



# The Effect of Main Outfall Drain Water Quality on the Physical Properties of Al-Hammar Marsh Soil



Hussain Ali Al Kinany<sup>1</sup>, Rouhollah Amirabadi<sup>1</sup>, Jamal S. Makki<sup>2</sup>, Ahmed A. Dakheel<sup>2\*</sup>

<sup>1</sup> Department of Civil Engineering, Faculty of Engineering, University of Qom, 3716146611 Qom, Iran

<sup>2</sup> Civil Engineering Department, College of Engineering, University of Thi-Qar, 64001 Nasiriyah, Iraq

\* Correspondence: Ahmed A. Dakheel ([msc\\_ahmed@utq.edu.iq](mailto:msc_ahmed@utq.edu.iq))

**Received:** 11-12-2025

**Revised:** 04-01-2026

**Accepted:** 05-13-2026

**Citation:** H. A. Al Kinany, R. Amirabadi, J. S. Makki, and A. A. Dakheel, "The effect of main outfall drain water quality on the physical properties of Al-Hammar Marsh soil," *Int. J. Environ. Impacts.*, vol. 9, no. 3, pp. 725–734, 2026. <https://doi.org/10.56578/ije090308>.



© 2026 by the author(s). Licensee Acadlore Publishing Services Limited, Hong Kong. This article can be downloaded for free, and reused and quoted with a citation of the original published version, under the CC BY 4.0 license.

**Abstract:** This study investigates the influence of three distinct water sources on the physical and chemical properties of soil in the Al-Hammar Marsh of southern Iraq. Fifteen geo-referenced soil samples were collected from zones affected by (i) Euphrates River freshwater, (ii) saline agricultural drainage from the Al-Khamisiya canal, and (iii) brackish water intrusion from the Aramco feeder channel. Samples were tested for gypsum content, pH, electrical conductivity (EC), organic matter (OM) content, bulk density, porosity, texture, and the concentration of basic ions. Spatial variability was evaluated utilizing geographic information system (GIS)-based interpolation methods. The highest salinity levels (mean EC, (EC)= 2,292  $\mu\text{S}/\text{cm}$ ) were found in regions influenced by the main outfall drain (MOD), marked by high concentrations of chloride and sulfate, reduced porosity, and heightened soil alkalinity. Conversely, Umm Al-Wudaa, affected by Euphrates freshwater, exhibited superior soil structure, elevated levels of OM (7.86%), and reduced salinity (EC = 1,960  $\mu\text{S}/\text{cm}$ ), signifying efficient natural leaching. Areas supplied by Aramco exhibited the presence of gypsum and marine ions, along with an intermediate salinity (EC = 2265  $\mu\text{S}/\text{cm}$ ). The places with the highest salinity were detected, and the dilution of salt downstream was confirmed via GIS analysis. The findings highlight the need for integrated salinity management in Al-Hammar Marsh through controlled freshwater releases, targeted soil amendments, wetland-based pretreatment of drainage inflows, and continuous GIS-supported monitoring.

**Keywords:** Al-Hammar Marsh; Soil salinity; Geographic information system mapping; Main outfall drain drainage; Euphrates freshwater; Soil remediation

## 1 Introduction

The main outfall drain (MOD) is a vital source of water for the Al-Hammar Marsh, which is a large wetland ecosystem in southern Iraq. The quality of water from the MOD directly influences the physical characteristics of the marsh soil, whose texture, porosity, bulk density, and hydraulic conductivity are essential to maintaining the ecological and hydrological functions of the marsh. Understanding the influence of MOD water quality on soil properties is essential to preserving the resilience and functionality of this unique wetland ecosystem [1, 2].

The marshlands are located in the southern part of Iraq, where the Tigris and Euphrates rivers meet. They take up about 15000–20000 km<sup>2</sup> of land [3]. The marshlands of Mesopotamia are the largest wetland ecosystem in the Middle East and western Eurasia [4]. Iraq's wetlands are comprised of three major marsh areas: the Al-Hammar Marshes, the Central Marshes, and the Al-Hawizeh Marshes [5]. Each of these marsh zones contains a network of hydraulically linked shallow lakes and ponds [3]. The primary sources of water feeding into the marshes are the Tigris and Euphrates, along with their branches. However, inflows into the marshes have decreased in recent years due to the construction of large hydraulic structures and dams in the upstream regions of these rivers, located in Turkey and Syria [6, 7]. Additionally, between 1980 and 1990, the previous Iraqi regime implemented massive drainage projects that further exacerbated the devastation of the marshes. Post- 1991, five significant drainage projects were carried out to prevent or limit the flow of water from the Tigris and Euphrates Rivers into the marshland area for political reasons [8]. As a consequence, the marshland area was reduced to less than 15% of its original size.

Following partial re-flooding post-2003, restoration efforts improved hydrological connectivity in several marsh sectors; however, recovery remained sporadic because water quality, salinity intrusion, and drainage return flows continued to constrain ecosystem rehabilitation.

During the wet seasons, the area of the marshlands ranges from 2,800 km<sup>2</sup> to 4,500 km<sup>2</sup> [9]. The marshland experienced a dry period between 2005 and 2009, which significantly disrupted the local flora and fauna. In response, the UN Environment Program and the United Nations Educational, Scientific, and Cultural Organization have collaborated to ensure the long-term improvement of the Iraqi Marshlands by adding them to the World Heritage List. These unique wetlands are recognized for their outstanding universal historical, cultural, environmental, hydrological, and socio-economic value [10, 11]. Between 2023 and 2025, research and restoration activities shifted toward understanding the relationship between water and soil quality in Iraq's Al-Hammar Marsh, an essential component of the wetland ecosystem. Numerous studies have found salinity, heavy metals, and nutrient enrichment from the MOD are damaging to the soil structure of the estuary. Increased salinity levels, often surpassing legal thresholds, have been shown to reduce soil porosity and hydraulic conductivity, consequently restricting water infiltration and retention [12, 13]. The introduction of heavy metals, such as chromium (Cr) and lead (Pb), via industrial discharges; leads to a deterioration in soil structure by reducing aeration and increasing density, consequently impairing microbial and plant activity [14]. Excess nutrient loading from drainage inflows may accelerate eutrophication and alter microbial turnover, indirectly affecting organic matter (OM) dynamics and soil structural stability [2]. Hydrodynamic modeling has become an essential tool, allowing researchers to simulate salinity transport and enhance water flow to alleviate the associated consequences. Optimized outlet locations were reported to reduce salinity from 15000 to 6982 mg/L, thereby improving local water quality [13].

The Mesopotamian wetlands, particularly the Al-Hammar Marsh, are amongst the most significant natural ecosystems in the Middle East. Nonetheless, they are subject to considerable problems from increasing salinity, water scarcity, climate change, and industrial pollution. A review of previous studies on the Mesopotamian wetlands shows that the majority of such investigations have focused on vegetation status and water-quality assessment, whereas comparatively fewer studies have examined salinity-induced changes in soil structure and biogeochemistry. The effects of salinity on soil structure and biogeochemistry are predominantly unexplored. Despite the ecological importance of Al-Hammar Marsh, previous studies in the Mesopotamian wetlands have largely emphasized water quality, vegetation status, and hydrological restoration, whereas comparatively limited attention has been paid to how contrasting inflow sources alter the spatial variability of wetland soil physical structure and salinity-related geochemistry. In particular, field-based comparisons between freshwater, agricultural drainage, and brackish inflows remain scarce. Accordingly, this study addresses this gap by integrating field soil measurements with geographic information system (GIS)-based spatial interpretation to evaluate how different water sources control soil texture, salinity indicators, and major chemical properties in Al-Hammar Marsh. This study addresses these limitations by combining field soil analyses with GIS-based spatial assessment to evaluate salinity-related changes in wetland soil properties. The study also proposes effective management solutions for mitigating soil degradation due to salinity, ensuring the long-term sustainability of Iraq's essential wetlands. The findings are expected to assist in developing more effective strategies for the protection and restoration of the Mesopotamian wetlands. The study contributes a site-specific assessment of how contrasting water sources influence soil salinity, texture, and related physicochemical properties in Al-Hammar Marsh, providing evidence to support wetland restoration and soil-management-related decisions.

## 2 Study Area

The Al-Hammar Marsh in southern Iraq, one of the largest and most significant wetlands in Mesopotamia, is essential to the preservation of aquatic ecosystems, the administration of water resources, and the augmentation of biodiversity in the area. The principal water sources supporting the wetland include the Al-Khamisiya Agricultural Drainage; (part of the MOD), freshwater from the Euphrates River (Umm Al-Wada), and the influx of Persian Gulf water through the Aramco pipeline. The wetland is situated between the Tigris and Euphrates rivers, adjacent to the cities of Nasiriyah, Suq Al-Shuyukh, and Al-Basra.



**Figure 1.** Al-Hammar Marsh, Iraq and the Mesopotamian Marshes with drainage features

Figure 1 illustrates the geographical location of the study area in southern Iraq and the location of soil sampling points in the Hur Al-Hammar Marsh. The Al-Hammar Marsh currently faces serious environmental threats due to reduced freshwater input, the ingress of saline agricultural drainage, and seawater intrusion, which affect soil quality and the sustainability of the entire ecosystem.

### 3 Methodology and Sampling Procedure

The methodology of this study has three main components: (i) field sampling and site characterization; (ii) laboratory analysis of the physical and chemical properties of soil; and (iii) data processing, including statistical evaluation and GIS-based spatial analysis. With the use of global positioning system (GPS), fifteen georeferenced sampling points were set up, five in each zone, to allow for accurate spatial analysis and repeatability. The sampling density was designed to provide representative coverage of the three dominant inflow environments in a logistically difficult wetland setting. Although the number of samples was sufficient for exploratory comparison between zones, it remains limited in terms of fine-scale spatial generalization. Soil sampling was conducted near three primary water sources, with samples stored and analyzed according to Food and Agriculture Organization (FAO) [15], USDA [16], and ASTM D422-63 [17] standards utilizing an applied research framework. Soil samples were collected from the 0–20 cm layer at fifteen georeferenced points, with five samples representing each inflow zone. Laboratory analyses were carried out to determine soil physical and chemical properties, including particle-size distribution, bulk density, porosity, pH, electrical conductivity (EC), total dissolved solids (TDS), OM, gypsum content, bicarbonate, and major soluble ions ( $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ , and  $\text{Mg}^{2+}$ ). All analyses were conducted according to the referenced standard procedures. The data collected were analyzed statistically to compare the three zones, explore inter-parameter relationships, and generate GIS-based spatial distribution maps of key soil indicators. Soil sampling was performed at a depth of 0 to 20 cm, with physical and chemical soil parameters, including texture, bulk density, porosity, pH, salinity EC, TDS, OM, gypsum, and major ions, then being measured. For spatial analysis, the measured soil properties were linked to their GPS coordinates and interpolated in GIS to produce thematic distribution maps for selected indicators. The interpolation outputs were used for comparative spatial interpretation among the three inflow zones rather than for high-resolution prediction, given the limited number of sampling points. In addition to laboratory analyses, the data were spatially analyzed via a GIS, and spatial distribution maps of soil indicators were prepared.

The data comprises a coordinate Table 1 that illustrates sample locations and water-source category, which can be enhanced with GIS maps and imagery depicting sampling sites and environmental context. This research employed a systematic sampling method to evaluate soil properties affected by three different water sources in Al-Hammar Marsh: mean source-water salinity differed among the three feeders, with the highest values recorded in Al-Khamisiya drainage, intermediate values in the Aramco channel, and the lowest values in the Euphrates-fed Umm Al-Wudaa sector. In late spring of 2025, when soil moisture was intermediate and flooding was minimal, a representative sample was taken to demonstrate the seasonal fluctuation.

**Table 1.** Sampling locations and water-source category

No.	Location Name	Code	Latitude	Longitude	Water-Source Category
1	Aramco	A1	30°45'10.24"N	47°5'14.93"E	Mix
2	Aramco	A2	30°45'4.51"N	47°5'13.30"E	Mix
3	Aramco	A3	30°45'8.62"N	47°5'14.35"E	Mix
4	Aramco	A4	30°45'4.56"N	47°5'13.60"E	Mix
5	Aramco	A5	30°45'5.62"N	47°5'14.82"E	Mix
6	Umm Al-Wudaa	M1	30°49'16.93"N	46°31'6.60"E	Euphrates
7	Umm Al-Wudaa	M2	30°49'16.88"N	46°31'6.52"E	Euphrates
8	Umm Al-Wudaa	M3	30°49'27.13"N	46°31'6.19"E	Euphrates
9	Umm Al-Wudaa	M4	30°49'16.72"N	46°31'7.01"E	Euphrates
10	Umm Al-Wudaa	M5	30°49'17.63"N	46°31'6.46"E	Euphrates
11	Al-Khamisiya	K1	30°50'0.11"N	46°26'9.48"E	MOD
12	Al-Khamisiya	K2	30°50'2.67"N	46°26'10.25"E	MOD
13	Al-Khamisiya	K3	30°50'0.18"N	46°26'10.21"E	MOD
14	Al-Khamisiya	K4	30°50'3.47"N	46°26'11.75"E	MOD
15	Al-Khamisiya	K5	30°50'9.04"N	46°26'10.91"E	MOD

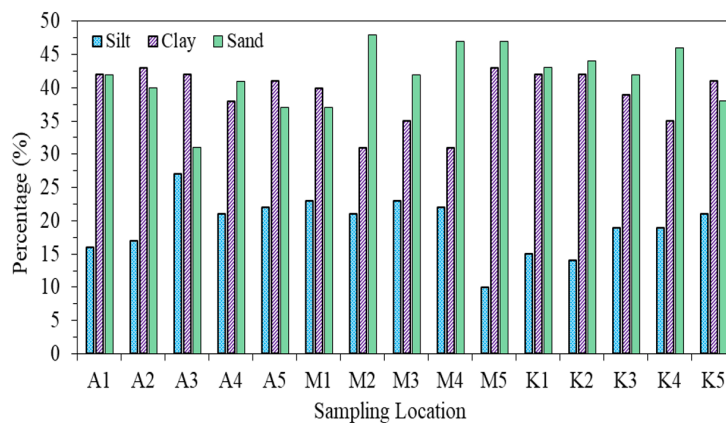
Note: MOD, main outfall drain.

## 4 Results and Discussion

### 4.1 Soil Characterization and Texture Distribution

The soil texture of the samples collected from different regions of the western Al-Hammar Marsh was analyzed

according to the percentages of sand, silt, and clay present. The results indicate that the majority of samples fall into the clayey loam soil category. According to the data reported in Table 1, the percentage of clay in most sampling points is above 40%, whilst the percentages of sand and silt vary. A high clay fraction increases the capacity of soil to retain water and nutrients. However, it may also reduce permeability and aeration, thereby influencing wetland soil functioning [18, 19]. The important role of soil texture in determining physical properties such as porosity, water retention capacity, and permeability has made it important to the accurate identification of identify the spatial distribution of soil texture using GPS and GIS devices, in addition to laboratory analysis. Figure 2 illustrates the percentage composition of soil texture at each sampling point, which clearly shows that areas close to the freshwater inlets of the Euphrates River have soil textures with relatively higher sand and silt percentages and lower clay percentages, while areas affected by saline waters (Aramco area) have more clay textures.



**Figure 2.** Distribution of soil texture components (sand, silt, clay) by sampling point

These spatial patterns are indicative of the influence of different water sources in shaping and changing soil texture characteristics. The finer texture observed in saline-affected areas may be related to enhanced flocculation and deposition of fine particles under higher ionic strength, although this interpretation needs to be supported by either statistical evidence or a cited reference. Also, intermediate areas with a combination of water inlets have been seen as transitional in terms of both textural composition and physical properties, indicating complex hydrodynamic processes and interactions between freshwater and saline water. The observed textural differences between the three zones are important because clay-rich soils typically retain more water and dissolved ions, but are also more vulnerable to reduced permeability under saline conditions. In Al-Khamisiya and Aramco-influenced areas, the combination of finer particles and elevated salt content likely promotes pore restriction and weakens soil structural quality. By contrast, the comparatively fresher conditions in Umm Al-Wudaa favor reduced ionic stress and more balanced soil functioning.

The analysis of the soil texture composition reveals that the spatial distribution of soil particles is directly related to the quality and source of the water supply, confirming the importance of managing inflow water resources to improve and preserve wetland soils. The findings are directly aligned with the research aims, which seek to evaluate the influence of water quality on soil properties, with the ultimate aim of improving the adaptation and sustainability of wetland ecosystems. Therefore, an accurate understanding of the factors contributing to soil texture is of great importance as a basis for further analyses of soil's chemical and physical properties and for providing practical management strategies.

#### 4.2 Water Quality Parameters and Soil Salinity

In this section, the quality of water entering the Western Al-Hammar Marsh and its effects on the physical and chemical properties of the soil are examined. Data collected from the three main water supply sources, including Aramco drainage waters (mostly influenced by saline seawater), the Euphrates River (freshwater), and agricultural drainage in the Al-Khamisiya area, are reported separately in Tables 2 and 3. The results indicate that the electrical conductivities are in an average range of 2265 to 2693  $\mu\text{S}/\text{cm}$ , which represents the average salinity of the waters. The comparison of EC, TDS, and pH across 15 sampling points reveals clear spatial differences in the water quality associated with the type of water source feeding the western Al-Hammar Marsh. The Al-Khamisiya region was found to have the highest average EC (2693  $\mu\text{S}/\text{cm}$ ) and TDS (1481 ppm), indicating pronounced salinization due to agricultural drainage inflow. The Aramco site, influenced by brackish marine water, had a moderate EC of 2265  $\mu\text{S}/\text{cm}$  and a slightly higher TDS concentration of 1456 ppm, presumably reflecting a diverse ionic composition resulting from tidal effects. By comparison, Umm Al-Wudaa, which receives freshwater from the Euphrates, was found to have

the lowest TDS at 1310 ppm and a comparatively lower EC of 2473  $\mu\text{S}/\text{cm}$ , indicating a more dilute ionic composition. Across all locations, pH remained consistently within a slightly alkaline range (7.66–7.76), suggesting that despite variations in salinity, the buffering capacity of the soil-water interface remains relatively steady. The data suggests that the characteristics of the water supply are the principal factors influencing salt accumulation and the chemical equilibrium of the impacted soils. The TDS/EC ratios for all samples fall within a typical range of 0.5–0.7 [20–22] indicating appropriate ionic equilibrium in soil solution.

**Table 2.** Electrical conductivity (EC), total dissolved solids (TDS), and pH for the 15 sampling points across the three regions

Site	No.	EC ( $\mu\text{S}/\text{cm}$ )	TDS (ppm)	pH	TDS/EC
Aramco	A1	2824	1435	7.89	0.51
	A2	2198	1563	8.18	0.71
	A3	2156	1321	7.28	0.61
	A4	1867	1198	7.28	0.64
	A5	2178	1345	8.15	0.62
	Ave	2265	1456	7.76	0.64
	SD	351	136	0.45	–
Umm Al-Wudaa	M1	1987	1123	7.56	0.57
	M2	2564	1274	8.11	0.50
	M3	2668	1276	7.93	0.48
	M4	2879	1675	7.45	0.58
	M5	2155	1342	7.33	0.62
	Ave	2473	1310	7.68	0.53
	SD	369	205	0.33	–
Al-Khamisiya	K1	2891	1672	7.93	0.58
	K2	2133	1198	8.11	0.56
	K3	3012	1734	7.19	0.58
	K4	2612	1377	7.77	0.53
	K5	2815	1423	7.29	0.51
	Ave	2693	1481	7.66	0.55
	SD	345	221	0.40	–

Note: EC, electrical conductivity; TDS, total dissolved solids.

**Table 3.** Recorded concentrations of various chemical elements at different sites

Site	No.	$\text{Cl}^-$ (ppm)	$\text{SO}_4^{2-}$ (ppm)	$\text{Mg}^{2+}$ (ppm)	$\text{Ca}^{2+}$ (ppm)	$\text{Na}^+$ (ppm)	$\text{K}^+$ (ppm)
Aramco	A1	266	544	67	196	209	62
	A2	376	488	68	163	266	63
	A3	287	552	41	173	216	74
	A4	264	520	62	184	217	59
	A5	265	523	69	134	223	72
	SD	48	25	12	24	23	6.6
	Ave	292	525	61	170	226	66
Umm Al-Wudaa	M1	213	423	55	188	211	54
	M2	311	511	51	177	231	58
	M3	251	478	69	187	235	61
	M4	254	418	72	213	219	77
	M5	297	593	66	183	287	79
	SD	39	72	9	14	30	11.4
	Ave	265	485	63	190	237	65.8
Al-Khamisiya	K1	362	612	79	169	284	72
	K2	326	632	52	198	276	69
	K3	251	529	58	146	266	63
	K4	316	512	69	175	231	62
	K5	375	522	72	143	245	66
	SD	49	56	11	23	22	4.2
	Ave	326	561	66	166	260	66.4

From a soil-science perspective, elevated EC and TDS reflect greater concentrations of dissolved salts in the

soil-water system, which can influence aggregate stability, osmotic conditions, and root-zone functioning. The higher salinity indicators recorded for Al-Khamisiya are consistent with drainage-derived salt loading, while the lower values found for Umm Al-Wudaa indicate a stronger dilution and leaching effect associated with freshwater inflow. According to Tables 3 and 4, elemental analysis of the soils across the three sites demonstrates distinct chemical signatures that mirror the salinity origin and transport processes. The ionic composition further clarifies the origin of salinity stress. The dominance of chloride, sulfate, and sodium in Al-Khamisiya suggests that agricultural drainage is a major source of soluble salt accumulation, whereas the Aramco zone reflects mixed brackish influence. In contrast, the relatively lower levels of chloride and gypsum in Umm Al-Wudaa indicate less severe salt loading and more favorable conditions for soil productivity. The Al-Khamisiya region exhibits the greatest average concentrations of chloride ( $\text{Cl}^- = 340$  ppm), sodium ( $\text{Na}^+ = 260$  ppm), sulfate ( $\text{SO}_4^{2-} = 561$  ppm), and gypsum (GYP = 954.4 ppm), indicating significant salinization due to agricultural drainage laden with soluble salts. Likewise, the bicarbonate concentrations ( $\text{HCO}_3^- = 301$  ppm) were raised, indicating increased carbonate buffering activity. The Aramco site exhibited a more equilibrated ion composition, characterized by marginally reduced salinity indicators (e.g.,  $\text{Cl}^- = 292$  ppm,  $\text{Na}^+ = 226$  ppm) alongside an elevated average OM content of 7.62%, signifying moderate salinity coupled with organic nutrient accumulation, presumably resulting from estuarine mixing and deposition processes. Umm Al-Wudaa soils exhibited little ionic stress, as indicated by the having lowest concentrations of  $\text{Cl}^-$  (265 ppm) and GYP (823.8 ppm), along with a comparatively high OM content of 7.86%, implying conducive conditions for soil productivity. The data indicates that salinity and soil chemical profiles are significantly influenced by the characteristics of entering water, with drainage-fed regions such as Al-Khamisiya presenting the highest risk of salt accumulation and potential for decline in fertility.

**Table 4.** Recorded concentrations of chemical elements at different sites

Site	No.	P (%)	N (%)	$\text{HCO}_3$ (ppm)	GYP (ppm)	OM (%)
Aramco	A1	1.990	0.657	233	924.8	9.45
	A2	2.541	0.612	387	829.6	8.19
	A3	2.623	0.476	233	938.4	7.28
	A4	2.345	0.623	248	884.0	6.98
	A5	2.775	0.559	398	889.1	6.20
	SD	0.303	0.071	85	42.4	1.20
	Ave	2.455	0.5854	300	893.2	7.62
Umm Al-Wudaa	M1	1.580	0.287	243	719.1	9.56
	M2	2.317	0.598	265	868.7	8.29
	M3	2.189	0.611	234	812.6	6.44
	M4	2.314	0.734	241	710.6	7.56
	M5	2.812	0.634	245	1008.0	7.44
	SD	0.441	0.168	12	122.4	1.16
	Ave	2.242	0.573	246	823.8	7.86
Al-Khamisiya	K1	2.574	0.587	219	1040.0	9.22
	K2	2.148	0.684	422	1074.0	5.19
	K3	2.456	0.553	234	899.3	8.54
	K4	2.564	0.534	241	870.4	7.82
	K5	2.334	0.587	388	887.4	8.39
	SD	0.178	0.058	96	95.4	1.56
	Ave	2.415	0.589	301	954.4	7.83

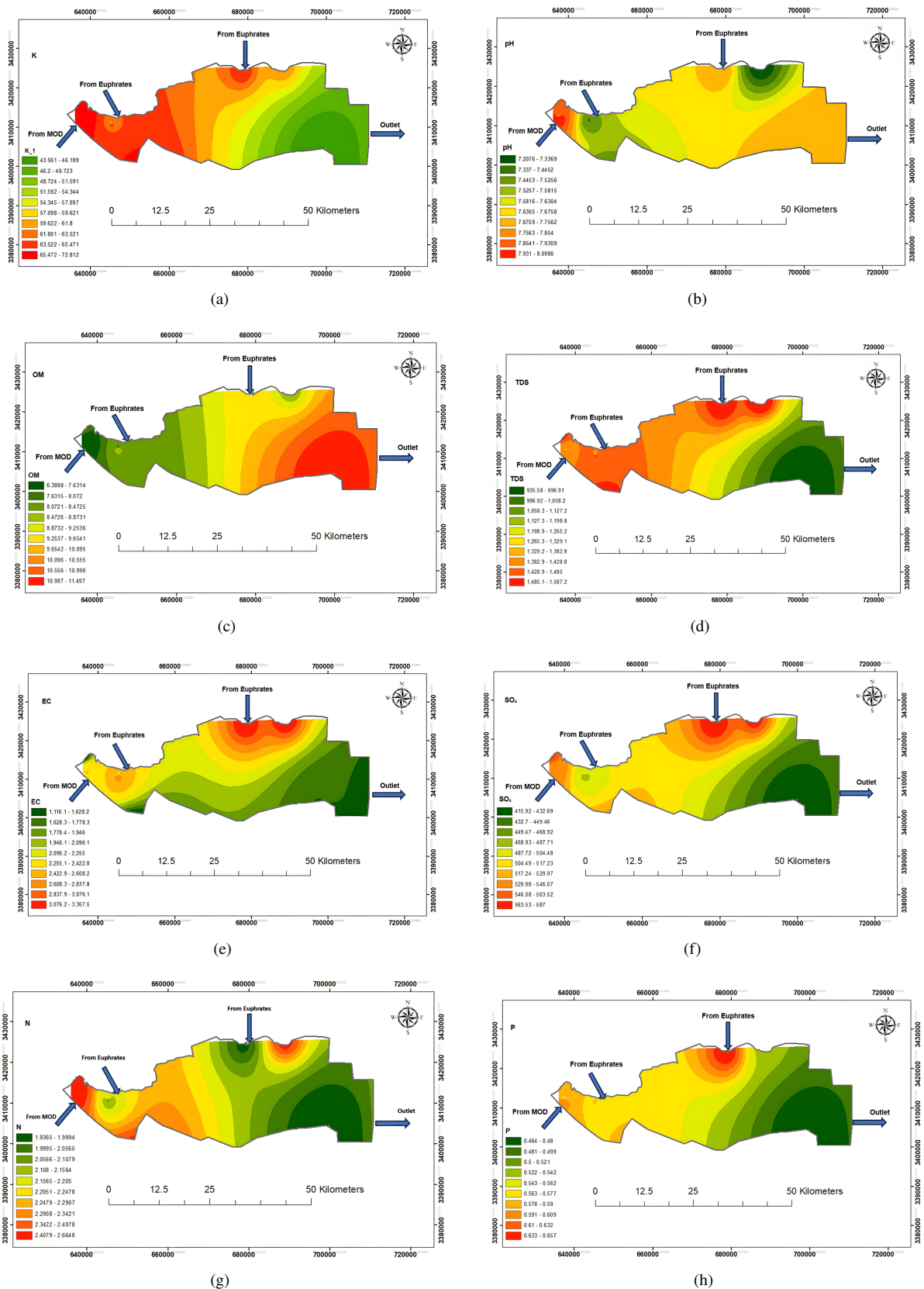
Note: GYP, gypsum; OM, organic matter.

Taken together, these data indicate that the observed differences are not random site-to-site variations, but are systematically associated with the dominant inflow regime in each zone.

### 4.3 Spatial Analysis and Interpretation of Soil Properties

By using a GIS and the collected field and laboratory data, the spatial distribution of important soil parameters such as  $\text{K}^+$ , pH, OM, TDS,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ , EC, and  $\text{SO}_4^{2-}$  in the western Al-Hammar Marsh has been analyzed and interpreted in detail. This spatial analysis, based on the precise coordinates of soil samples (Table 1) and the qualitative and quantitative soil data leads to a deeper understanding of how various water sources and environmental conditions affect changes in soil quality and properties.

The GIS outputs are valuable for identifying relative salinity hotspots and spatial contrasts among zones; however, they should not be interpreted as exact continuous-field predictions. Their main strength in the present study lies in their support for comparative environmental interpretation and management prioritization.



**Figure 3.** GIS-based spatial distribution of soil properties in Al-Hammar Marsh: (a) Potassium (K); (b) pH; (c) organic matter (OM); (d) total dissolved solids (TDS); (e) electrical conductivity (EC); (f) Sulfates ( $\text{SO}_4^{2-}$ ); (g) Nitrogen (N); (h) Phosphorus (P)

The maps prepared (Figure 3) demonstrate the distribution of these elements and physical properties of the soil,

based on potassium being more concentrated in the northern areas and close to the saline water sources of the Armco region; this indicates the effect of saline water in terms of increasing the concentration of potassium in the soil. The pH map suggests that in areas affected by high salinity, such as around Armco, the soil pH is also increased, which indicates the effect of saline water on soil alkalinity. The OM map suggests that the highest levels are found in the southern and central areas of the wetland, particularly near the freshwater inlets of the Euphrates River, which explains the high accumulation of OM and biological activity in these areas. Furthermore, the TDS and EC maps illustrate the distribution of dissolved salts in the soil, which was found at high levels in the northeastern parts of the wetland and areas affected by saltwater. The distribution of sulfates follows a similar trend and is concentrated in the same areas. The color scheme of these maps, based on the color spectrum, illustrates areas with high concentrations with warm colors (orange and red) and areas with lower concentrations with cool colors (green and blue). From the spatial analysis of these maps, it can be concluded that the spatial distribution of soil elements and properties is directly affected by different sources of incoming water; seawater, industrial drainage, and freshwater from the Euphrates River, each having specific patterns in terms of the dispersion of these parameters, which has led to diversity and complexity in the quality of wetland soil.

These differences in the spatial distribution of soil elements and properties could potentially be caused by hydrodynamic processes and chemical reactions at the soil surface, such that areas close to saline water see an accumulation of dissolved salts and an increase in pH, which may lead to soil structure degradation and reduced permeability. In contrast, the conditions in areas adjacent to freshwater with higher quality OM and a more balanced pH are more favorable for biological activity and plant growth. Water resource management in the region, which includes controlling saltwater inflow and maintaining the natural flow of freshwater from the Euphrates River, plays a key role in maintaining the chemical and physical balance of the wetland soils. Moreover, spatial analysis via GIS is clearly effective as a tool for delineating areas of concern and accurately mapping zones based on soil quality and water influence. These observations can inform effective conservation and land management practices. The remaining properties of the spatial maps are presented in Table 5, which reports the distribution of other elements such as EC,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{Na}^+$ , and  $\text{Mg}^{2+}$ , amongst others. Each map has been individually analyzed to clarify the impact of various water sources on the elements in the soil. This analysis helps to build a comprehensive picture of how these water sources affect soil quality. Spatial analysis of soil properties in the western Hammar Marsh via GIS confirms that soil quality and characteristics are significantly affected by different water input sources. Areas affected by seawater salinity, especially in the northeast of the wetland, are showing high salt accumulation, increased pH, and decreased soil quality, which together pose a serious threat to the local ecosystem and agriculture. In contrast, the freshwater inputs from the Euphrates River help maintain the balance of OM and an appropriate pH, providing better conditions for biological activity.

**Table 5.** Spatial interpretation of selected soil properties and chemical indicators in Al-Hammar Marsh

Map No.	Main Source	Element	Spatial Distribution	Spatial Interpretation
1	Aramco	Calcium ( $\text{Ca}^{2+}$ )	Increase in the north	Higher concentrations in the north due to saline water
2	Aramco	Chloride ( $\text{Cl}^-$ )	Gradual increase	Higher concentrations near saline water
3	Al-Khamisiya	Electrical conductivity (EC)	Increase in the northeast	Higher conductivity near saline water sources
4	Umm Al-Wad	Gypsum (GYP)	Even distribution	Gypsum distribution depends on the influence of freshwater
5	Aramco	Bicarbonates ( $\text{HCO}_3^-$ )	Increase in the center	Higher bicarbonates in more saline areas
6	Umm Al-Wad	Potassium ( $\text{K}^+$ )	Gradual increase	Lower potassium distribution near saline water
7	Aramco	Magnesium ( $\text{Mg}^{2+}$ )	Increase in the north	Higher magnesium near saline water sources
8	Al-Khamisiya	Nitrogen (N)	Even distribution	Even nitrogen distribution in the soil
9	Aramco	Sodium ( $\text{Na}^+$ )	Increase in central areas	Higher sodium concentrations in areas influenced by saline water
10	Umm Al-Wad	Phosphorus (P)	Gradual increase	Higher phosphorus near the river
11	Aramco	Sulfates ( $\text{SO}_4^{2-}$ )	Gradual increase	Higher sulfates in areas affected by saline water
12	Aramco	Potassium 1 (K)	Increase in the north	High concentrations in the north due to saline water
13	Aramco	pH	Increase in the north	Higher pH in more saline areas
14	Umm Al-Wad	Organic matter (OM)	Even distribution	Highest organic matter concentrations near the Euphrates River
15	Aramco	Total dissolved solids (TDS)	Gradual increase	Higher salt concentrations in areas near saline water

The mapped salinity hotspots indicate that Al-Khamisiya and the northeastern sector near saline inflows should be prioritized for intervention through controlled freshwater flushing, drainage pretreatment, and periodic monitoring of EC, TDS,  $\text{Cl}^-$ , and  $\text{SO}_4^{2-}$ . However, the spatial patterns presented here should be interpreted as indicative rather than fully predictive because the interpolation is based on a limited number of field samples distributed across a heterogeneous wetland environment.

## 5 Conclusions

The results confirm that soil degradation in Al-Hammar Marsh can be primarily associated with externally driven saline inflows rather than uniform internal soil processes. The results further suggest that external saline inflows are likely to be a major driver of soil degradation in Al-Hammar Marsh, although broader seasonal sampling would be needed to confirm the full spatial and temporal extent of this influence. The measured data show a consistent zonal pattern: Al-Khamisiya had the highest mean salinity indicators and major soluble ion concentrations, Aramco showed intermediate mixed signatures, and Umm Al-Wudaa generally displayed more favorable soil conditions under the influence of freshwater. These differences support the interpretation that inflow water quality is a key control of soil physicochemical variability within the study area. Soils subject to salty inflows from the Al-Khamisiya drainage and the Aramco brackish water channel exhibited elevated clay content (up to 43%), increased bulk density ( $\sim 1.5 \text{ g/cm}^3$ ), and reduced porosity (35%–40%), all of which impede soil aeration and permeability. Conversely, soils irrigated with Euphrates freshwater showed superior characteristics, such as finer textures, increased porosity (by up to 55%), and reduced bulk density ( $\sim 1.2 \text{ g/cm}^3$ ), hence enhancing drainage and biological activity. From a chemical standpoint, the peak salinity (EC =  $2600 \mu\text{S/cm}$ ; TDS  $\approx 1550 \text{ mg/L}$ ) were found in Al-Khamisiya soils, accompanied by heightened concentrations of  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Na}^+$ , and  $\text{Mg}^{2+}$ , which are recognized for destabilizing soil aggregates and compromising structural integrity. Concurrently, soils irrigated by the Euphrates exhibited reduced salinity, elevated levels of  $\text{Ca}^{2+}$ , and a nearly neutral pH ( $\sim 7.6$ ), promoting flocculation and improving soil structure. GIS-based spatial analysis further revealed distinct zones of salinity buildup in the northeast and nutrient accumulation in central areas, illustrating the importance of hydrological sources in determining soil quality. The analysis in Al-Hammar Marsh highlights the complexity of salt accumulation in wetland soils. EC serves as a moderately reliable indicator of TDS, while its correlation with  $\text{Cl}^-$  is weaker due to environmental and geochemical variability. Spatial distribution patterns show that external sources, such as agricultural drainage and marine water inflows, are the main drivers of soil salinity. Therefore, integrated multi-parameter monitoring is essential to fully understand salinity dynamics and to inform the sustainable soil and water management strategies that safeguard agricultural productivity and ecosystem health. Overall, the findings emphasize that exogenous saline inputs, not internal soil processes, are the primary drivers of soil degradation in this marsh ecosystem. Within the present dataset, Al-Khamisiya consistently showed the highest mean levels of EC, TDS, chloride, sulfate, sodium, and gypsum, whereas Umm Al-Wudaa generally showed lower salinity indicators and comparatively better OM conditions, supporting the interpretation that the type of inflow is a primary controller of soil quality differences. From a management perspective, the results suggest that priority should be given to regulating saline drainage inflows in the Al-Khamisiya sector and enhancing freshwater flushing from the Euphrates during critical periods. Based on the present dataset, controlled freshwater flushing, and targeted monitoring appear to be the most immediately defensible management priorities. Soil amendments such as gypsum should be considered site-specific measures and preferably linked to additional assessment of sodicity risk. In addition, localized soil remediation measures, such as gypsum application in areas with elevated sodium levels and the implementation of GIS-based monitoring programs, are recommended to control salinity progression and support long-term wetland sustainability.

## Author Contributions

Conceptualization, H.A.A.K. and R.A.; methodology, H.A.A.K. and R.A.; software, H.A.A.K. and R.A.; validation, J.S.M. and A.A.D.; formal analysis, J.S.M. and A.A.D.; writing—original draft preparation, H.A.A.K. and R.A.; writing—review and editing, J.S.M. and A.A.D. All authors have read and agreed to the published version of the manuscript.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The author declares no conflict of interest.

## References

- [1] M. A. Tahir, A. K. Risen, and N. A. Hussain, "Monthly variations in the physical and chemical properties of the restored southern Iraqi marshes," *Marsh Bull.*, vol. 3, no. 1, pp. 81–94, 2008.

- [2] H. T. Al-Saad, M. A. Al-Hello, S. M. Al-Taein, and A. A. Z. DouAbul, "Water quality of the Iraqi southern marshes," *Mesopotamian J. Mar. Sci.*, vol. 25, no. 2, pp. 188–204, 2010. <https://doi.org/10.58629/mjms.v25i2.204>
- [3] R. A. Yasir, K. A. Rahi, and Z. N. Abudi, "Water budget for abu zirig marsh in Southern Iraq," *J. Eng. Sustain. Dev.*, vol. 22, no. 1, pp. 25–33, 2018.
- [4] M. Marghany, H. A. Hasab, S. Mansor, and A. R. B. M. Shariff, "Developing hydrological model for water quality in Iraq marshes zone using Landsat-TM," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 37, no. 1, p. 012073, 2016. <https://doi.org/10.1088/1755-1315/37/1/012073>
- [5] C. Aoki, A. Al-Lami, and S. Kugaprasatham, "Environmental management of the Iraqi marshlands in the post-conflict period," in *Water and Post-Conflict Peacebuilding*. Routledge, 2014, pp. 117–136.
- [6] N. Al-Ansari, "Management of water resources in Iraq: Perspectives and prognoses," *Engineering*, vol. 5, no. 6, pp. 667–684, 2013. <https://doi.org/10.4236/eng.2013.58080>
- [7] N. Al-Ansari and S. Knutsson, "Possibilities of restoring the iraqi marshes known as the Garden of Eden," in *Water and Climate Change in the MENA-Region: Adaptation, Mitigation and Best Practices*, Berlin, Germany, 2011.
- [8] A. A. Ali, "Morphology of Tigris River inside Baghdad City," Ph.D. dissertation, Luleå University of Technology, Luleå, Sweden, 2013. <https://hess.copernicus.org/articles/16/3783/2012/>
- [9] A. Al-Saboonchi, A. R. M. Mohamed, A. H. M. J. Alobaidy, H. S. Abid, and B. K. Maulood, "On the current and restoration conditions of the southern Iraqi marshes: Application of the CCME WQI on East Hammar Marsh," *J. Environ. Prot.*, vol. 2, no. 3, pp. 316–322, 2011. <https://doi.org/10.4236/jep.2011.23035>
- [10] Z. Amr and T. Garstecki, "Biodiversity and ecosystem management in the Iraqi marshlands: Screening study on potential World Heritage nomination." IUCN, 2011. <https://iucn.org/resources/publication/biodiversity-and-ecosystem-management-iraqi-marshlands-screening-study>
- [11] H. F. A. Al-Gburi, B. S. Al-Tawash, and H. S. Al-Lafta, "Environmental assessment of Al-Hammar Marsh, southern Iraq," *Heliyon*, vol. 3, no. 2, 2017. <https://doi.org/10.1016/j.heliyon.2017.e00256>
- [12] H. R. Wahaab, M. A. Sultan, and S. S. S. Aldeen, "Determination of environmental factors on some water and sediments quality parameters of eastern Al-Hammar Marsh," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 1120, no. 1, p. 012034, 2022. <https://doi.org/10.1088/1755-1315/1120/1/012034>
- [13] K. Jaafar and T. Mohammed, "Effect of the proposed outlets on the hydrodynamic behavior and water quality of the south-west part of the Al Hammar Marsh," *J. Eng.*, vol. 29, no. 2, pp. 16–36, 2023. <https://doi.org/10.31026/j.eng.2023.02.02>
- [14] E. R. Gdawa and K. K. Fahad, "Measurement of pollution of water and sediment of the Al-Hammar Marsh for some heavy elements," *Univ. Thi-Qar J. Agric. Res.*, vol. 13, no. 2, pp. 100–106, 2024. <https://doi.org/10.54174/kf0a6c38>
- [15] R. S. Ayers and D. W. Westcot, *Water Quality for Agriculture*. Rome: Food and Agriculture Organization of the United Nations, 1985.
- [16] United States Department of Agriculture, *Soil Survey Manual*. Washington, DC: Soil Conservation Service, 1993.
- [17] ASTM International, "Standard Test Method for Particle-Size Analysis of Soils," 2007. <https://store.astm.org/d0422-63r07.html>
- [18] J. S. Makki, A. A. Dakheel, and B. M. AL-zaidi, "Prediction of the pollution index in Al Khamissiya Canal, Thi Qar Province, Iraq," *Civ. Environ. Eng.*, vol. 21, no. 1, pp. 427–436, 2025. <https://doi.org/10.2478/cee-2025-003>
- [19] J. S. Makki and R. Z. Al Zubaidy, "Location of the outlet of the west part of Al Hammar Marsh," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 737, no. 1, p. 012164, 2020. <https://doi.org/10.1088/1757-899X/737/1/012164>
- [20] J. Rhoades, A. Kandish, and A. M. Mashali, "The use of saline waters for crop production," *FAO Irrig. Drain. Pap.*, vol. 48, pp. 93–119, 1992.
- [21] J. D. Hem, *Study and Interpretation of the Chemical Characteristics of Natural Water*. Department of the Interior, US Geological Survey, 1985.
- [22] A. N. Jabar, J. S. Makki, and S. A. Al Maliki, "Restoration of Al Hammar Marsh with the minimum concentration of the total dissolved solid," *AIP Conf. Proc.*, vol. 3219, no. 1, p. 020032, 2024. <https://doi.org/10.1063/5.0237464>