure also shows the overall declining trend in the total rainfall, especially during the mid-period. The years after 2019 saw an overall increase in rainfall, but there was a clear trend in the decline of total rain, indicating that the rainfall levels would not reach the levels seen prior to 2019. This trend has been documented in previous work chronicling the decline in the total annual rainfall within Iraq and Southwest Asia (Allami et al., 2024; Al-Azawi et al., 2024). This pattern is aligned with the IPCC 2021 report, which confirms that the Earth's surface temperatures are increasing and that there are inversions of the hydrological cycles that are co-occurring with a decline in the efficiency of precipitation, leading to extreme weather conditions characterized by prolonged droughts and low precipitation events (Giorgi, 2019). The increasing trends in rainfall events that are characterized by low efficiencies have significant implications at the soil and hydrologic levels.

Suboptimal rainfall leads to increased surface runoff, and in years of deficient precipitation, more rainfall will evaporate before the moisture can soak into the upper soil layer, creating a soil moisture deficit which, in turn, limits groundwater recharge and reduces the moisture-holding capacity of the root zone to a greater depth (Neukum et al., 2022; Fatah et al., 2025). Prolonged periods of drought also induce the formation of surface crusts and (in the case of clay) shrink-swell behavior, which will both increase the soil moisture episodically, also reducing the moisture content of the soil to an increased degree.

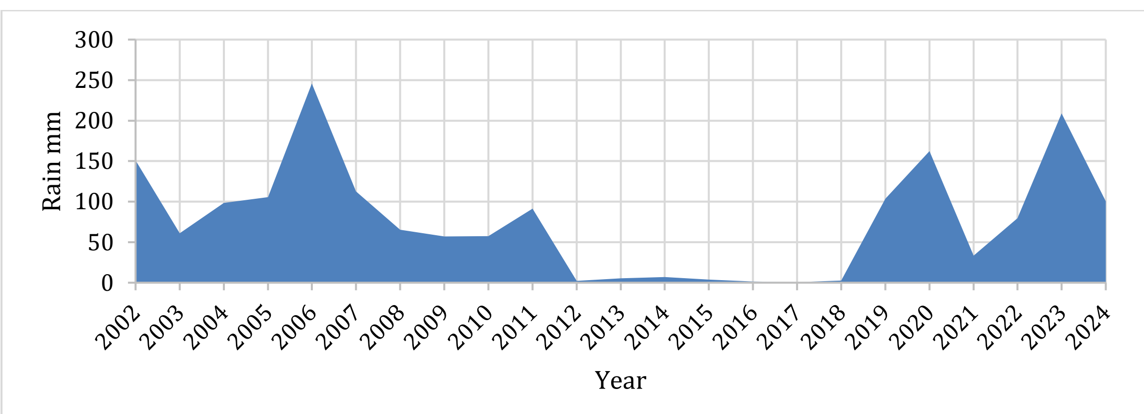

Figure 2. Depicts the timescale intervals of precipitation for the years 2002 through 2025 in the location of the given study

The temporal succession of dry periods, which is compounded by a lack of precipitation or dry periods following irrigated phases, will increase the risk of soil salinity accumulation, which is caused by unbalanced water flows (restricted leaching) and evaporation, with direct consequences for the spatial distribution of soil salinity (podzolization) within the landscape (Jabbar & Ati, 2025). The variability of precipitation, with episodes of drought, also leads to increased complex challenges for water resource management. e.g., the interplay between water availability and drought; the short (hazardous, flooding) rainfall periods also interleave dry periods (Barendrecht et al., 2024).

Evaporation

Figure 3 gives the amounts of evaporation for the years ranging from 2002 to 2025 in the study area. The results show significant variability because of the extreme weather conditions. The average evaporation rate was 162.63 millimeters per year, but the result had a deviation range of 154.65, with a total variation of 95.1%. The variation in evaporation rates showed inconsistency with the rates measured in other annual time periods. 2010 showed the most excellent evaporation rate with a total of 349.67 mm/year. 2017 measured the lowest evaporation rate with a total of 5.48 mm/year. The extreme variation in the annual records was expected with the rate in the marsh environment. There are certain years with a lot of rainfall and a lot of water. It also suffers from extreme drought in other years. There is also climate change, which affects the water balance in the area.

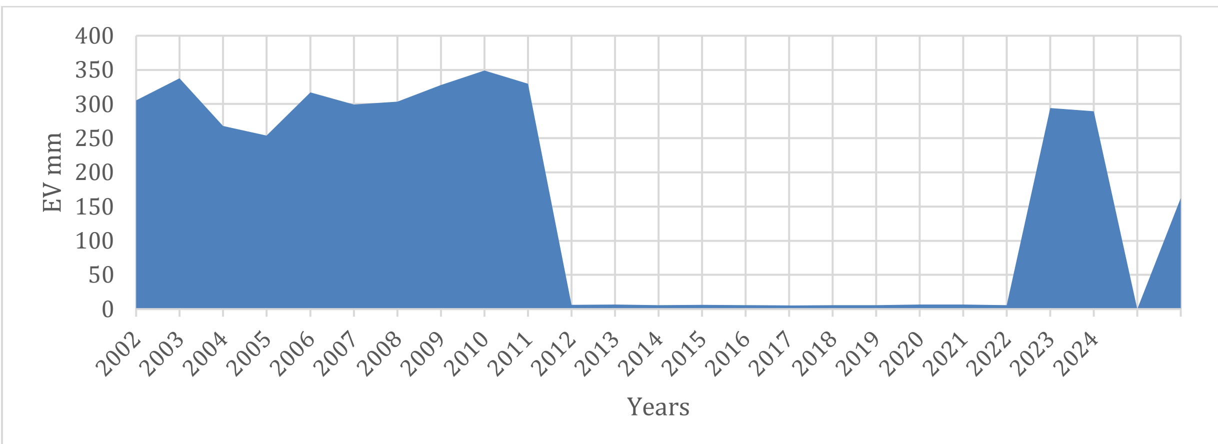

Figure 3. Time series analysis of rainfall for the study period

The Role of Temperature

The above table displays trends of maximum, minimum, and average temperature for 2002–2025, and shows a steady increase during that timeframe, which is most likely a result of the global trends of climate change. Over the specified period, an average maximum temperature of 34.7°C and an average minimum of 19.2°C, with an overall average of 27.1°C, brings on the classification of the region as a semiarid region with high temperature and therefore high thermal amplitude. Over the length of the study, the maximum temperature increased by an average of 0.05°C, which is a total increase of 1.2°C, and shows the seriousness of climate influences and change regionally.

Minimum temperatures have also shown a slight increase, rising by 0.03 °C on average and totaling 0.7 °C, a change which indicates that compared to the 2000s, nights are warmer. These rising minimums are perhaps the most critical sign of local climate change caused by the trapping of greenhouse gases that store heat and prevent the land from cooling at night. Evidence also supports that the mean temperature increased by 0.04 °C per year, which amounts to 1 °C over 24 years. Comparable warming in semiarid areas is reported in most global studies, which is consistent with the results here. 2010 was the hottest year, with a mean annual temperature of 28 °C, and was also associated with severe drought. In contrast, the yearly average temperature in 2004 was around 26 °C, making it one of the coolest years, which highlights that the climate of the area is quite irregular. But the primary trend is clearly upward, emphasizing that climate change is shown by long-term changes rather than short-term variations.

This warming trend has severely shortened winter and increased summer, while also intensifying heatwaves, which places further strain on the local ecosystem and agricultural systems. The impact of higher temperatures on soils is multiple. They carry off moisture, but also accelerate the desecration of soils. Temperature impacts moisture retention; high evaporating temperatures raise the moisture loss ratios. In hotter climates, a lone increase of 1 degree Celsius is estimated to increase moisture loss ratios in crops by 7 to 10%. Increased temperatures also raise the minimum temperatures within a region. Pruned vegetation hinges on temporal loosening to structurally leach the salt, which further soils salinize, impoverishing the soil, lowering agricultural outputs, and exacerbating the unsustainability of the farming systems. Increased diurnal shifts in temperature also increase the degree of stress moisture-balanced crops suffer, especially those moisture-balanced summer crops, which exponentially depend on stabilized temperature flux to maintain physiological functions to achieve full presence. The documented phenomena in the region appear to fall within the framework of Desertification, especially within the documented framework of Hashim et al., 2022. The temperature rise is also drying up the vegetation that previously covered the irrigation marshes, a process by which the biodiversity within the region is also being lost.

The predicted thermal patterns demonstrate the congruity of global models' average temperature increases of 2-4 °C within middle-century time frames for Iraq (Delgado-Torres et al., 2023). This suggests that the challenges of the future will be more chronic than current ones. This makes it imperative that adaptive agricultural methods be implemented immediately. This includes the sustainable management of soils and water. This includes the use of varying degrees of advanced geomatics to track differential heating and cooling of the land. The use of moderately improved irrigation and other advanced methodologies that help integrate heat and drought-resistant crop varieties to shape the issues is more urgent (Dzvene et al., 2025). The evidence from this area of study is the figures of maximum, minimum, and mean, which demonstrate that this area has a definite rising thermal trend. This is a testament to the impacts of climate change on the southern border of Iraq. The increased mean temperatures will act as a stressor while also being a climatic signal. This will act as a stressor on the agricultural sector, the ecosystem, and the natural resources. This underscores the significance of Climate change as the primary focus across all industries of future planning for the environment, society, and the economy.

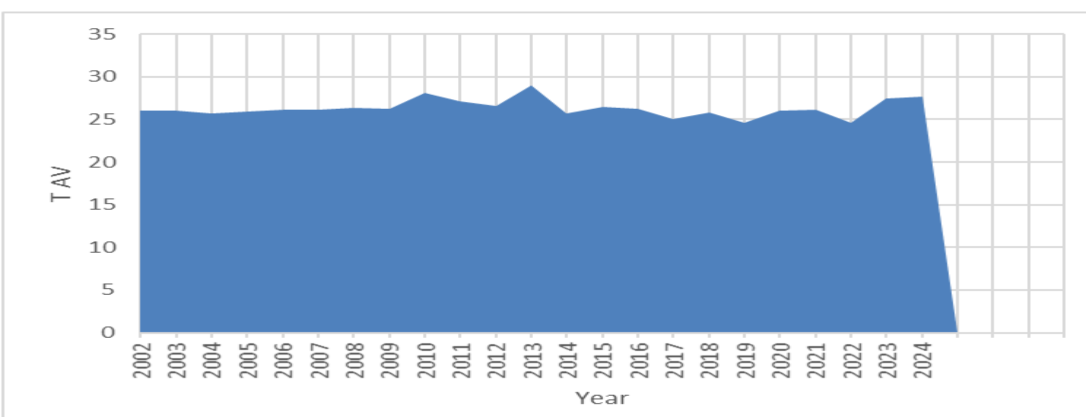

Figure 4. Time series of mean temperature during the study period

Figure 4 foreshortens a series of temperature timespans (2002–2025) displaying equilibrated seasonal variations (low temperature in winter and high temperature in summer) in alignment with the temperature regime of semiarid climates. The slight elevations of the peaks and the troughs assure a slight temperature rising trend and reinforce the impact of climate change and global warming in the study region (Pirani et al., 2024).

Humidity

Among the various climatic elements, humidity is the most critical because it governs the water and thermal equilibrium of ecosystems. The consequences of humidity on soils and on the physical and hydrological processes thereof, and on the vegetation and biological diversity are profound. Table 2 shows the relative humidity statistics for the study area for the years 2002 to 2025, and it indicates very marked inter-annual variability, albeit with a downward drift. This is a testimony to the impact of climate change and the increasing aridity of the southern Iraq region. The relative humidity during the initial five years of the study (2002-2005) was significantly elevated compared to subsequent years, occasionally surpassing 55%. After 2010, there was a clear drop, with yearly averages between 45% and 50%. Years characterized by low rainfall and higher temperatures, such as 2018 and 2022, recorded the lowest humidity levels, in some months dropping below 40%. This declining trend aligns with the increasing vulnerability of southern Iraq to accelerated aridity and declining relative humidity because of global climate change and anthropogenic pressures on surface and groundwater resources (Ahmad et al., 2025). Humidity is greatly controlled by seasons. In most places, higher values of relative humidity are recorded during the cool wet months of winter and spring, while low extreme values are realized in the hot dry summer and early autumn months when evaporation rates are high. This sets up an inverse relationship between temperature and relative humidity. Climatic behavior has been documented in several works of literature. Results have also indicated that dry to semi-dry areas show a great sensitivity to thermal changes, where a 1–2 °C increase in temperature results in about a 3–5% decrease in relative humidity (Al-Janabi et al., 2025).

The decrease of relative humidity in the area under study is also reflective of its geographical disposition: near arid lands and far from any direct maritime influences. The southern Iraqi marshes that had once been supposed to play the role of natural reservoirs of humidity, making the local climate milder, are degraded and thus even more arid. Evapotranspiration, or the combined processes of evaporation and transpiration, removes more moisture from the atmosphere. The recent drying of surface water bodies results in more moisture being removed from the ecosystem. Surface water bodies help to mitigate extreme climate or humidity swings, and, without them, the ecosystem faces more extreme climate fluctuations. The 2020 to 2025 period exhibited extreme swings of moisture in the atmosphere, which demonstrates that the ecosystem's climate is changing. The long-term, gradual heating of the environment, coupled with extreme weather, is changing the ecosystem's moisture in the atmosphere. Potentially, more dry days with short, heavy rainfall in events followed by long periods of moisture. The decrease in humidity and moisture in the atmosphere is a direct consequence of more extreme weather events. The extreme weather events directly push the ecosystem's moisture into the atmosphere. The increase in moisture is directly correlated to more extreme weather conditions, including drought. The process of transpiration and evaporation is part of the weather alteration cycle. The ecosystem's moisture declines and the resultant high temperatures impact the vegetation cover, soil structure, and ultimately the soil compost. The vegetation cover structure decays because of higher transpiration and moisture. The soil structure, compost, and the protective vegetation cover degrade soil more rapidly because of climate change. The soil's protective vegetation cover is removed by erosion more rapidly, and moisture in the atmosphere is removed more rapidly. Soils decay more quickly because of higher moisture in the atmosphere, which also leads to more rapid decay of vegetation cover. Soils decay more quickly because of erosion and moisture in the atmosphere, and moisture in the atmosphere also leads to vegetation cover decay. Absence of moisture, or more direct heat, has also been shown to lead more quickly to soil accumulation of salts and higher soil sodality.

This proves that drying trends with falling atmospheric and soil moisture in Iraq's arid and semiarid regions heighten salinity risk. Changes in humidity also affect hydrological processes within soils, such as infiltration and recharge. Rising temperatures with reduced humidity lower infiltration capacity and increase surface runoff. This is a direct threat to the sustainability of water resources. Reduced humidity also reduces the efficiency of the local hydrological cycle by disturbing the balance between evapotranspiration and water percolation. Relative humidity data show a downward trend over the past two decades due to climate change and the degradation of local water resources. If trends continue, it would be a massive crisis for both agriculture and ecological systems; thus, wetlands restoration as a natural reservoir of humidity and afforestation programs to increase vegetation covers in addition to percolating capacity improvement in soils would be included in adaptive strategies together with efficient water resource management (Condon et al., 2020; Dawod et al., 2024).

Relationship between Rainfall, Temperature, and Evaporation

Figure 5 illustrates the relationship among rainfall, evaporation, and annual mean temperatures. The results show a clear positive relationship between rainfall and evaporation. In wetter years, evaporation follows the same trend as rainfall: as precipitation increases, temporary water bodies are formed, and soil moisture rises (a characteristic feature of the dry marshland environment). Consequently, actual evaporation also increases, since in arid environments the main limiting factor is the scarcity of water rather than the atmosphere's evaporative capacity. Hence, peaks of evaporation are almost synchronized with rainfall peaks, as observed in 2006–2011 and again toward the end of the period in 2023–2024. Conversely, in arid years, there is no moisture, so there is no evaporation, and it is not a question of temperature, radiation, or wind. Thus, there is a contradiction, and evaporation is relatively low, despite the fact that the region is hot. This is in accordance with the hydrological balance in arid and semiarid systems. In these systems, the evaporation of moisture is controlled by what is termed the 'limiting factor' - that is, the atmospheric conditions and the moisture availability. So, it will result in a low moisture evaporation rate as rainfall is low, and will increase the rate during wet years.

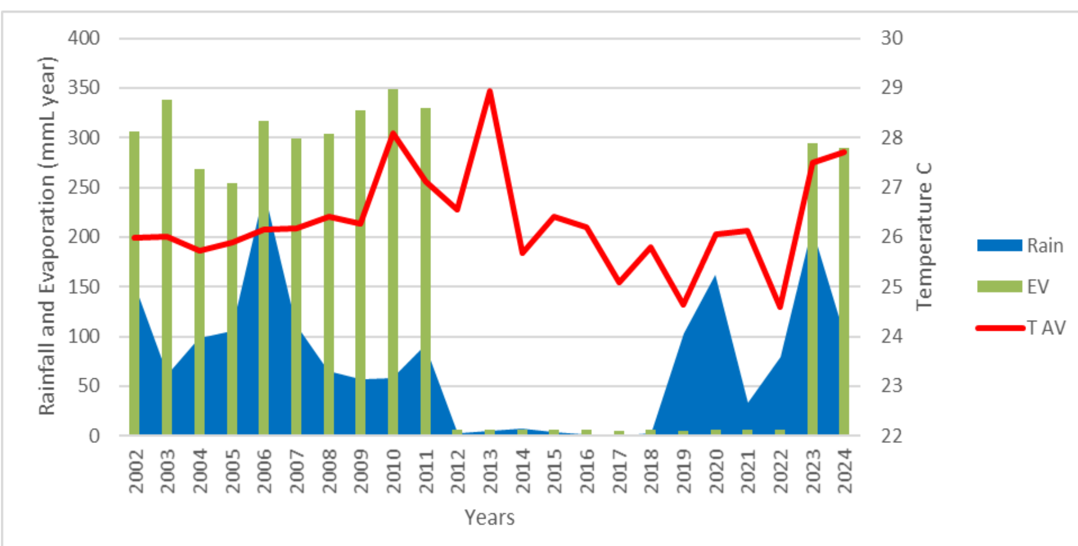

Figure 5. The relationships among precipitation, temperature, and evapotranspiration

The annual average temperature readings were relatively consistent over the years and fell in the range of 25–28 °C. Temperature displayed minimal tendency to increase, or so, over several years. This more or less suggests that the temperature, more so, acts as a balance factor rather than the active driving force of the variability. To put it in layperson's terms, the temperature, in the absence of moisture, does not drive evaporation, and it does amplify to a more significant level the difference when moisture is present. The region's ecological sensitivity explains it rather well. After any wet season, there is a very rapid and significant loss of moisture to the atmosphere in the form of evaporation. Conversely, with any dry season, the water deficit becomes aggravated as rainfall is very low, and evaporation is relatively low as well, due to a lack of surface water. Hence, the water balance of the area becomes more and more erratic.

Soil-Adjusted Vegetation Index (SAVI) for the Year 2002

Figure 6 represents the SAVI maps and Table 3 the values for 2002. In the 2002 SAVI, there was class dominance of the study area vegetation class in the Weak Vegetation category at 96.28%, representing 135.467 km of the study area, with SAVI values of 0 – 0.15, indicating a significant and weak vegetation cover. Such values are indicative of substantial vegetation cover and are consistent with NDVI values of the same year. Weak vegetation cover and unsustainable vegetation cover values are indicators of vegetation degradation from different sources, and quite a lot of low soil moisture and poor soil fertility. Low SAVI values are indicative of higher-than-normal bare unsurfaced soil area and lower biological productivity of the vegetation.

The area of the study with no vegetation was 0.3530\%, representing 0.497 km with no SAVI values (-0.0811 – 0), indicating completely unsurfaced land. Unlike the Moderate Vegetation class, whose SAVI values ranged from 0.15 to 0.3 and made up 3.343% (4.705 km²) of the total area. Areas with SAVI class values of 0.15 to 0.3 exhibit vegetation of moderate density with seasonal water availability and changes in vegetation density type, and are more responsive to agricultural and water management changes (Zhen et al., 2021). Dense Vegetation class with a SAVI class of 0.3 to 0.4411 was minimal, with a class area percent of 0.0147 (0.0207 km²). So small a percent is unlikely to bring the area to some level of ecological balance. There is a disturbed ecological balance with non-vegetated and weak categories of vegetation. The results show clearly the absence of the upper classes of vegetation, showing that the study area soils are either exposed or partially exposed, increasing the erosion, moisture evaporation, and the loss of organic matter. This finding agrees with the (Kugedera et al.,2023) study that reported that dryland soils are highly susceptible to degradation when vegetation density is reduced.

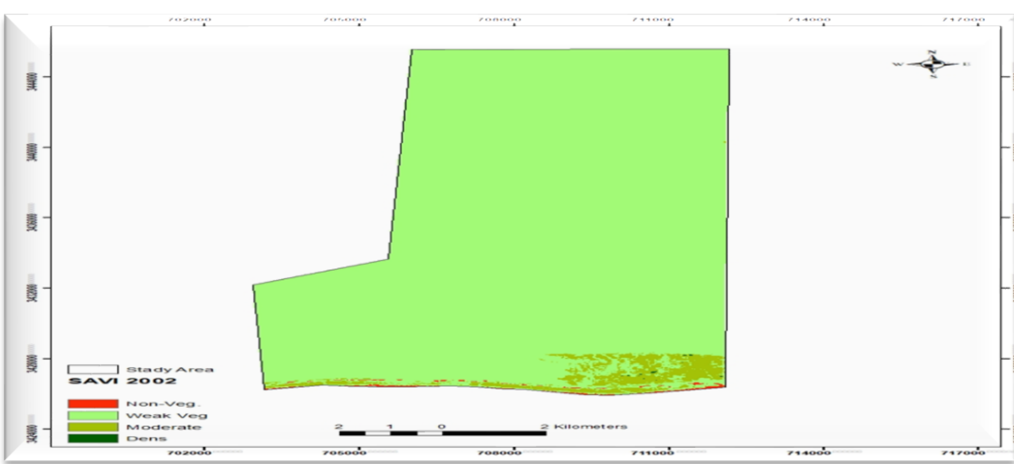

Figure 6. SAVI-based vegetation cover map for 2002

Table 3. Soil-Adjusted Vegetation Index (SAVI) for the study years

Year	SAVI			
	Type	**%**	**Area Km2**	**Value**
2002	Non-Veg.	0.353077	0.49674	-0.081195176 - 0
	Weak Veg	96.288218	135.466959	0 - 0.15
	Moderate	3.343994	4.704632	0.15 - 0.3
	Dens	0.014712	0.020698	0.3 - 0.441101015
2025	Type	%	Area Km2	Value
	Non-Veg.	20.861584	29.34996	-0.310616225 - 0
	Weak Veg	71.157094	100.110224	0 - 0.15
	Moderate	7.610336	10.706908	0.15 - 0.3
	Dens	0.370986	0.521937	0.3 - 0.589435339
2002 And 2025	Type	%	Area Km2	Value
	Non-Veg.	35.908916	50.519906	-0.484122694 - 0
	Weak Veg	63.21095	88.930872	0 - 0.15
	Moderate	0.749648	1.054673	0.15 - 0.3
	Dens	0.130485	0.183578	0.3 - 0.504153848

Soil-Adjusted Vegetation Index (SAVI) for 2025

Illustrated in Figure 7 and summarized in Table 3, the 2025 SAVI values averaged out and mapped to reflect the area expectations in the vegetation cover 2025 as predicted, and the vegetation cover estimated in 2002, as expected, SAVI values averaged out. A reported 0.0 to 0.15 SAVI values indicate Weak Vegetation, while 2002 SAVI showed 96.288%, while 2025 SAVI showed 71.157%. 100.110 square kilometers were reported as Weak Vegetation, the most land cover area, but it decreased. A reported 20.861% were reported as 0.310 to 0 SAVI, which was 29.349 square kilometers, and was clearly non-vegetated. Included were areas classified as either barren lands, wetlands, surface water perimeters, or degraded, structurally weak, and easily erodible land formations. Li et al. (2020) correlated the degradation of arid to SAVI in every case, which is an adverse reaction. Reported as Moderate Vegetation, 7.610% of 10.706 square kilometers were accounted for, an increase overall, to 3.343% from 2002. More of the land cover area was due to increased sustainable management practices, land reclamation, and modern irrigation.

This agrees with the observations made by Olmos-Trujillo et al. (2020) that incremental improvements in vegetation cover in arid and semiarid regions can be monitored effectively through the use of SAVI.

It actually occupied 0.370% of the area, which is equivalent to 0.521 km², and that, despite being very minimal in extent, it was already an improvement from 2002 because there were already small patches with very high-density vegetation that started to develop. This means that, with maximum SAVI reaching up to 0.589, the ecosystem can support vegetation growth and cover at its optimal state when conditions are made favorable by interventions like organic fertilization and efficient irrigation, as indicated. This would also mean fewer barren soil categories and moderate plus dense vegetation categories, indicating an ecological trend toward a stable system set-up type of improvement, enhancing biological diversity, improving the soil physical properties, mainly on porosity and resistance to erosion, strengthening the hydrological regulation function of vegetation cover as an ecological barrier to Desertification.

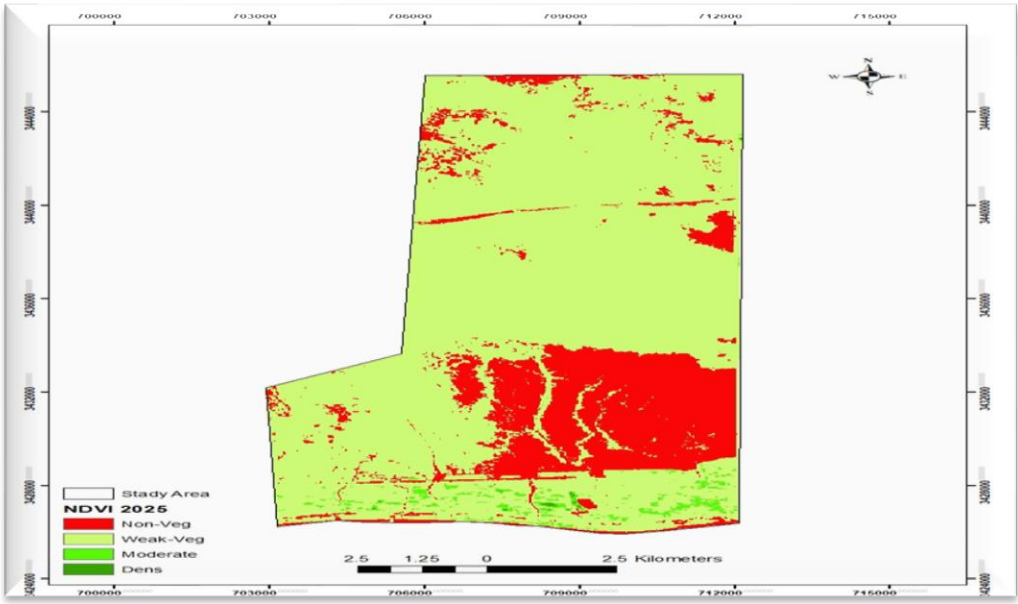

Figure 7. SAVI-based vegetation cover map for 2025

Difference in Soil-Adjusted Vegetation Index (SAVI) between 2002 and 2025

Figure 8 illustrates the difference map of the Soil-Adjusted Vegetation Index (SAVI) between 2002 and 2025, while Table 3 summarizes the corresponding values. The different forms of vegetation cover have changed significantly in the area of the study. The Non-Vegetation category was the primary contributor of change, still, at 35.908% of the total difference area (50.519 km²), with SAVI values between 0.484 and 0. A large proportion of the land still remains degraded, as is the case with large deterioration values, which corresponds to what is said by Xie et al., (2022) and others (2024) that degradation is more likely to take place in fragile areas with a lack of management and with the absence of permanent controls. The second highest value was recorded for the Weak Vegetation class, which accounted for 63.2109% of the area of difference (88.930 km²) with a SAVI value of 0.0 to 0.15. This indicates that in parts of the study area, the change from a non-vegetated state to one that is weakly vegetated is at an early stage of ecological recovery. These conclusions correspond with the findings, which noted that the weakly vegetated cover is one of the early signs of recovery in open vegetation cover and is particularly associated with the recovery signs in semiarid regions as a result of water improvement measures.

The Moderate Vegetation class consisted of 0.749 of the total difference area. (1.054 km2). Such increases can also indicate profile changes, such as the transition of some weak vegetation patches into a moderately dense cover, serving as indicators of structural and functional improvements in the properties of the soil, especially in soil aggregation and retention. Dense vegetation consisted of only 0.130 (0.183 km2). Even though the area was not large, the presence of different results suggests true localized vegetation growth, most likely in response to very site-specific environmental restoration initiatives such as native vegetation rehabilitation, sustainable agricultural practices, and so on. SAVI was diagnosed by Afuye et al. 2024) as a sensitive index toward improvement of vegetation in dry areas, and the value of 0.5041, which indicates dense vegetation in some places. Even though the changes are of limited extent, they also indicate a positive change in difference, which is a change from non-vegetated conditions to vegetated conditions. The active ecological dynamics within the study area are observed throughout the study period. This suggests that community initiatives whereby they enhanced soil fertility and controlled vegetation, could have induced positive restoration dynamics. This evidence was corroborated as well by UNCCD (2023), reporting restoration of the land in the western part of Asia, due to water harvesting and other soil-conserving agricultural activities reported in the region.

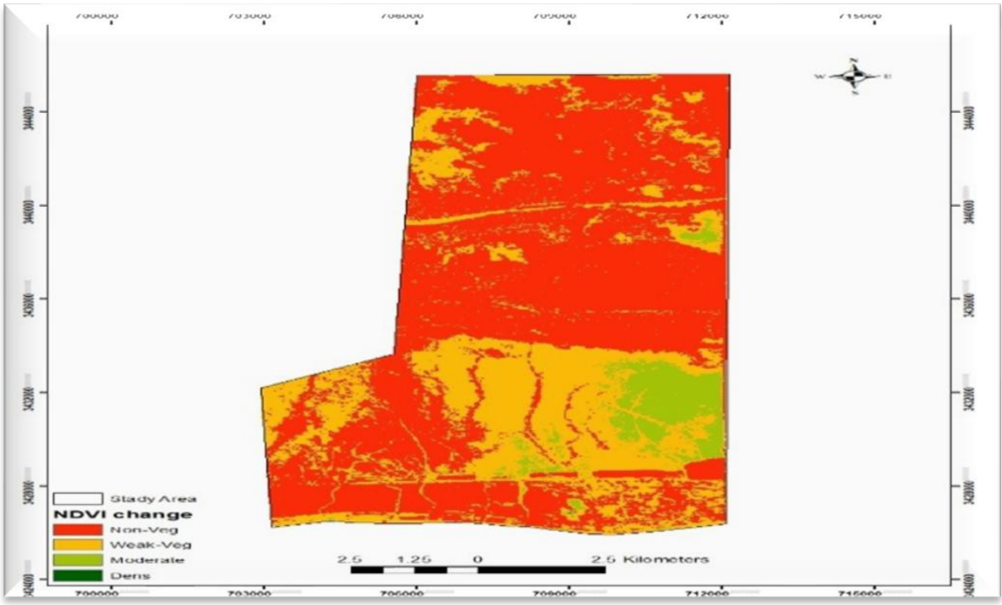

Figure 8. Difference map of the soil-adjusted vegetation index (SAVI change)

Modified Normalized Difference Water Index (MNDWI) for 2002

Table 4 shows the rounded percentages and areas, and Figure 9 shows the study region in its entirety, along with the map of the MNDWI for 2002. The data show that the non-water class was the most common in the research region, making up 99.551% of the area (140.0582 km²). The water class, on the other hand, made up just 0.4483% of the area (0.630824 km²). The spectral index values for the dry regions ranged from 0.286 to 0, while the spectral index values for the water-covered regions ranged from 0 to 0.103. The area's extreme scarcity of surface water resources, in conjunction with the climatic drought and rainfall deficiencies that have impacted western Iraq for decades, supports the assessment of water degradation in arid zones (Darvishi Boloorani et al., 2024).

There appears to be a correlation between the aforementioned variables that resulted in extreme desiccation and the fact that the majority of the study area's soils, during the year 2002, were virtually vacant of surface moisture and vegetative cover, and the study area's soils were almost vacant of surface moisture and vegetative cover. These variables include ample scale marsh drainage, high temperatures, extreme desiccation, low soil storage capacity, and high evapotranspiration rates. Drought-affected soil undergoes various changes pertaining to soil structure, hydraulic conductivity, and reduced cation exchange capacity. Speculative to 2002, MNDWI also detects surface drought and surface water deficiency, indicative and characteristic of the extreme state of drought and water deficiency affecting the region during that time.

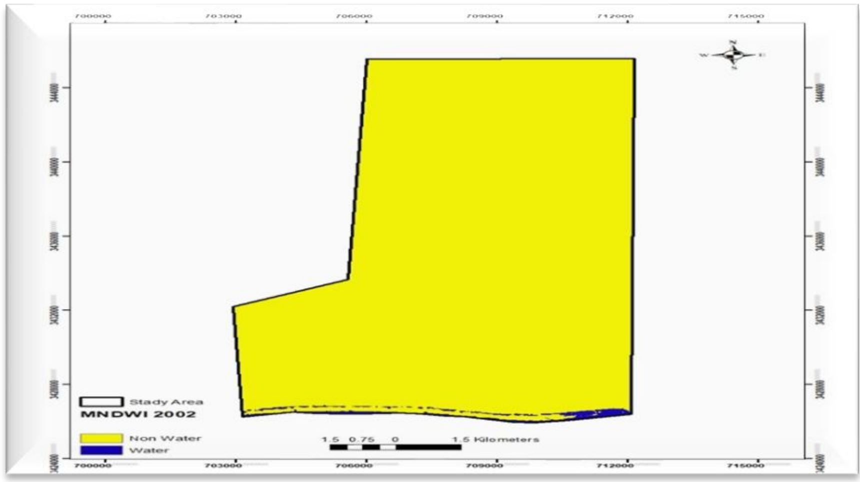

Figure 9. MNDWI For the Year 2002

Table 4. MNDWI for the analytical years

Year	NDWI			
2002	Type	%	Area Km2	Value
	Non-Water	98.949085	139.210507	-0.277547985 - 0
	Water	1.050915	1.478522	0 - 0.149802342
2025	Type	%	Area Km2	Value
	Non-Water	60.340284	84.89216	-0.262821019 - 0
	Water	39.659716	55.796869	0 - 0.325430363
2002 And 2025	Type	%	Area Km2	Value
	Non-Water	98.082385	137.991154	-0.550563693- 0
	Water	1.917615	2.697875	0 – 0.261476249

Modified Normalized Difference Water Index (MNDWI) for 2025

The output of MNDWI spatial analysis for the year 2025, as shown in Figure 10 and tabulated in Table 4, indicates a further considerable spatial change over the 2002 surface water area. The area under water class leveled 55.796 km², which is 39.659% of the entire study area, and the non-water class accounted for 60.340% (84.892 km²) of the area. The spectral ranges for MNDWI fall between 0.2628 and 0 in the dry and 0 and 0.3254 in water covering. Those positive spectral index values indicate the presence of plenty of permanent or high surface water bodies.

The significant spatial change and improvement at the eco-environmental and hydrological levels from the almost zero value surface water area of 2002, and improvement of surface water availability from either the natural (time to seasonal flooding of the marshes) or human (water management, wetland rehabilitation, controlled irrigation) actions. The climatic conditions have also changed, which could have caused the surface water and water vapor to redistribute. The MNDWI value for the year 2025 is in a favorable balance to provide a measure of the ecosystem hydrological condition and the impact of water management.

Difference in Modified Normalized Difference Water Index (MNDWI) for the Years 2002 and 2025

In Figure 10, the MNDWI Difference map for the elevation years in the study area, showing respective spectral data in Table 4, is presented. Differences over the given time period demonstrate a minimal degree of dispersion in the liquid surface water over the years 2025 and 2002, where the majority of the area (98.0823%, 137.991 km sq.) shifted from and/or remained in the non-water category, while only 1.9176% (2.697875 km sq.) of the area transitioned to and/or positively shifted in the Water Class.

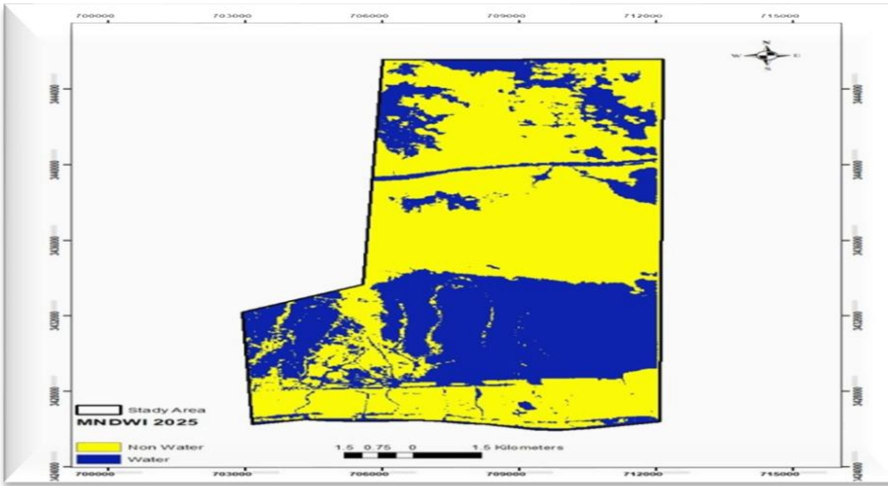

Figure 10. Modified normalized difference water index (MNDWI) for 2025 difference map

The area of study has shown little evidence of improvement in the percentage of surface water, which has shown, at most, a growth of 2%. Therefore, most of the study area was still classified as non-water for both time periods, which differs from the increase in water surface area. At first glance, the 2025 result indicates a significant improvement, but the difference values indicate a geographically disparate rise in surface water, if improvement was at all, during that time period. Weak hydrologic stability was observed in the study area, which is a common occurrence in arid and semiarid environments, as the surface water is dynamic and exists for very short time periods (Wang et al., 2023). Hydrologic properties of the soil, especially water conductivity, are also unlikely to change due to surface water, and it is likely that the hydrologic properties of the soil will be the same if effective reclamation measures are not put in place, as drought and surface crusting are also expected to be present. Therefore, very little change in the MNDWI value, especially little change from a spectral and spatial perspective, confirms that surface water showed very little change, both in the MNDWI values of 2022 and 2025. The potential requirement for further analysis using various spectral bands and a shorter time to derive serial hydrological changes in water-sensitive environments has come to the fore.

Conclusion

The Eastern Euphrates Project within the Hoor Al-Huwaizah wetlands of southern Iraq analyses climatic data and satellite indices (SAVI & MNDWI) to assess changing climatic variables and ecosystems. Evidence of refined climatic and ecosystem data interprets the region over the specified timeframe (2002-2025) as a response to positive and negative climatic and anthropogenic variables. Evidence of ecosystem data supports the diagnostics of an incomplete ecosystem's stabilization and recovery. Evidence of hydrological and vegetative loss stabilization of the ecosystem surrounding the Eastern Euphrates Project demonstrates the impact of positive ecosystem rehabilitation activities. Evidence of escalating temperatures and variable precipitation supports the hypothesis that deficient climatic and hydrological variables are stabilizing the ecosystem and the Eastern Euphrates Project's ecosystem. The evidence of ecosystems flexibly stabilizing endorses the hypothesis of ecosystem positive rehabilitation support. The scope of positive climatic stabilization supports that the region not only needs to implement the Ecosystem Reclamation & Rehabilitation

Programs already initiated, but it also needs to accelerate their modernization and implementation regionally. The ecosystem of the Eastern Euphrates Project and the surrounding region no longer needs only significant and strategic modernization to support the rapid deployments of the ecosystem's flexible stabilizing. It needs to support the fast, flexible, and positive stabilization of the ecosystem's humanitarian activities implemented. Modernized humanitarian activities will unequivocally support the ecosystem. The holistic balance of stabilized ecosystems surrounding the Eastern Euphrates Project ecosystem will stabilize. The humanitarian activities implemented to stabilize the ecosystem will support its modernization.

To this end, the use of remote sensing indicators like the SAVI and MNDWI would provide the early warning and time series database for developing policy and tracking environmental degradation. Increasing the number of remote sensing indicators to include ground hydrology and soil moisture and temperature indicators, like the NDVI, NDMI, and LST, would provide the basis for further studies. To help develop adaptive systems, data collection and hydrology monitoring, and socio-economic data, such as agricultural practices and water-use behaviors, would be critical. The geomatic tools of this study stand as a testament to the analytical and practical use science has to offer for the sustainable management of land and water resources for Iraq and other arid lands.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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