

Geospatial Assessment of Soil Sustainability Indicators in AL-Hammar Marsh

Hasan Riyadh Dakhil AL-Jaleeli , Aurass Muhi Taha AL-Waeli 

Department, AlKarkh University of Science , Remote Sensing and Geophysics College , Remote Sensing Department

Department, AlKarkh University of Science , Remote Sensing and Geophysics College , Remote Sensing Department

E-mail: Hassan_jalely3@kus.edu.iq

E-mail: aurasssoil@kus.edu.iq

Abstract

This study aims to investigate the sustainability of the soils of the Al-Hammar Marshes region. During this study, we monitored the state of agricultural drought, surface temperature, soil degradation, and Vegetation health, all of which were derived from remote sensing data for the period from winter 2002 to 2025, especially data derived from Landsat sensors, as the ArcGIS Pro environment allowed us to do. By integrating basic soil values (salinity, percentage of exchangeable sodium, and soil organic matter content) with Sentinel-2 data within the framework of spatial analysis using geostatistics, we employed the normalization technique for the study indicators to calculate the Sustainable Development Index (SDI) using Geometric Aggregation. This study highlighted the environmental degradation resulting from climate change and harmful human activity. The study revealed a harsher climate due to extended dry seasons and a rapidly increasing global surface temperature. Climate change has led to salt accumulation and the transformation of soils into barren saline deserts, with the exception of some halophytic Vegetation communities. Our study also indicated an increase in the percentage of exchangeable sodium in the soil, leading to the deterioration of vegetation cover. Furthermore, the results showed a decline over time in the values of related soil and Vegetation spectral indicators. We believe this study provides decision-makers with insights that, if adopted through periodic monitoring of environmental indicators and field and laboratory testing, can inform the development of long-term soil sustainability strategies in the Al-Hammar Marshes. Southern Iraq.

Keyword: *ESI, NDVI anomaly, IDW, Normalization, and Geometric Aggregation.*

I. INTRODUCTION

The Hammar Marshes, covering a vast area in the marshes of southern Iraq, are a unique ecosystem. They have been affected by geopolitical factors, including forced drainage, and the harsh effects of climate change, characterized by severe droughts and their accompanying aridity, have negatively impacted the transformation of large areas into barren desert. Satellite monitoring of the southern Iraqi marshes from 1981 to 2016, conducted by Hashim et al. (2019), revealed the deterioration of vegetation cover due to the shrinking of water bodies. Drought, decreased rainfall, and rising temperatures have contributed to the desertification of this region. Furthermore, Alwan and Aziz (2022) relied on remote sensing data in their study of the marsh environment to monitor and assess environmental changes in the southern Iraqi marshlands from 1990 to 2020. This data revealed the rate of environmental improvement during the years when the area was reflooded, highlighting the importance of remote sensing data in understanding the environmental history of the region. The study (Nama et al, 2024) indicates the importance of developing strategic plans for the sustainability of the marsh environment, based on an assessment of the impact of climate change on this environment. The period from 2009 to 2020 was adopted, and their study provided comprehensive results on the state of water demand and the expected deficit due to natural and geopolitical water scarcity, and the importance of sustainable environmental planning to control this environmental



disaster. The study by Al-Mufraji and Mohammed (2024) indicates that climate change and the resulting water crisis in the region in general, and in southern Iraq, particularly the marshes, are among the biggest obstacles to implementing sustainability plans. It emphasizes the necessity of adopting remote sensing data as an effective tool for conducting environmental surveys in the Al-Hammar Marshes region due to its speed and accuracy in describing the environmental reality studied in this area, especially when managing spatial spectral data within the ArcGIS software environment. This approach was also adopted by Taha et al. (2024) in their study of the impact of climate change, specifically agricultural drought and surface temperature, and its integration with spectral indicators derived from Landsat data. They assessed the state of ecological balance in agricultural areas south of Baghdad that have deteriorated due to climate change and transformed into barren, arid lands. Furthermore, Al-Waeli and Al-Azawi (2025) concluded that integrating remote sensing data with soil properties measured in the laboratory and in the field is crucial for developing a sustainability strategy for the Ghammas soils. Similar to the Al-Hammar marshes, these areas were once stable marshes, but drought transformed them into a desert environment unsuitable for cultivating economically important Vegetations. Therefore, this study aims to assess the environmental sustainability index of the Al-Hammar marshes based on climate, soil, and vegetation factors, using a remote sensing data integration approach with soil characteristics within the ArcGIS Pro environment. The goal is to develop a sustainable strategy for monitoring and evaluating the ecological balance in this region.

II. MATERIALS AND METHODS

A. Study Area Location

This study was conducted south of Suq al-Shuyukh in the Iraqi governorate of Dhi Qar, with coordinates between latitudes 30°52'25.8005"N and 31°01'22.9189"N and longitudes 46°23'08.9451"E and 46°42'17.8200"E. The study area covered 400 square kilometers of the Hammar Marsh (the dry part of the marsh), as shown in Figure (1-A). Thirty soil samples were sampled at a depth of 30 cm, and their coordinates were recorded according to the GNSS coordinate system, as shown in Figure (1-B).

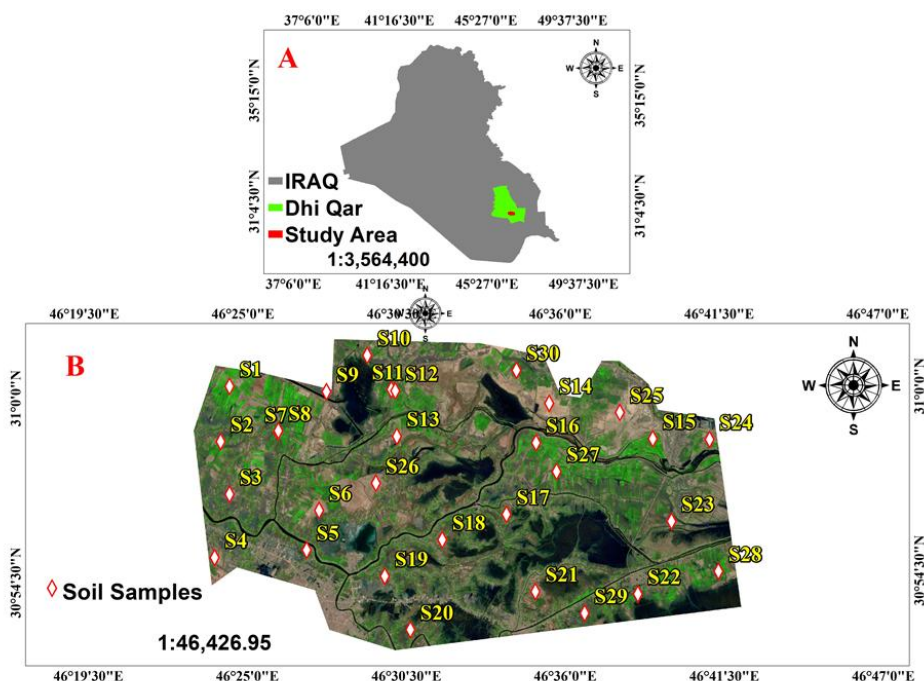


Figure (1): A. Location of the study area in Al-Hammar Marshes in Dhi Qar Governorate, Iraq. B. Locations of soil sampling points in the study area.

B. Remote Sensing Data Processing

To calculate agricultural drought, numerous satellite images were required, along with an understanding of the Earth's surface temperature variations over time, specifically for the period from 2002 to 2025. Landsat7 ETM+ and Landsat8 OLI data were utilized, along with other relevant spectral indicators, to assess the condition of water, soil, and vegetation during this period. Our reliance on Sentinel-2 data is, in fact, an investment in enhancing the spatial accuracy that this data provides.

C. Processing Landsat Sensors

Landsat7 ETM+ and Landsat8 OLI data were obtained from <https://earthexplorer.usgs.gov/> . Landsat 7 ETM+ data for the period from winter 2002 to spring 2013 and Landsat 8 OLI/TIRS data for the period from winter 2014 to spring 2025. Digital processing was performed on the data using the same mechanism employed by AlWaeli et al. (2024) for processing Landsat spectral and thermal data. This was implemented using ENVI5.6 software. The Normalized Difference Vegetation Index (NDVI) (Rose et al., 1973) was then calculated, as shown in Equation (1):

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \dots\dots\dots(1)$$

Agricultural drought was calculated for Iraq conditions according to (Al-Waeli et al, 2020) by taking the average NDVI during the wheat growing season during winter and spring for the years (2002 until the end of spring 2025), where the value of NDVI anomaly (agricultural drought function) was calculated according to equation (2):

$$NDVI_{anomaly(i)} = \frac{NDVI_{growingseason(i)} - \overline{NDVI}}{NDVI} * 100 \dots\dots\dots(2)$$

Agricultural drought was classified as follows (see Table 1) according to (Nanzad et al., 2019):

TABLE (1): SHOWS THE CLASSIFICATIONS OF AGRICULTURAL DROUGHT ACCORDING TO (Nanzad et al., 2019):

Description	NDVI anomaly values (%)
Normal (Non-drought)	> 0%
Mild drought	0 – (-10%)
Moderate drought	(-10%)-(-25%)
Severe drought	(-25%)-(-50%)
Very severe drought	< -50%

The Optimized Soil-Adjusted Vegetation Index (OSAVI) (Heute et al., 1997) and Enhanced Vegetation Index (EVI) (Heute et al., 2002) spectral indices were calculated as in equations (3-5):

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \dots\dots\dots(3)$$

$$OSAVI = \frac{(NIR - Red)}{(NIR + Red + 0.16)} \dots\dots\dots(4)$$

$$EVI = 2.5 \left[\frac{(NIR - Red)}{(NIR + 6 * Red - 7.5 * Blue + 1)} \right] \dots\dots\dots(5)$$



For the purpose of calculating the Earth's surface temperature from Landsat sensor data, the procedures of (Chander et al, 2009) were followed in converting the digital thermal beam values to Brightness Temperature (BT), as in Equation (6):

$$\text{BrightnessTemperature}(BT) = \frac{K_2}{\left(\frac{K_1}{L_\lambda} + 1\right)} \dots\dots\dots(6)$$

Since K_2 and K_1 are constants that can be obtained from the MTL file of satellite images and L_λ is the thermal beam processed according to what was reported by (ALWaeli et al, 2024), therefore the Earth's surface heat index ESTI was calculated as in equation (7):

$$LSTI = \frac{BT}{1 + \left(\frac{L_\lambda * BT}{\rho}\right) + \ln(\epsilon)} \dots\dots\dots(7)$$

Where ρ equals 14380 and ϵ represents the emissivity, the calculation method for which can be found in Robertson and Bakimchandra (2025).

D. Sentinel-2 Processing

Processed using ENVI5.6 as described by Al-Waeli and Al-Azawi (2025) on the image obtained from the Copernicus Browser on March 17, 2025.

E. Laboratory Analysis of Soil Samples

Thirty soil samples were processed according to (Estefan et al., 2013). This involved preparing them as a saturated paste according to the specifications of the American Laboratory for Soil Testing. All analyses included measuring the electrical conductivity of the extracted solution of the saturated soil paste to measure (ECe) using an EC-Meter and the soil pH value using a pH-Meter. CaCO₃ in the soil was measured with a Calcimeter, and gypsum was precipitated using an acetone solution, with the electrical conductivity of the precipitate being measured. The soil organic content was measured by wet oxidation with potassium dichromate and the addition of concentrated sulfuric acid as a heat source, followed by titration with ferrous ammonium sulfate. The cation exchange capacity (CEC) was measured using the method specific to gypsum and calcareous soils. Exchangeable sodium in the soil was measured by extracting it with ammonium acetate and then measured using a Flamephotometer. The percentage exchangeable sodium (ESP) was calculated as in Equation (8):

$$ESP = \frac{\text{Exchangeable} - Na}{CEC} \times 100 \dots\dots\dots(8)$$

F. Environmental Sustainability Index (ESI)

As proposed by (Gan et al, 2017), and for the purpose of assessing the balance in the Al-Hammar Marsh environment, we adopted in this study the Environmental Sustainability Index (ESI) as it is an analytical tool based on the principles of the Sustainable Society Index (SSI), which adopts normalization and equal weighting within Geometric Aggregation to obtain a fair and accurate composite average value that expresses the reality of environmental sustainability on a scale ranging between 1 and 10, when applied to the three environmental elements (climate, soil, and vegetation) according to equation (9):

$$ESI = (ClimateIndex * SoilIndex * VegetationIndex)^{1/3} \dots\dots\dots(9)$$



The normalization method was applied to the above indicator elements according to what was suggested by (Becker, 2022) by adopting equation (10) for negative indicators and (11) for positive indicators, as follows:

$$NegativeIndicator = \frac{X_{max} - X_i}{X_{max} - X_{min}} \times 10 \dots\dots\dots(10)$$

$$positiveIndicator = \frac{X_i - X_{min}}{X_{max} - X_{min}} \times 10 \dots\dots\dots(11)$$

Therefore, the classification of the indicators and their components for the purpose of implementing the above equations is based on normalization, as shown in Table (2).

TABLE (2) CLASSIFICATION OF ENVIRONMENTAL SUSTAINABILITY INDICATOR COMPONENTS IN THE AL-HAMMAR MARSHES

Ecological Indicators	The Elements	Type and Ecological Significance
Climate	Agricultural Drought	Positive, (Higher NDVI values indicate abundant moisture and minimal drought stress, improving the ecosystem's resilience.)
	Earth Surface Temperature(ESTI)	Negative, (Elevated surface temperatures contribute to thermal stress and ecosystem aridification.)
Soil	Soil Salinity (ECe)	Negative, (High salinity levels result in chemical degradation affecting soil fertility and crop yields.)
	Exchangeable Sodium Percentage (ESP)	Negative, (Increased ESP causes soil dispersion and reduces permeability, impacting soil structure adversely.)
	Soil Organic Matter (SOM)	Positive, (Organic matter status indicates soil fertility, biological activity, and structural integrity.)
	OSAVI (Optimized Soil-Adjusted Vegetation Index)	Positive, (Reflects vegetation vigor relative to soil exposure, improving accuracy in soil-Vegetation interaction assessment.)
Vegetation	(NDVI) Normalized Difference Vegetation Index	Positive, (Monitors photosynthetic activity and green biomass density, key to ecosystem productivity)
	(EVI) Enhanced Vegetation Index	Positive, (Provides refined vegetation status by minimizing canopy background and atmospheric distortions.)

$$ClimateIndex = (AgriculturalDrought * EarthSurfaceTemperature(ESTI))^{1/2} \dots\dots(12)$$

$$SoilIndex = (ECe * ESP * SOM * OSAVI)^{1/4} \dots\dots\dots(13)$$

$$VegetationIndex = (NDVI * EVI)^{1/2} \dots\dots\dots(14)$$

G. Statistical Analysis

The SPSS 26 methodology (AL-Waeli, 2020) was used for descriptive statistical analysis of the study indicators. GenSTAT 12 was used to study the temporal variability between environmental indicators derived from remote sensing data, namely agricultural drought, land surface temperature index, OSAVI, and EVI. Microsoft Excel 2024 was used for the graphs attached to the study indicator map templates in ArcGIS Pro V.3.



H. Geostatistical Analysis

The Inverse Distance Weighted (IDW) interpolation application (ALWaeli et al., 2024) geostatistical methodology in ArcGIS Pro. V.3 was used to map the study indicators. The CoKriking function was used to analyze the combined spatial variance between the environmental indicators, Vegetation health status, and the environmental sustainability index.

I. Classification in Study Indicator Maps

Soil properties were classified according to what was reported by (Al-Rifae, and Al-Rubay, 2017) because it is suitable for studying the Iraqi environment, while in our study we proposed classifying environmental sustainability indicators to be according to the classification in Table (3):

TABLE (3): CLASSIFICATION OF ENVIRONMENTAL SUSTAINABILITY INDICATORS FOR AL-HAMMAR MARSHES

ESI	Description	Sustainability Classes
> 8	Rarely stressed, all dimensions healthy and resilient.	Excellent Sustainability
6 - 8	Most dimensions healthy; minor environmental limitations.	Good Sustainability
4 - 6	Multiple environmental pressures identified; requires management.	Moderate Sustainability
< 4	Significant stress or degradation across dimensions; urgent restoration needed.	Low Sustainability

III. RESULTS AND DISCUSSION

A. Climate Index

Table (4) shows the most important descriptive statistical values of the climate index in the study area, which indicated the existence of tangible variations between the minimum and maximum values of agricultural drought and the Earth's surface temperature index (ESTI). The geopolitical conditions of the region and what they have changed through the climate characteristic towards aridity have led to the transformation of the environment in the Al-Hammar marshes from a semi-balanced environment in the mid-seventies of the twentieth century to an unstable environment fluctuating between severe drying, which sometimes extends for several years, and sudden flooding, which increases the dynamics of the re-salinization of both water and soil, which has accelerated the deterioration of the agricultural environment chemically and turned vast parts into desert conditions that hinder sustainability (Hashim et al, 2019). The details of this can be understood from studying the agricultural drought index and the ESTI.

TABLE (4) . DESCRIPTIVE STATISTICS OF CLIMATE INDEX

	N	Range	Minimum	Maximum	Mean	Std. Deviation
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic
Agricultural Drought	30	72.41	-93.80	-21.39	-69.72	22.09
ESTI	30	8.47	288.29	296.76	292.36	2.54

Figure (2) shows that the study area was affected by two classifications of agricultural drought, severe and very severe. The areas of these two classifications fluctuated due to the fluctuation in the abundance of marsh water provided by the surpluses of the Euphrates River and the rainfall, which is almost non-existent in most



rainy seasons during the study period. These temporal and spatial variations of water bodies, and consequently the two classifications of agricultural drought mentioned above, have been noted by researchers since the 70s of the 20th century. From the increasing drying due to human factors, which witnessed its peak in the mid-eighties of the last century until the nineties, for the purpose of utilizing the land for agriculture, the dry part reached 85% of the flooded area in the natural Al-Hammar Marsh. Although the flooding reached clear percentages in years such as 2019 and 2020, the aridity of the years since the beginning of this century prevented a return to flooding areas that achieved the ecological balance before the human factor disrupted it, supported by the harsh climate and drought (Al-Mufraji and Mohammed, 2024).

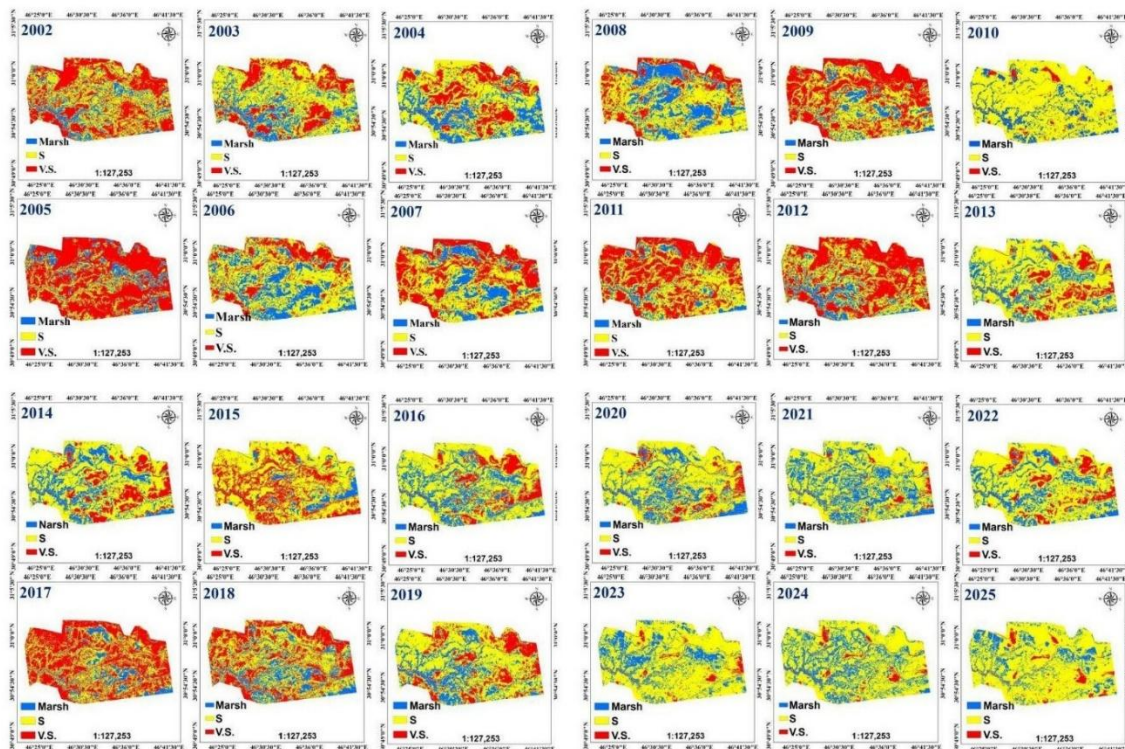


Fig (2): Spatial distribution of drought-resistant crop varieties in the study area for the period (2002-2025).

Figure (2) shows that the flooded areas and their surroundings reduce the impact of drought relatively compared to dry years that are characterized by less flooded areas. This decline is accompanied by an increase in evaporation rates, especially in the middle and end of spring in the conditions of the study area. This study, based on agricultural drought rates derived from NDVI values processed according to Landsat sensor data, has influenced environmental survey procedures without the need for drought estimates measured from meteorological stations, while providing an interpretive view of the spatial interactions between flooding and drought conditions within the space monitoring time of this phenomenon (Nama et al, 2024). Figure (3) shows a significant variation in agricultural drought rates over time, as the year 2017 witnessed the lowest agricultural drought rate, reaching -75.13, while the highest agricultural drought rate reached -75.13 in the year 2016. This is attributed to the fact that the decrease in annual marsh areas fluctuates within a wide range.

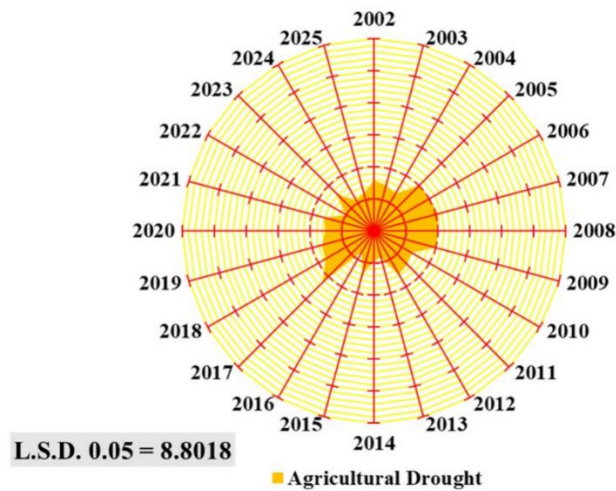


Fig (3): Significance of temporal variation in agricultural drought classifications in the study area for the period (2002-2025).

Figure (4) shows the Earth's surface temperature index (ESTI) in the marshland area. Flooding reduces the index, as the marshland is part of an arid environment. Furthermore, reflooding the dry areas of the marshland means that the solar energy will be concentrated primarily on the water, thus lowering the ESTI value. Meanwhile, the dry land will be exposed to the effects of solar heating. The marshland area in southern Iraq is generally characterized by cooler temperatures relative to the surrounding saline deserts. (Alwan and Aziz, 2022).

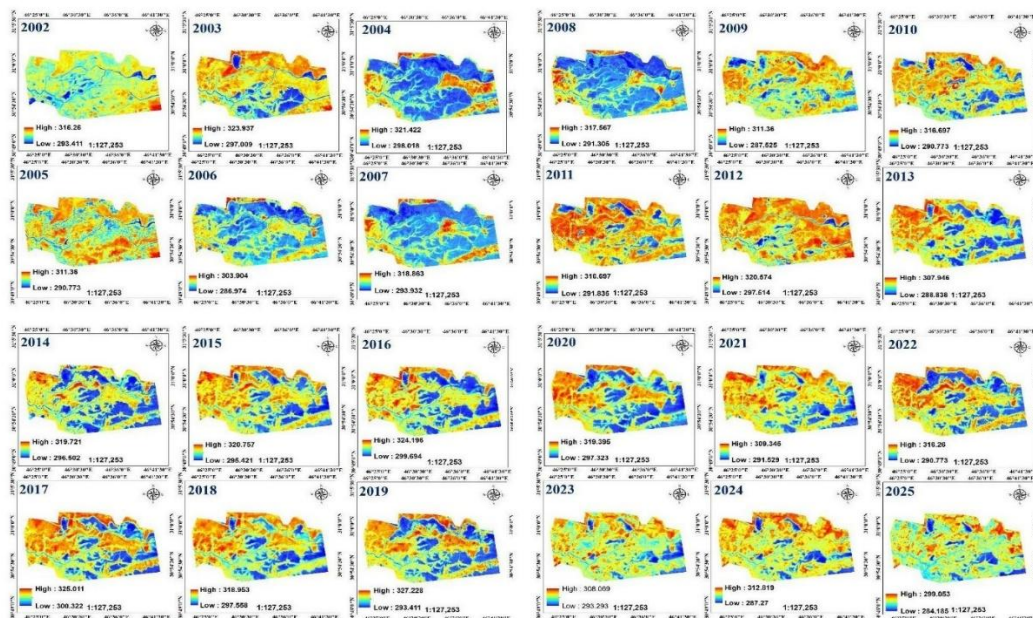


Fig (4): Spatial distribution of Earth's surface temperature in the study area for the period (2002-2025).

Figure (5) shows a significant variation in ESTI rates over time. The lowest ESTI rate was recorded in 2025 at 289.28, while the highest rate was 311.33 in 2012. This significant difference, as mentioned above, is attributed to the fluctuation in seasonal reflooding and draining, which are inextricably linked to geopolitical conditions. Specifically, since the 1980s, human activity has been detrimental to the ecological balance, leading to increasingly harsh and arid climates in this region. It should be noted that vegetation plays a clear and fundamental role in the variation of ESTI rates, as it is responsible for differences within a single season, as well as across the years of our study. This aligns with the findings of Hashim et al. (2019). Furthermore, since the 1990s, droughts and the decline in water supplies from the Tigris and Euphrates rivers, in addition to the reduction of marshland areas to a point of no return, have caused significant degradation. Vegetation cover and increased temperature levels of environmental elements, most importantly the Earth's surface, in the dried-up marshlands of southern Iraq.

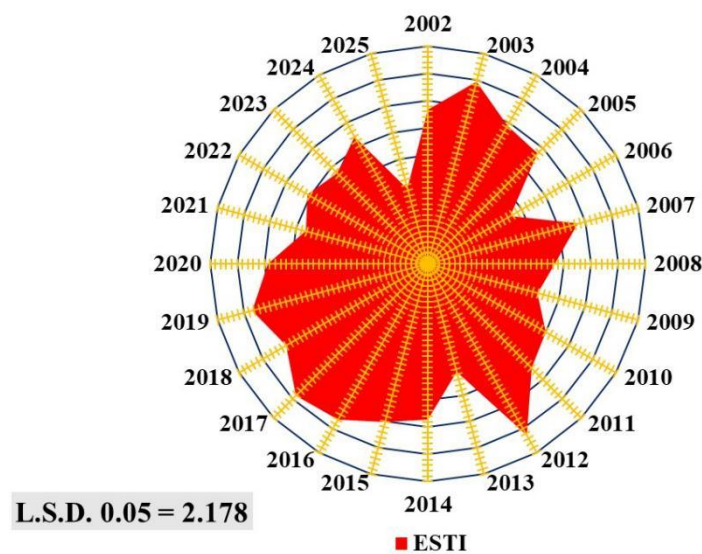


Fig (5): Significance of temporal variability between ESTI rates in the study area for the period (2002-2025).

B. Soil Index

Table (5) shows the descriptive statistical values of the soil index, indicating a state of chemical degradation represented by high soil salinity and exchangeable sodium values. This directly causes the deterioration of vegetation cover, which is reflected in the decrease in soil organic matter content. As Taha et al. (2024) demonstrated in their study of soil conditions in central Iraq using Landsat data, the impact of agricultural drought and surface temperature is evident in the transformation of agricultural areas and other former swamps and marshes into dried-up areas due to the severity of climate change. This is clearly manifested in soil salinization and a decrease in organic matter content, which is a key indicator of agricultural activity in Iraq. This represents the forced abandonment of agriculture by farmers, leading to unemployment and social problems as a result of these destructive environmental impacts on the economic structure.

TABLE (5). DESCRIPTIVE STATISTICS OF SOILS

	N	Range	Minimum	Maximum	Mean		Std. Deviation
					Statistic	Std. Error	
PH	30	.62	7.16	7.78	7.5483	.037	.20
ECe	30	12.36	2.46	14.82	8.8390	.684	3.74
S.O.M.	30	11.00	4.17	15.17	9.8500	.47	2.55
Lime	30	26.60	262.15	288.75	279.38	1.42	7.83
Gypsum	30	.55	1.74	2.29	2.09	.029	.16
EX_Na	30	4.34	2.18	6.520	4.945	.24	1.29
CEC	30	3.87	24.24	28.11	27.25	.16	.89
ESP	30	14.64	8.55	23.19	18.02	.79	4.34
OSAVI	30	.16	.01	.18	.06	.01	.04

In Figure (6), it is noted that most of the study area is chemically degraded and is likely to become arid deserts in the near future unless basic administrative measures are taken to avoid this serious environmental disaster due to climate change. Perhaps one of the most prominent solutions offered for the sustainability of the soils of the study area is to Vegetation them with Vegetations that absorb salt, which means turning them into tools for reclaiming soils degraded by salts, in addition to what they produce of Vegetation organic waste that contributes to raising the soil content of organic matter, as in the study of (Izadi et al, 2025) in this regard, as it suggested Vegetation halophilic Vegetations for the purpose of reclaiming soils that are depleted by water due to severe evaporation in the conditions of the Gulf region.

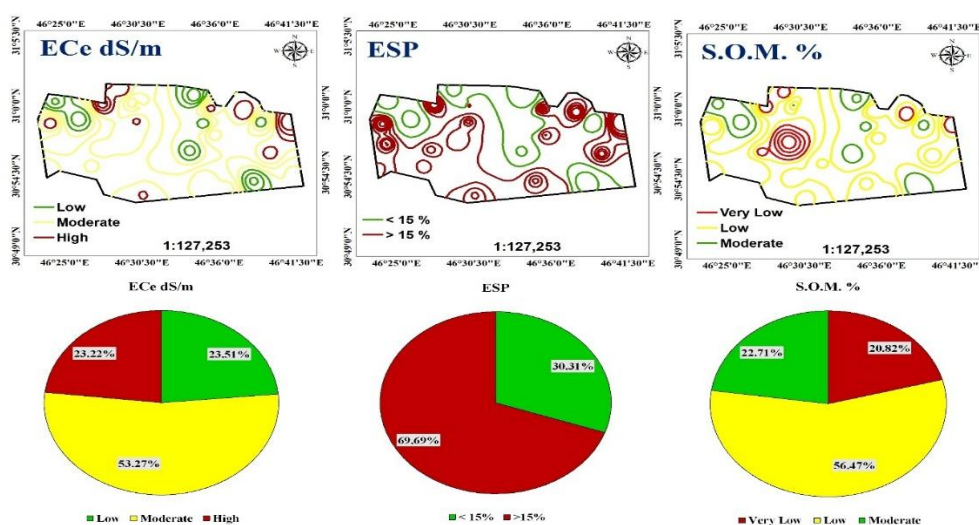


Fig (6): Spatial distribution of soil properties in the study area.



In recent research, to highlight the role of spectral indicators in sustainable development studies, OSaVI was used as a function of soil condition. High positive values of this indicator suggest stable vegetation cover due to continuous farming and agricultural exploitation (Taha et al., 2024). Figure (7) shows that OSaVI values indicate fluctuations in agricultural exploitation and, consequently, vegetation density in the study area. Naturally, this vegetation cover is linked to soil salinity and the risk of high sodium levels, which are a direct indicator of the negative impact of climate change, especially drought, on the agricultural ecological balance (Al Waeli et al., 2024).

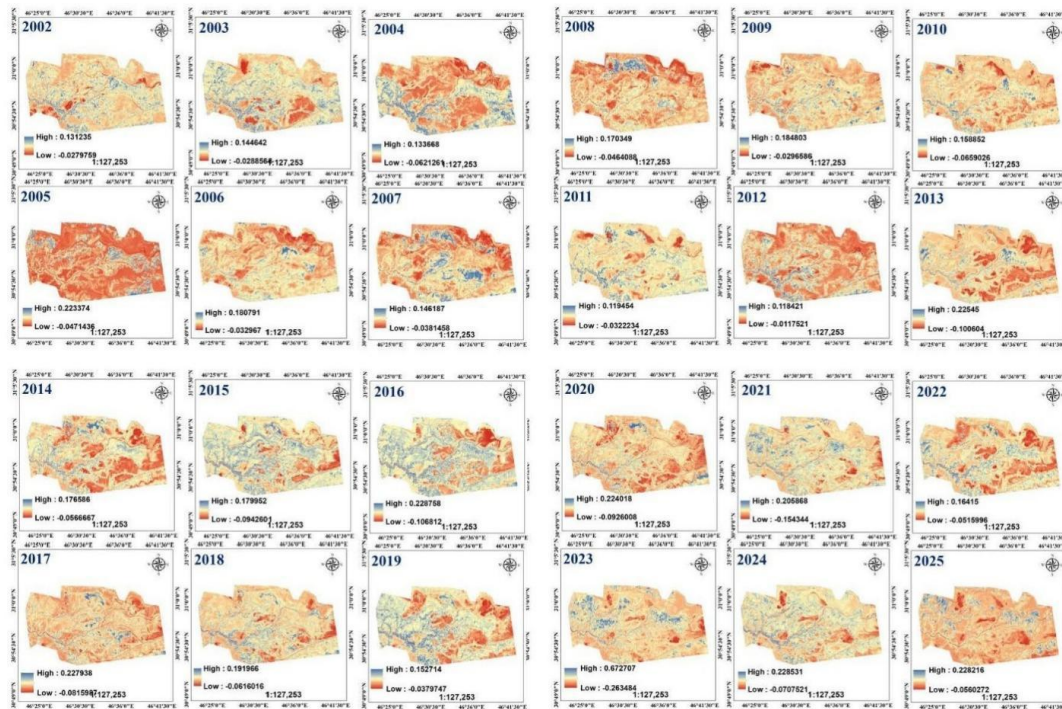


Fig (7): Spatial distribution of OSaVI values in the study area for the period (2002-2025).

Figure (8) shows significant variations in OSaVI values in the study area for the period (2002-2025). The lowest OSaVI value was recorded in 2013 at 0.0095, while the highest value was recorded in 2025 at 0.0969. This significant difference is attributed to the role of soil salinity, which increases due to drought and high evaporation rates, especially chloride salt compounds with sodium and magnesium. The resulting salt stress negatively impacts physiological conditions, most notably inhibiting chlorophyll bioactivity, leading to weakened vegetation cover, reduced organic content, and accelerated decomposition of accumulated organic matter due to microbial activity in alkaline, calcareous soil conditions (Al Waeli et al., 2020).

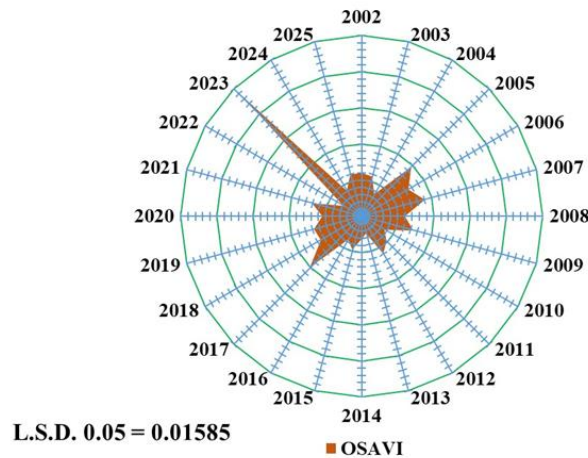


Fig (8): Significance of temporal variation in OSAVI rates in the study area for the period (2002-2025)

C. Vegetation Index

Figure (9) shows the impact of Vegetation health status, expressed by the EVI spectral index. Healthy vegetation cover fluctuated according to increased drought, rising temperatures, and the detrimental effects of salinity and exchangeable sodium in the soil, negatively impacting Vegetation physiology. A study by Akhtar et al. (2015) indicates that low soil moisture content contributes to increased salinity and reduces the wheat Vegetation's ability to absorb nutrients, leading to a decline in its health due to salinity damage. In this study, we confirm that soil salinization caused by climatic changes resulting from prolonged drought in the study area was a contributing factor to the physiological decline of Vegetations, with the exception of the presence of halophilic Vegetations such, which, according to soil surveyors, indicate desertification in the region.

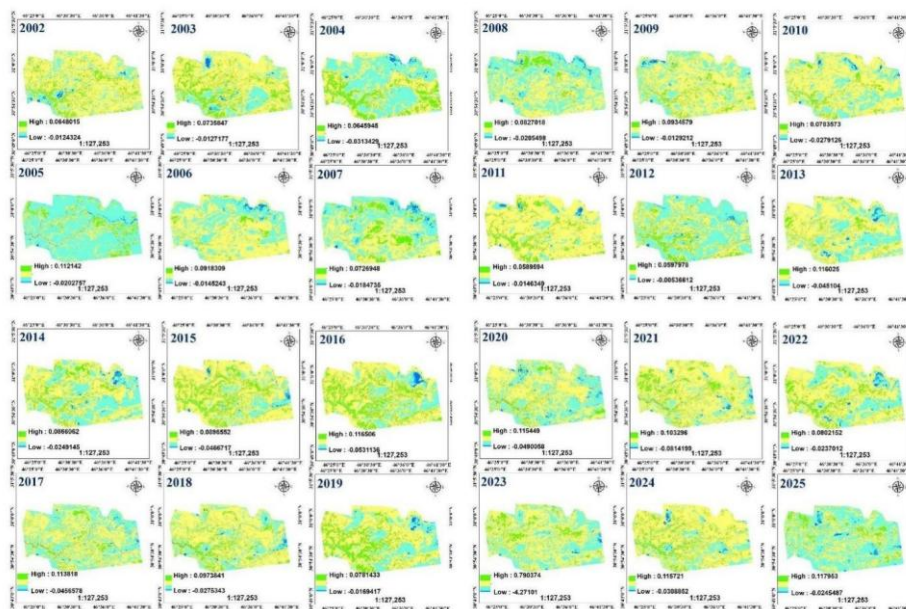


Fig (9): Spatial distribution of EVI values in the study area for the period (2002-2025).



Figure (10) shows significant variations in OSAVI values in the study area for the period (2002-2025), where the year 2013 witnessed the lowest EVI rate, which reached 0.00503, while the highest rate reached 0.09594 in the year 2025. This significant difference is attributed to the hydrochemical fluctuation of water, which, due to drought conditions, causes solutes to precipitate from it to penetrate the rhizosphere, generating an osmotic potential that reduces the leaf area and weakens the physiological activity of chlorophyll, with the appearance of needle-like desert Vegetations in which EVI values decrease. This is consistent with the study of (Taha et al, 2024), which indicates that agricultural drought was significantly associated with a decrease in EVI values and the deterioration of vegetation cover due to chemical soil degradation and accelerated desertification due to the activation of climate changes for salt accumulation, especially sodium compounds in Iraqi soils.

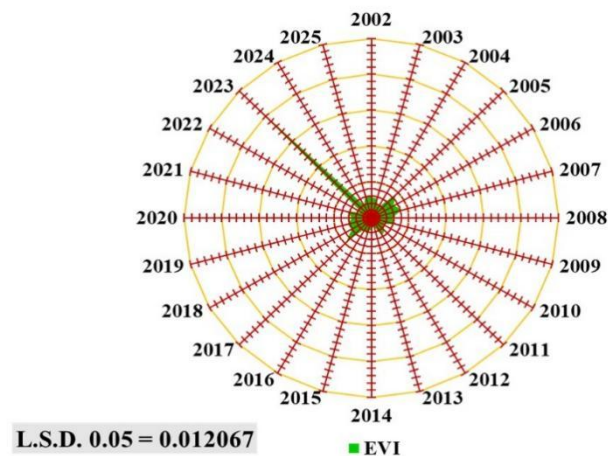


Fig (10): Significance of time-related variability between EVI rates in the study area for the period (2002-2025).

D. Environmental Sustainability Index (ESI)

Figure (11) shows that low environmental sustainability occupied 14.66%, 19.59%, and 33.71% of the study area, while moderate sustainability occupied 57.49%, 44.16%, and 42.62%. The Good category occupied 23.09%, 25.87%, and 17.29%, and the Excellent category occupied 4.76%, 10.38%, and 6.38%, respectively. These percentages represent the climate, soil, and plant indices. This convergence in the indices' responses and their similar impact on the ESI may be attributed to the complex interactions and reciprocal effects of climate change on soil degradation and vegetation cover, leading to ecological imbalance in the study area. The significant reduction in the flooded area of the Al-Hammar Marshes is due to weakened water supplies from the Euphrates River coupled with increasing evaporation rates. It negatively affected the three elements of the environmental sustainability index (climate, soil, and vegetation), and therefore requires the investment of remote sensing data for monitoring and diagnosing environmentally degraded areas in order to limit their expansion and develop strategic plans for their sustainability (AL-Waeli and Al-Azawi, 2025).

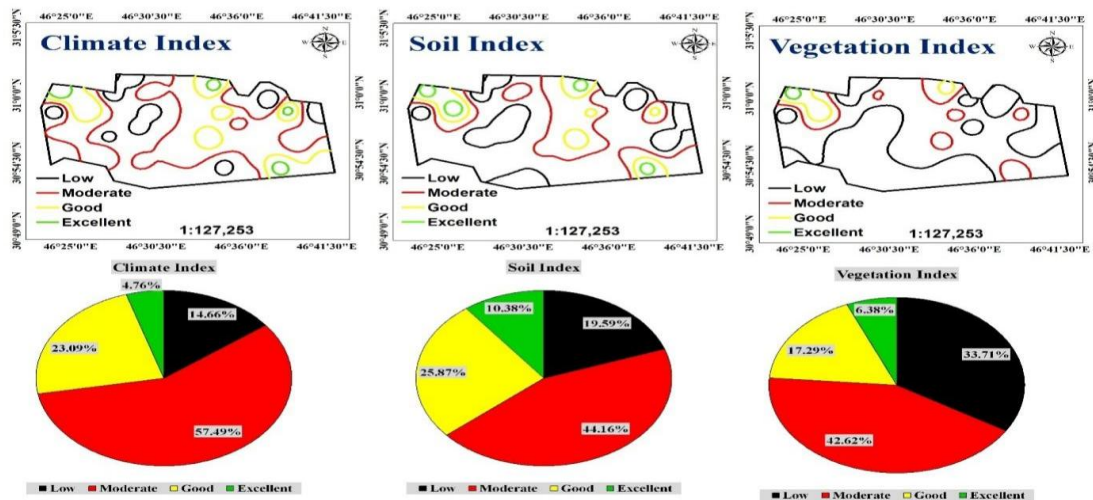


Fig (11): Spatial distribution of the three environmental sustainability indicators in the study area.

Figure (12) shows that the Environmental Sustainability Index (ESI) in the dried soils of the Al-Hammar Marsh was distributed as follows: 24.05 for the Low category, 35.11 for the Moderate category, 30.19 for the Good category, and 10.65 for the Excellent category, as percentages of the study area. Therefore, both degraded and moderate areas urgently need to develop vigorous plans to prevent their permanent loss without economic investment at the environmental, economic, tourism, and, most importantly, agricultural levels (AbdelRahman et al., 2022). In our study, we identified that soil quality is better the closer it is to the remaining water bodies in the Al-Hammar Marsh. The strategic plans that decision-makers should adopt are those that incorporate global environmental sustainability plans implemented in degraded aquatic environments that have been affected globally by climate change. To leverage the spatial accuracy of the data, Sentinel-2 data was used for remote sensing data indices related to the OSAVI, NDVI, and other indicators. EVI.

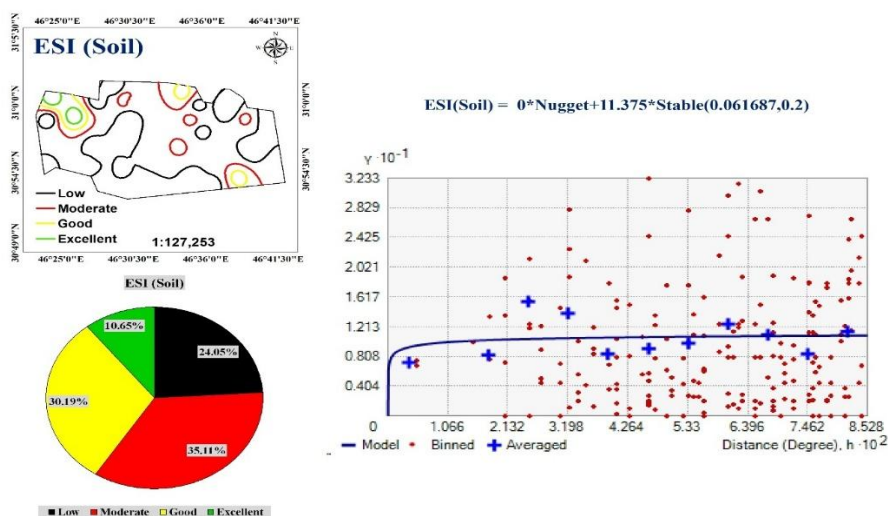


Fig (12) Spatial Analysis for ESI and Semivariogram in the Soils of the Study Area.

In this study, we relied on spatial analysis procedures based on geostatistical concepts. This enabled us to visualize the nature of the spatial relationships between environmental sustainability indicators. It is indeed a sound method for assessing the state of ecological equilibrium, especially in areas exposed to salinization due to climate change in Iraq (Taha et al., 2024). We believe that remote sensing and the integration of its data, from which climate and vegetation indices can be derived, along with laboratory analyses of soil properties, significantly contribute to developing sustainable development strategies in the Al-Hammar Marsh environment (Figure 13). We also believe that this method significantly reduces the costs of traditional surveys, provides continuous monitoring of the Al-Hammar Marsh environment, and allows for mitigating risks before they escalate.

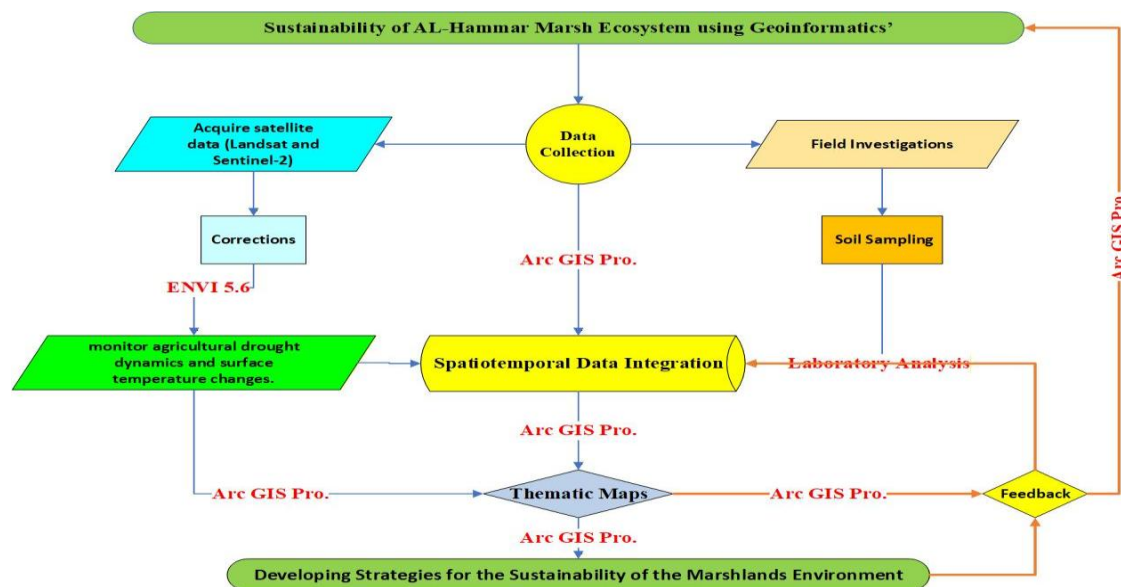


Fig (13) Flowchart of the sustainability of the Al-Hammar Marsh environment.

Conclusion: The study area embodies a unique model of the active interaction between climatic elements, soil characteristics, plant health, and biodiversity. We believe our proposed model for assessing environmental sustainability is effective in diagnosing environmental imbalances to inform strategic planning by decision-makers to restore the area to equilibrium. Therefore, focusing on the availability of water supplies from the Euphrates River and ensuring the introduction of high-quality water suitable for diverse human and agricultural uses is crucial to mitigating the environmental damage caused by increased soil salinity due to climate change. Furthermore, it is essential to establish mechanisms for continuous ESI monitoring using SENTINEL-2 data and incorporating it into spatial analysis and forecasting models within the ArcGIS Pro digital environment. We believe this is the most suitable approach for managing the Al-Hammar Marsh environment in the short term, particularly regarding monitoring soil chemical changes and the intrusion of invasive plant species that harm the essential biodiversity in this complex environment under extremely arid conditions.

IV. REFERENCES

Abdel Rahman, A.E.M., Engel, B., Eid, S.M. and Aboelsoud, H.M. (2022) 'A new index to assess soil sustainability based on temporal changes of soil measurements using geomatics – an example from El-Sharkia, Egypt', *All Earth*, 34(1), pp. 147–166. Available at: <https://doi.org/10.1080/27669645.2022.2103953>

- Akhtar, S.S., Andersen, M.N. and Liu, F. (2015) 'Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress', *Agricultural Water Management*, 158, pp. 61–68. Available at: <https://doi.org/10.1016/j.agwat.2015.04.010>
- Al-Waeli, A.M.T. and Al-Azawi, F.W. (2025) 'Geospatial analysis of management indicators for some Ghammas soils in integration with Sentinel data', *Sarhad Journal of Agriculture*, 41(2), pp. 946–957. Available at: <https://dx.doi.org/10.17582/journal.sja/2025/41.2.946.957>
- Al-Waeli, A.M.T., Al-Azawi, F.W. and Hamid, H.M. (2024) 'Evaluation of the sensitivity of Al-Husseiniya soils in Karbala to erosion using Landsat sensors', *Environmental Challenges*, 14. Available at: <https://doi.org/10.1016/j.envc.2024.100857>
- Al-Waeli, A.M.T. (2020) 'Assessment of soil sensitivity for physical degradation in Abi-Garaq by geomatics techniques', *International Journal of Agricultural and Statistical Sciences*, 16(Suppl. 1), pp. 1865–1873. Available at: <https://connectjournals.com/pages/article/details/toc032967>
- Al-Mufraji, N.Y. and Mohammed, R. (2024) 'Land cover dynamics of Al-Hammar Marsh: Restoration plan methodology assessment', *International Journal of Sustainable Development and Planning*, 19(10), pp. 3849–3859. Available at: <https://doi.org/10.18280/ijstdp.191013>
- Al-Rifaei, M.K.I. and Al-Rubay, A.A.M. (2017) 'Effect of adding irrigation water quality index to MEDALUS model in environmental sensitivity to desertification in Sheikh Saad project, Wasit Governorate', *Iraqi Journal of Agricultural Research*, 22(1), pp. 101–116. Available at: <https://iasj.rdd.edu.iq/journals/uploads/2025/07/01/390a5b82d124107c63e764d68deb64ce.pdf>
- Al-Waeli, A.M.T., Taha, S.M. and Mahmood, S.S. (2020) 'Evaluation of drought impact on agricultural status for some Wasit soils using geomatic techniques', *Plant Archives*, 20(2), pp. 554–565. Available at: <https://pdfcandy.com/ar/result/2982f4833fb7c1e8.html>
- Alwan, I.A. and Aziz, N.A. (2022) 'Monitoring of surface ecological change using remote sensing technique over Al-Hawizeh Marsh, Southern Iraq', *Remote Sensing Applications: Society and Environment*, 27, 100784. Available at: <https://doi.org/10.1016/j.rsase.2022.100784>
- Becker, W. (2022) *Composite indicator development and analysis in R with COINr*. European Commission Joint Research Centre. Available at: <https://bluefoxr.github.io/COINrDoc/normalisation.html>
- Chander, G., Markham, B.L. and Helder, D.L. (2009) 'Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM+, and EO-1 ALI sensors', *Remote Sensing of Environment*, 113(5), pp. 893–903. Available at: <https://doi.org/10.1016/j.rse.2009.01.007>
- Estefan, G., Sommer, R. and Ryan, J. (2013) *Methods of soil, plant, and water analysis: A manual for the West Asia and North Africa region*. 3rd edn. ICARDA. Available at: <https://kh.aquaenergyexpo.com/wp-content/uploads/2022/11/Methods-Of-Soil-Plant-And-Water-Analysis-A-Manual-For-The-West-Asia-And-North-Africa-Region.pdf>
- Gan, X., Fernandez, I.C., Guo, J., Wilson, M., Zhao, Y., Zhou, B. and Wu, J. (2017) 'When to use what: Methods for weighting and aggregating sustainability indicators', *Ecological Indicators*, 81, pp. 491–502. Available at: <https://doi.org/10.1016/j.ecolind.2017.05.068>
- Hashim, B.M., Sultan, M.A., Attyia, M.N., Al Maliki, A.A. and Al-Ansari, N. (2019) 'Change detection and impact of climate changes to Iraqi southern marshes using Landsat 2 MSS, Landsat 8 OLI and Sentinel 2 MSI data and GIS applications', *Applied Sciences*, 9(10), 2016. Available at: <https://doi.org/10.3390/app9102016>



- Huete, A.R., Liu, H.Q., Batchily, K. and van Leeuwen, W. (1997) 'A comparison of vegetation indices global set of TM images for EOS-MODIS', *Remote Sensing of Environment*, 59, pp. 440–451. Available at: [https://doi.org/10.1016/S0034-4257\(96\)00112-5](https://doi.org/10.1016/S0034-4257(96)00112-5)
- Huete, A., Didan, K., Miura, T., Rodriguez, E., Gao, X. and Ferreira, L.G. (2002) 'Overview of the radiometric and biophysical performance of the MODIS vegetation indices', *Remote Sensing of Environment*, 83(1–2), pp. 195–213. Available at: [https://doi.org/10.1016/S0034-4257\(02\)00096-2](https://doi.org/10.1016/S0034-4257(02)00096-2)
- Izadi, Y., Nabipour, M. and Ranjbar, G. (2025) 'Variations in growth, physiology and fodder quality among *Salicornia persica* ecotypes irrigated with Persian Gulf seawater', *Scientific Reports*, 15, 28850. Available at: <https://doi.org/10.1038/s41598-025-15008-6>
- Nama, A.H., Alwan, I.A. and Pham, Q.B. (2024) 'Climate change and future challenges to the sustainable management of the Iraqi marshlands', *Environmental Monitoring and Assessment*, 196(1), 35. Available at: <https://doi.org/10.1007/s10661-023-12168-8>
- Nanzad, L., Zhang, J., Tuvdendorj, B., Nabil, M., Zhang, S. and Bai, Y. (2019) 'NDVI anomaly for drought monitoring and its correlation with climate factors over Mongolia from 2000 to 2016', *Journal of Arid Environments*, 164, pp. 69–77. Available at: <https://doi.org/10.1016/j.jaridenv.2019.01.019>
- Robertson, N. and Bakimchandra, O. (2025) 'Land surface temperature estimation from satellite imagery in Imphal-Iril River Catchment, Manipur, India', *SSRG International Journal of Geo-informatics and Geological Science*, 12(2), pp. 1–8. Available at: <https://doi.org/10.14445/23939206/IJGGS-V12I2P101>
- Rouse, J.W., Haas, R.H., Schell, J.A. and Deering, D.W. (1973) 'Monitoring vegetation systems in the Great Plains with ERTS', in *Proceedings of the Third ERTS-1 Symposium*, NASA SP-351, 1, pp. 309–317. Available at: <https://ntrs.nasa.gov/api/citations/19740022614/downloads/19740022614.pdf>
- Taha, A.M., Ibrahim, I.A., Abduladeem, H., Yassen, M.Q., Ahmed, O.K. and Abdul-Allah, T.N. (2024) 'Assessing drought conditions in Southern Baghdad (1988–2023) using NDVI anomaly and its impact on soil and vegetation', *Pakistan Journal of Agricultural Research*, 37(3), pp. 241–249. Available at: <https://dx.doi.org/10.17582/journal.pjar/2024/37.3.241.249>

