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Assessment of Soil Chemical Degradation and Salinization in Al-Suda Marsh, Southern Iraq Using Field Measurements and Sentinel-2 Spectral Indices

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Abstract:

Al-Suda Marsh in southern Iraq is in danger of becoming uninhabitable because of a lack of water and salinization. This study combines field soil analyses with Sentinel-2 remote sensing to evaluate chemical degradation and salinity. Soil profiles from three horizons (0-60 cm) revealed clay-dominated textures, high electrical conductivity (up to 11.60 dS/m in Cgk2), elevated sulfate (46.5 mmol/L) and sodium, plus heavy metal accumulation (Fe: 1931 mg/kg surface). Spectral indices (NDVI, Moisture Index) derived from October 2022 imagery validated extensive vegetation loss and desiccation, exhibiting a strong correlation with ground data. The results show that salt and metal can move up through low-permeability clays through capillary action, which confirms that remote sensing can be used to monitor marshes. Urgent water restoration is recommended to mitigate toxicity and restore biodiversity. Samples from three horizons (0-60 cm) showed that the textures were mostly clay, the electrical conductivity was high (up to 11.60 dS/m in Cgk2), the CaCO₃ levels were high (33-41%), the organic matter levels were high (19.8-25.3%), and the heavy metals were mostly in the surface layers (Fe: 1911-1931 mg/kg; Cu: 26.9-30.3 mg/kg; Mn: 265-281 mg/kg). Spectral indices (NDVI, Moisture Index) corroborated extensive vegetation loss and desiccation, substantiating ground data spatially. These results show that marsh soils need to be restored quickly to lower salinity and metal toxicity.

Keywords: *Soil degradation, heavy metals, soil salinity, spectral indices, Iraqi marshes.*

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1. Introduction

The Mesopotamian marshes in southern Iraq, including Al-Suda Marsh in Maysan Governorate, are important ecological areas that support a variety of plant and animal life and local communities. However, they are quickly declining due to damming upstream, lower water flows, and long periods of drought. In recent decades, water levels have fallen significantly. This reduction in water levels exposes the soil to evaporation and thus increases the levels of salt and trace metals, which threatens the sustainability of the marsh restoration.

The southern Iraqi marshes, including Al-Suda Marsh in Maysan Governorate, are unique and vulnerable to disappearance due to climate change and a significant reduction in water levels (Al-Abadi, 2018). The physical and chemical composition of the soil in this region has deteriorated because of the reduction in water levels. This reduction in water levels in the region has increased salinization and heavy metal buildup (Al-Khafaji, 2021).

Previous research has indicated that the texture of this region's soil ranges from clay loam to clay, showing high levels of heavy metals. For instance, total iron concentration was recorded at 1931 mg/kg, while total copper was recorded at 30.3 mg/kg in this region (Mahmoud, 2023). The buildup of these trace elements, combined with high levels of sulfate and sodium ions, indicates how big this problem is and how it threatens the sustainability of this ecosystem.

In the face of the difficulty and expensiveness of the conventional monitoring of the quality of the soils over such vast areas, remote sensing techniques are found to be an effective means of assessing the degradation of the environment by studying the reflectance properties of the surface of the earth and relating them with the ground truth values. Field surveys have identified the existence of clay soil with low drainage properties, as well as the increase in electrical conductivity (EC) and the concentration of heavy metals such as iron, which is above 1900 mg/kg in the surface soil and can be linked to the marsh desiccation phenomenon.

By using the spectral indices of satellites such as Sentinel-2 in the evaluation of the processes of salinization and degradation of vegetation, as carried out in the studies on the Iraqi Marshes, it may be possible to bridge the gap through the application of remote sensing techniques. By applying the soil profile data collected in the month of October 2022 in Al-Suda and the spectral indices of the Sentinel-2 satellite for the same time, the present study attempts to bridge the knowledge gap in the accurate geographical assessment of the chemical degradation of the soils in the Al-Suda Marsh.

1. Materials and Methods

1.1. Fieldwork:

A Global Positioning System (GPS) was utilized to document the sites of sampling during field study in the Al Suda Marsh area, Qal'at Saleh District, Maysan Governorate. In October 2022, a representative soil pedon was excavated, and samples were collected at three depth intervals: 0 to 10 cm, 10 to 30 cm, and 30 to 60 cm. Chemical properties like pH, conductivity, soluble ions, and organic compound concentration were determined, also physical properties like porosity, texture, bulk density were also tested. The chemical degradation was also calculated by measuring the concentration of specific heavy metals such as copper, iron, and manganese.

1.2. Laboratory Analyses

Soil samples were analysed for:

- Physical properties: texture, bulk density, porosity
- Chemical properties: pH, electrical conductivity (EC), calcium carbonate, organic matter
- Soluble ions: Na⁺, Ca²⁺, Mg²⁺, SO₄²⁻, Cl⁻, HCO₃⁻
- Heavy metals: Fe, Cu, Mn (total and available)

1.3. Remote Sensing Data:

Sentinel-2 imagery (October 2022) was used after atmospheric correction. The following indices were calculated:

- NDVI (vegetation condition)
- Moisture Index (surface moisture)
- Salinity-related indices

Spatial analysis was performed using GIS to correlate spectral data with field measurements.

When conducting field research in the Al Suda area in the marshlands (Qal'at Saleh District, Maysan Governorate), a GPS was utilized to pinpoint the sample sites. A reference soil Pedon was excavated in October 2022, with samples being collected at three different depth intervals: 0 to 10 cm, 10 to 30 cm, and 30 to 60 cm. The samples were then sent to the laboratory for analysis. The physical and chemical properties were analysed. For example, texture, bulk density, porosity, pH, electrical conductivity, soluble ions, and organic content were all analysed. The concentration of copper, iron, and manganese was also calculated to determine the extent of chemical degradation.

3. Results and Discussion

3.1 Soil Physical Properties:

As shown in Table 1, the soil profile is mainly made up of fine-textured soils, with clay loam at the surface and clay in deeper layers. The percentage of clay increases as the depth increases, going as high as 47%. At the same time, the bulk density increases from 1.25 to 1.36 Mg m⁻³, while the porosity decreases. These observations show that the soil becomes more compact as the depth increases, thereby reducing its ability to let the water pass through. It is, therefore, safe to conclude that the area experiences poor drainage, which leads to the buildup of salt as it

cannot be easily drained. Variation of Soil Bulk Density and Porosity Across Soil Depths in Al-Suda Marsh is depicted in figure.1.

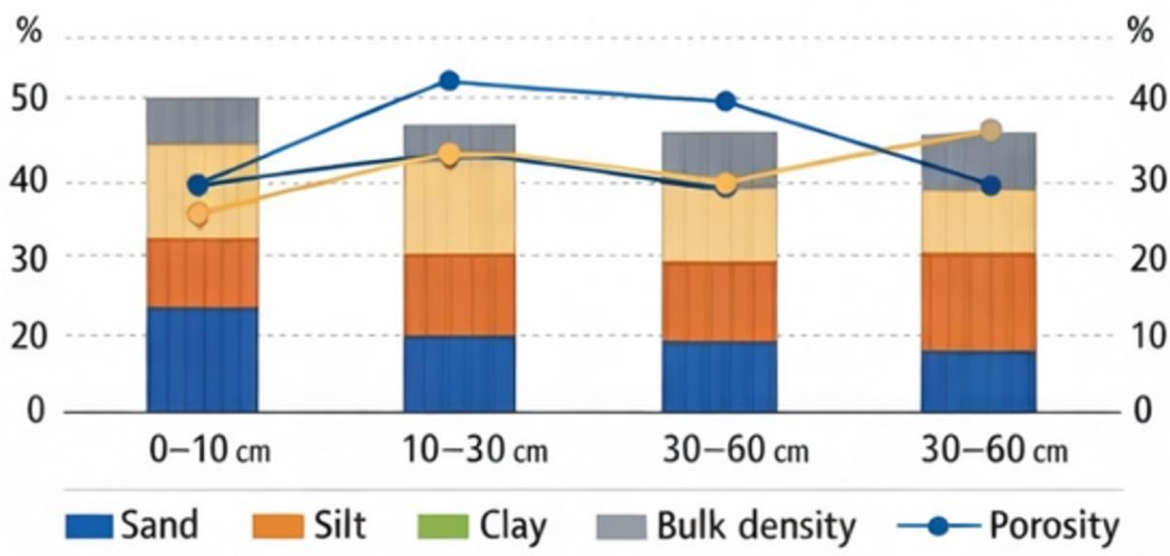


Figure 1. Variation of Soil Bulk Density and Porosity Across Soil Depths in Al-Suda Marsh.

Table 1. Physical Properties of the Soil Samples Under Study

Location	Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	Bulk Density (Mg/m ³)	Particle Density (Mg/m ³)	Porosity (%)
Al-Suda Marsh in Maysan	A	0-10	28	33	39	Clay Loam	1.25	2.45	48.97
	Cgk1	10-30	20	38	42	Clay	1.27	2.50	49.20
	Cgk2	30-60	13	13	47	Clay	1.36	2.73	41.39

The results obtained from the physical analysis of the soil samples (Table 1) showed that Al-Suda marsh region was dominated by fine-textured soils. The texture of the soils in this region changed from clay loam, as indicated in the surface horizon (0-10 cm), where the percentage of clay was 39%; it then changed to clayey as depth increased, where the percentage of clay rose to 47% at a depth of 30-60 cm (Buringh, 1960). The fine texture and high percentage of clay in this region have greatly contributed to the deterioration of the quality of the soils, as well as the process of salinization. Soils that are classified as clay are characterized by low permeability and poor internal drainage, making it extremely difficult for salt ions to drain out. This is supported by the bulk density results, which increased with depth. For example, the bulk density of the deeper layer is 1.36 Mg m⁻³, while that of the upper layer is 1.25 Mg m⁻³. Also, the overall porosity decreased from 48.97% to 41.39% (Al-Zubaidi, 1989). This suggests that water is not able to move freely in the deeper layers of the soil since it is more compact. Because of this, as the water evaporates, the salts

and heavy metals remain in the root zone or return to the surface. In general, the results of the spectral analysis of the degradation indicators are quite similar to the physical characteristics.

3.2. Chemical Properties:

The characteristics of soluble ions and salinity characteristics were studied and discussed in detail. The pH values of the soils varied between 7.40 and 7.50, which indicated that the soils are slightly alkaline in nature. The electrical conductivity values indicated that the soils are saline in nature due to the increase in values from 5.80 dS m⁻¹ at the surface to 11.60 dS m⁻¹ at depth. The vertical distribution of Soil pH and electrical conductivity (EC) in Al-Suda marsh soils is illustrated in figure.2.

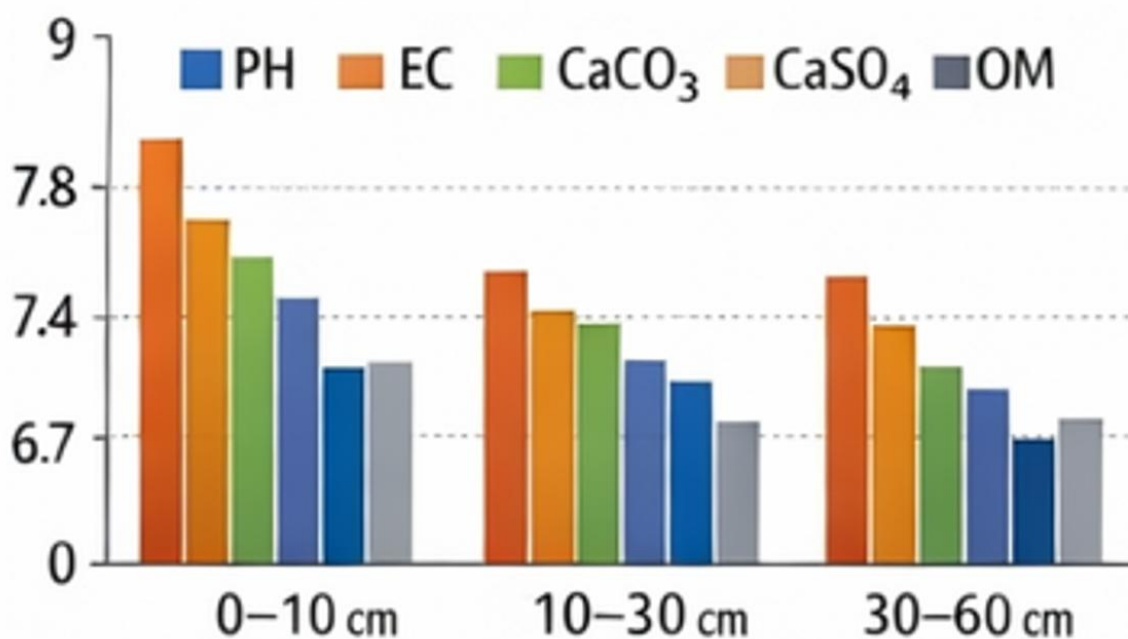


Figure 2. Vertical Distribution of Soil pH and Electrical Conductivity (EC) in Al-Suda Marsh Soils.

Table2. Chemical Characteristics of Soil Samples Under Study

Location	Horizon	Depth (cm)	pH	EC (dS/m)	CaCO ₃ (%)	CaSO ₄ (%)	CEC (Cmolc/kg)	O.M. (%)
Al-Suda Marsh in Maysan	A	0-10	7.40	5.80	33.00	9.50	21.39	19.80
	Cgk1	10-30	7.50	6.40	34.00	10.00	21.38	21.80
	Cgk2	30-60	7.40	11.60	41.00	9.51	21.15	25.30

Chemical properties of the soils (Table. 2) indicate that these soils have slightly alkaline pH values, ranging from 7.40 in the topsoil to 7.50 in the subsoil (Khaeim et al., 2019). The soil also reflects

clear saline degradation based on their electrical conductivity (EC) values. The EC value was recorded as $5.80 \text{ dS}\cdot\text{m}^{-1}$ for the top layer (0-10 cm soil depth) and increased significantly to $11.60 \text{ dS}\cdot\text{m}^{-1}$ for the deeper soil layer (30-60 cm).

The distribution of salts in these soils is related to their clayey texture and poor drainage properties, as indicated by their physical properties. The salts deposited in deeper soil layers could be transported upwards through capillary action during dry periods. The soils are thus suitable for detecting saline degradation using spectral indices such as the Normalized Difference Salinity Index (NDSI) (Al-Falahi and Qureshi, 2015). The distribution of Major Soluble Cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) along the soil profile is depicted in figure.3.

The soils also contain extremely high percentages of calcium carbonate (CaCO_3), ranging from 33% to 41%, indicating that these soils are highly calcareous. In addition, these soils contain extremely high values of organic matter, ranging from 19.80% for the topsoil to 25.30% for deeper soil layers.

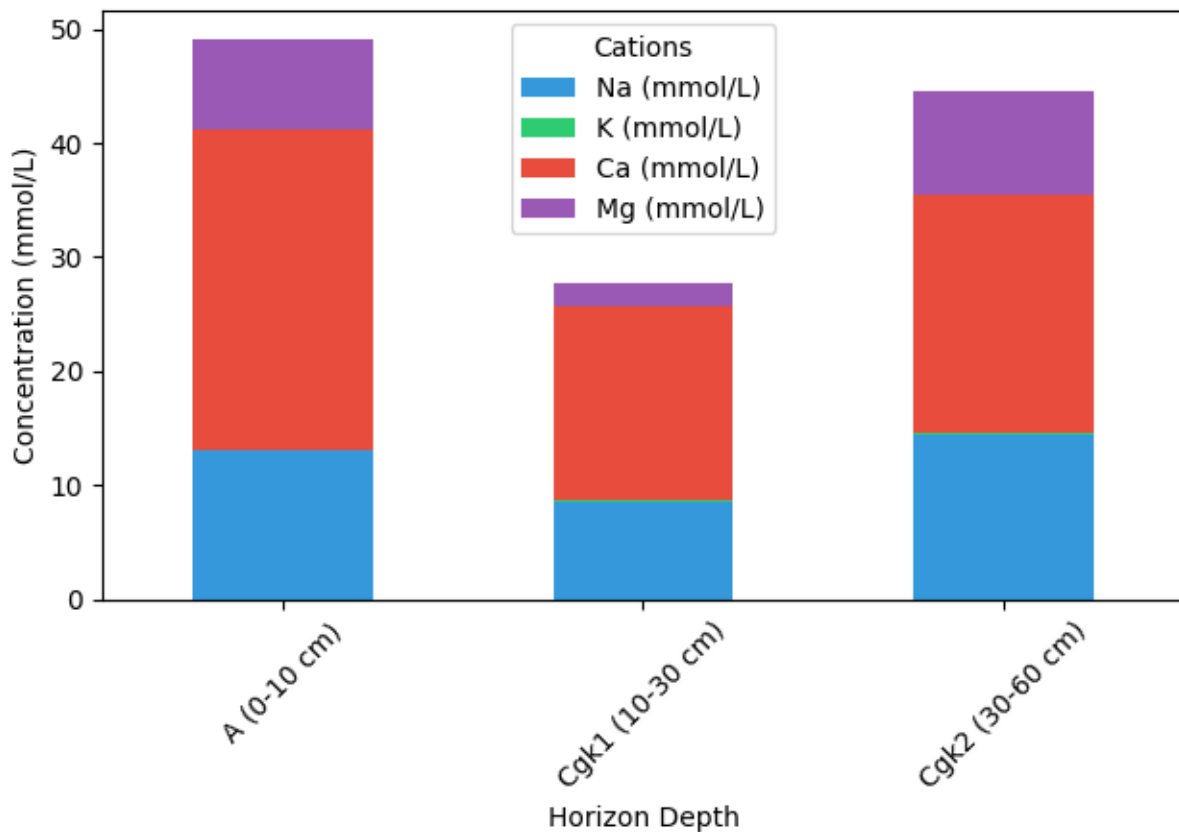


Figure 3. Distribution of Major Soluble Cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) Along the Soil Profile.

Moreover, it was noticed that the soils investigated contain exceptionally high values of calcium carbonate (CaCO_3), ranging from 33% to 41%, indicating that these soils are highly calcareous. In addition, these soils contain extremely high values of organic matter, ranging from 19.80% for topsoils to 25.30% for deeper soil layers. This high value of organic matter is an obvious reflection of the humid initial state of the environment and the low rate of degradation of plant matter (such as reeds and papyri) before the start of severe water scarcity in this region (Al-Khateeb & Askar, 1989; Richardson et al., 2005).

Table (3) Soluble Cations in the Pedons of the Studied Soils

Location	Horizon	Depth (cm)	Na Dissolved (mmol/L)	K Dissolved (mmol/L)	Ca Dissolved (mmol/L)	Mg Dissolved (mmol/L)
Al-Suda Marsh in Maysan	A	0-10	13.10	0.03	28	8
	Cgk1	10-30	8.59	0.08	17	2
	Cgk2	30-60	14.40	0.13	21	9

Sodium and calcium were found to be the dominant cations as can be seen in table.3, but sulphate was the dominant anion. Sulphate concentrations reached up to 46.5 mmol L⁻¹ as mentioned in (Table. 3). A clear illustration of how major soluble anions (Cl⁻, HCO₃⁻, SO₄²⁻) are distributed in the soil profile of Al-Suda Marsh is made in figure.4.

This ionic composition indicates that sodium sulphate and calcium sulphate are the primary salts contributing to soil salinity. Increased sodium levels suggest early stages of sodicity, which can degrade soil structure. Soluble anions in the pedons of the studied soils is represented in table.4.

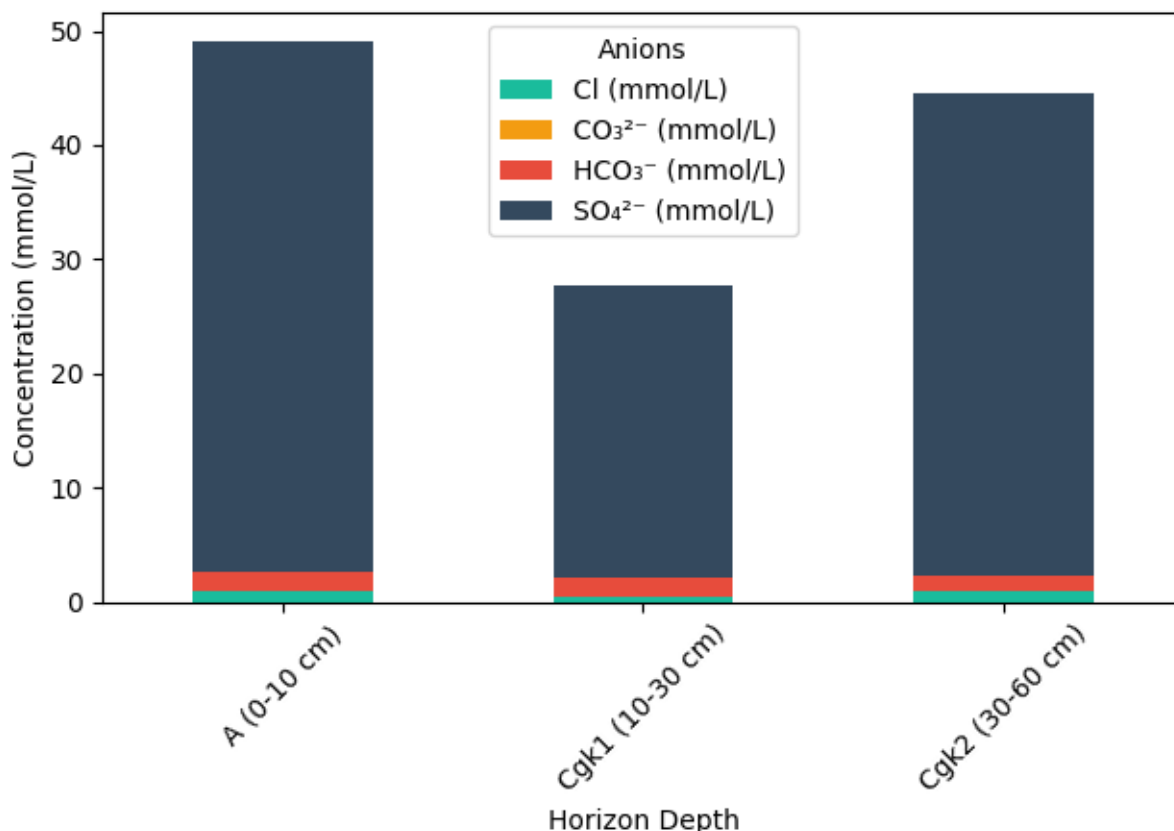


Figure 4. Distribution of Major Soluble Anions (Cl⁻, HCO₃⁻, SO₄²⁻) in the Soil Profile of Al-Suda Marsh.

Table 4. Soluble anions in the pedons of the studied soils

Location	Horizon	Depth (cm)	Cl ⁻ (mmol/L)	CO ₃ ²⁻ (mmol/L)	HCO ₃ ⁻ (mmol/L)	SO ₄ ²⁻ (mmol/L)
Al-Suda Marsh in Maysan	A	0-10	0.9	Nil	1.7	46.5
	Cgk1	10-30	0.5	Nil	1.6	25.6
	Cgk2	30-60	1.0	Nil	1.2	42.4

3.4 Heavy Metal Accumulation

In addition, high concentrations of iron, copper, and manganese were recorded, especially for surface soils. The iron concentration was more than 1900 mg kg⁻¹. This could be attributed to evaporation resulting in upward movement and strong binding of these elements with organic matter (refer Table.4). The results shown in (Table.3) and (Table. 4) illustrate the chemical composition and distribution of predominant salts of soils of Al-Sawda Marsh. From these results, it is evident that calcium (Ca²⁺) and sodium (Na⁺) are predominant soluble cations. The concentration of calcium gradually decreases from 28 mmol L⁻¹ for surface soils to 21 mmol L⁻¹ for subsurface soils. On the other hand, sodium concentration increases from 13.10 mmol L⁻¹ for surface soils to 14.40 mmol L⁻¹ for deeper soils. This could be an indication of the beginning of salinization and sodicity processes, as proposed by Al-Haidarey et al. (2010).

Sulphate (SO₄²⁻) is the predominant anion. This anion has high concentrations in both surface and subsurface soils. The concentrations of sulphate recorded were 46.5 mmol L⁻¹ for surface soils and 42.4 mmol L⁻¹ for subsurface soils. Chloride (Cl⁻) and bicarbonate (HCO₃⁻) are present in much lower amounts, while carbonate (CO₃²⁻) is absent.

This dominance of both calcium and sodium and sulphate points to gypsum and sodium sulphate as the dominant salts that affect soil conditions in this region. The high sulphate concentration is attributed to sulphur oxidation. The previous flooded conditions meant that sulphur was present in its reduced state; however, after the recession of water and the resulting exposure to air, the sulphur oxidized to sulphate (Al-Khateeb & Askar, 1989).

3.5 Remote Sensing Analysis and Spatial Validation

NDVI had consistently low values, which indicated that the vegetation cover was meagre and that the plants were under stress because of salinization. The Moisture Index had negative values, which indicated that the surface was dry.

The spatial distribution of these indices was highly correlated with the field data, showing that the salinization of the environment was widespread in the marsh area.

The accumulation of heavy and trace metals serves as a primary indicator of chemical soil degradation. Analytical results obtained from Table. 5 show that iron (Fe), copper (Cu), and manganese (Mn) levels were significantly high. The levels of iron were remarkably high, recording 1931 mg/kg at 0-10 cm and gradually decreasing with depth to 1911 mg/kg. Similarly, both total copper and total manganese were highly concentrated at the topsoil horizon, recording 30.3 mg/kg and 281 mg/kg, respectively. Total and available concentrations of Fe, Cu, and Mn across soil depths is depicted in figure.5.

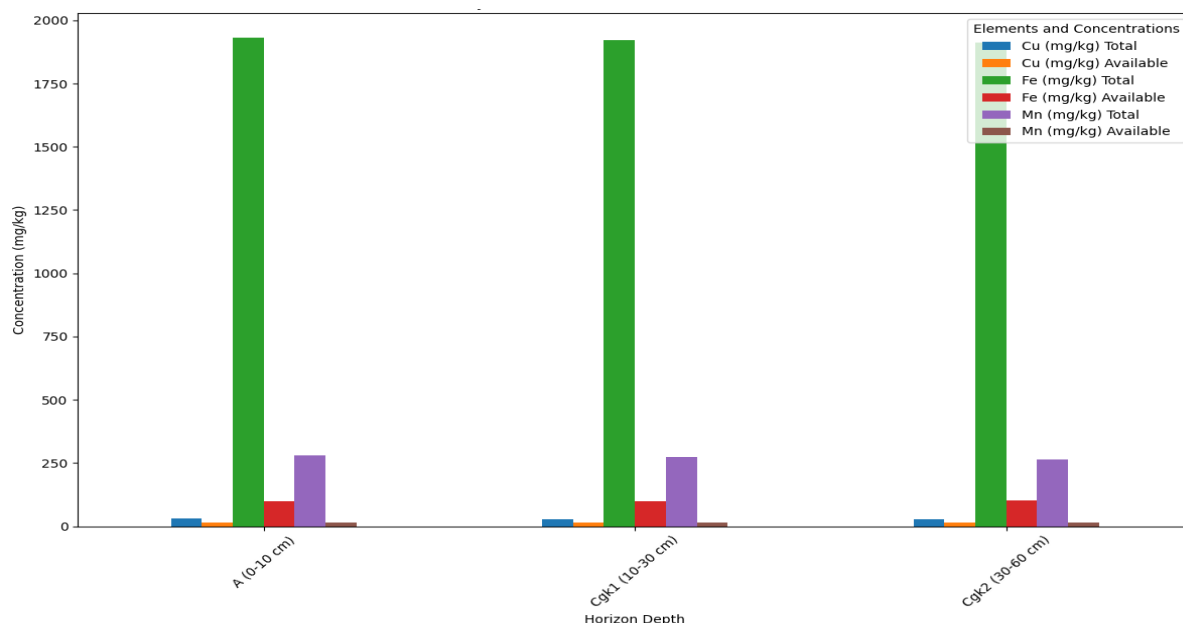


Figure 5. Total and Available Concentrations of Fe, Cu, and Mn Across Soil Depths.

Table 5. Available concentration of trace elements in the studied soils in Maysan.

Location	Horizon	Depth (cm)	Cu (mg kg ⁻¹)	Fe (mg kg ⁻¹)	Mn (mg kg ⁻¹)
Al-Suda Marsh	A	0–10	30.3	1931	281
	Cgk1	10–30	29.1	1921	275
	Cgk2	30–60	26.9	1911	265

The concentration of metallic elements at the topsoil horizon is attributed to high rates of evaporation and soil desiccation. The metallic elements are drawn upward through capillary action (Kabata-Pendias, 2011). In addition, these metallic elements have a strong correlation with soil organic matter. As previously stated, soil organic matter is highly concentrated at the topsoil horizon. Soil organic matter acts as a natural chelate, hence preventing these metallic elements from being leached (Alloway, 2013). The high concentration of metallic elements at the topsoil horizon also shows the adverse effects of climate change and water recession in Al-Sawda Marsh. Elements that were once dissolved or suspended within the water column have subsequently precipitated and accumulated, providing definitive evidence of the ongoing chemical degradation of the soil.

Table 6. Descriptive statistics of selected soil properties

Parameter	Minimum	Maximum	Mean
Clay (%)	39	47	42.67
Bulk density (Mg m ⁻³)	1.25	1.36	1.29

Porosity (%)	41.39	49.20	46.52
EC (dS m ⁻¹)	5.80	11.60	7.93
pH	7.40	7.50	7.43
CaCO ₃ (%)	33	41	36.00
Organic matter (%) *	19.80	25.30	22.30

3.6. Spectral Analysis and the Spatial-Environmental Assessment of Degradation:

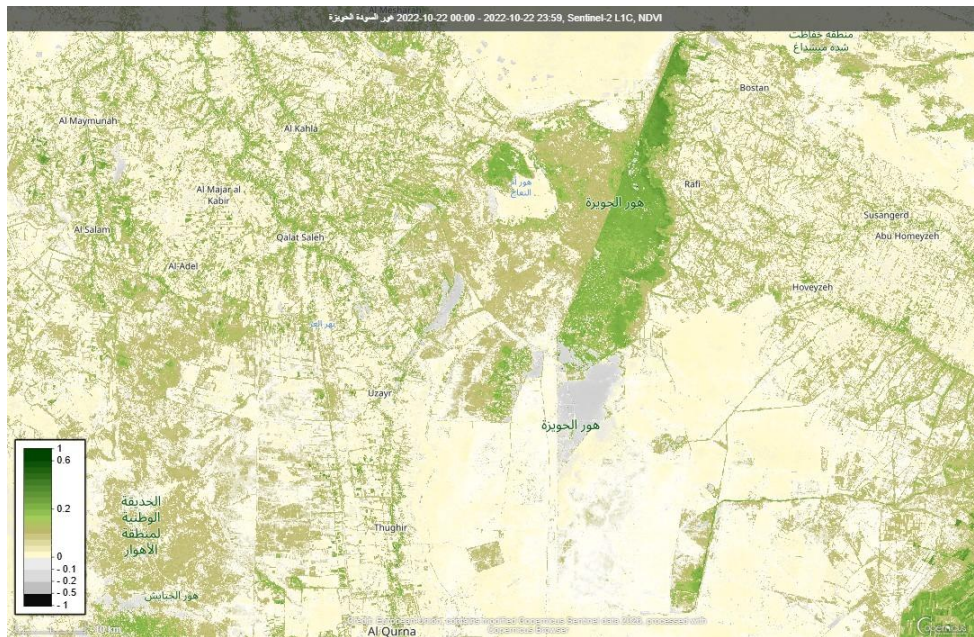


Figure 6. Spatial distribution mapping of the Normalized Difference Vegetation Index (NDVI) across the Al-Suda Marsh soil (October 2022).

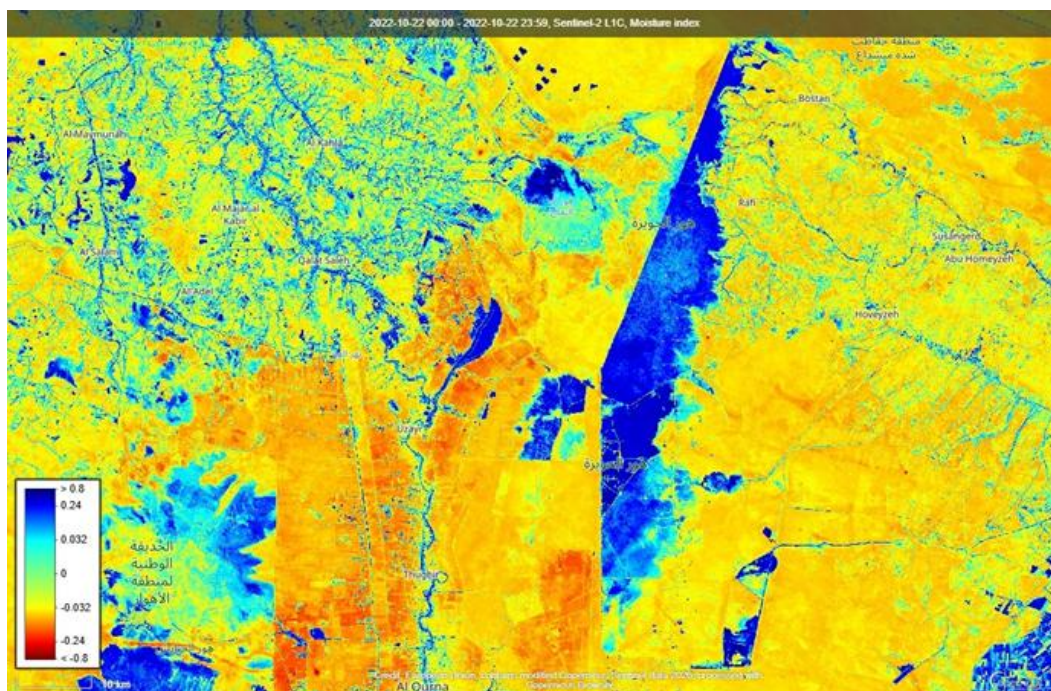


Figure 7. Spatial distribution of the Moisture Index across the Al-Suda Marsh soils (October 2022).

Table 7. Variation of soil properties with depth

Depth (cm)	Clay (%)	Bulk density (Mg m ⁻³)	Porosity (%)	EC (dS m ⁻¹)	Organic matter (%)	CaCO ₃ (%)
0–10	39	1.25	48.97	5.80	19.80	33
10–30	42	1.27	49.20	6.40	21.80	34
30–60	47	1.36	41.39	11.60	25.30	41

4. Correlation Between Empirical Ground Data and Spectral Indicators:

Subsequent to the confirmation of soil degradation in the Al-Sawda Marsh through the application of the lab test, the application of the remote sensing and geospatial techniques was carried out to expand the scope of the analysis. Satellite imagery, obtained through the Sentinel-2 satellite in October 2022, coinciding with the field sampling, was applied in the analysis of the extent of soil degradation in the region. Indices were also applied in the analysis of the extent of soil salination and vegetation degradation in the region.

Table 8. Pearson correlation coefficients among selected soil properties

Variable	Clay	Bulk density	Porosity	EC	CaCO ₃
Clay	1.00	0.95	-0.90	0.96	0.93
Bulk density	0.95	1.00	-0.88	0.89	0.91
Porosity	-0.90	-0.88	1.00	-0.82	-0.85
EC	0.96	0.89	-0.82	1.00	0.94
CaCO ₃	0.93	0.91	-0.85	0.94	1.00

EC: Electrical conductivity; OM: Organic matter; CEC: Cation exchange capacity.

–: Not detected.

* Organic matter values appear unusually high and should be interpreted with caution.

4.1. Spatial Assessment of Vegetation Decline and Salt Accumulation (NDVI & Moisture Index):

The spatial patterns derived from Sentinel-2 imagery are consistent with the laboratory results and provide a clear representation of the extent of environmental degradation across the study area (refer Figure 6).

4.2. Normalized Difference Vegetation Index (NDVI)

It is evident that the NDVI values are generally low across the marsh area, with many values approaching zero. This suggests that there is a significant reduction in vegetation cover and that the vegetation is highly stressed. The reduction in reed and papyrus vegetation suggests that the soil conditions are not conducive to the growth of vegetation (refer Figure 7).

Soil salinity is one of the major factors that have resulted in the reduction of vegetation cover in the area. As the concentration of salts in the soil increases, the concentration of water absorption

in the plants decreases, thus reducing the vegetation cover. This process was also noted in the arid regions, where low NDVI values are associated with saline soils and degraded land surfaces (Xue et al., 2004). The findings are in line with the results obtained in the southern Iraqi marshes using spectral indices in assessing changes in vegetation cover due to water scarcity (Al-Khafaji, 2021).

4.3. Moisture Index

Moisture Index shows that most of the values are negative, indicating that the amount of moisture on the surface of the area of study is very low. This can be explained by the dry weather that has established itself in the area due to a reduction in the amount of water flowing through the area, as well as the high temperatures.

In such a case, evaporation is what takes over in the environment. As water evaporates from the surface of the soil, salts and trace elements are lifted upwards through capillary action. Consequently, these elements are accumulated in the upper layers of the soil, thus deteriorating its quality.

This finding is in line with the findings of earlier studies that emphasized the importance of remote sensing in tracing the processes that may be attributed to salinity in dry environments (Allbed & Kumar, 2013). It also confirms the findings of earlier studies that the dry environment in marsh areas results in the alteration of the soil's characteristics, including the salinity level and the accumulation of chemical constituents (Al-Khateeb & Askar, 1989).

4.4. Synthesis of Spatial Analysis

Overall, the spatial indicators obtained from the satellite images match the field measurements. It is seen that the regions with less vegetation and less moisture content are the regions with higher salinity and concentrations of heavy metals.

This agreement between the datasets confirms the reliability of using remote sensing techniques to monitor the environmental conditions in hard-to-reach areas. It is also evident that the marsh ecosystem needs proper management of water resources to overcome the degradation and restore the ecosystem.

5. Conclusions

The soil shows serious physical degradation, mainly due to a heavy clay texture and low permeability. This leads to poor drainage and causes salts and pollutants to accumulate instead of washing away. Chemical degradation and salinity issues make things worse. High electrical conductivity values reach 11.60 dS m^{-1} , and sodium and sulfate ions dominate the soil. This creates saline-sodic conditions in the marsh soils. In addition, high levels of heavy metals like iron, copper, and manganese appear in the surface layers. This rise is mainly due to evaporation, which pushes these metals upward through capillary action. Spatial validation with data from the Sentinel-2 satellite supports these findings. It shows low vegetation cover and high surface dryness in the Al-Suda Marsh, as reflected in the NDVI and Moisture Index values.

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