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Groundwater Quality and Irrigation Suitability Assessment Using Geochemical and GIS-Based Approaches in Arid Regions

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Abstract

In arid and semi-arid climates, such as Iraq's Salah Al-Din Governorate, the availability of surface water is much lower than demand, so groundwater becomes a vital resource. Groundwater is one of the basic needs for agricultural irrigation, and therefore this study presents a suitable groundwater suitability assessment for agricultural irrigation based on a comprehensive assessment of groundwater geochemical properties and spatial distribution using the kriging technique within Geographic Information Systems (GIS). Key water quality parameters, including EC, TDS, pH, Cl^-, Na^+, K^+, NO_3^-, HCO_3^-, CO_3^{2-}, SO_4^{2-}, Ca^{2+}, and Mg^{2+}, were determined in a total of 51 wells across the study area. In addition, two wells located in the Al-Alam District of Salah Al-Din Governorate were remeasured in 2025 to assess changes in water levels. These measurements were compared to the static water levels recorded in 2014 for one well and in 2008 for the other. To determine irrigation suitability, the Water Quality Index, Sodium Adsorption Ratio, Residual Sodium Carbonate, and Total Hardness were calculated and analyzed. Groundwater quality was spatially variable, but several areas exceeded the FAO limits for safe agricultural use at all groundwater depths considered owing to salinity, sodicity, and anthropogenic contamination. Spatial mapping using GIS identified the risk zones and assisted in recommending appropriate management practices for sustainable groundwater development. Such findings emphasize the importance of regular monitoring together with appropriate irrigation management and remediation measures to reduce groundwater degradation and maintain agricultural development in Salah Al-Din Governorate.

Keywords: Groundwater Quality Parameters; Irrigation Water; Salinity; Salah Al-Din Governorate; Water Quality Index.

1. Introduction

Groundwater is an integral part of the global water supply, especially in areas where surface water is scarce. They are stored in the water beneath the surface of the Earth in underground reservoirs called aquifers that can bring forth large quantities of water. Natural groundwater recharge occurs mainly in three ways, which are precipitation, infiltration from surface water, and artificial recharge [1]. Groundwater is one of the most vital natural resources affecting human life and economic development, particularly in arid and semi-arid regions like the Salah Al-Din Governorate in northern Iraq. Groundwater is the main resource for drinking, agriculture, and industrial purposes in many regions with limited or unreliable surface water [2]. Groundwater extraction, which has been practiced since ancient times, has observed overexploitation mainly over the last 60 years due to advances in well-drilling, pumping technologies, and rising water demand driven by population growth, dietary changes, and urbanization [3]. Due to the rising population and increasing agricultural activities in the districts of Salah Al-Din, there has been an increase in groundwater extractions in the area;

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therefore, groundwater is at risk of quantity and quality. Regular assessments are vital for sustainable management practices that mitigate risks associated with poor groundwater quality in agriculture [4]. Iraq faces climate change and the depletion of water resources. Warming temperatures and changing precipitation patterns result in drought and lead rural populations to resort to using unsafe water sources [5].

Various natural and human-induced aspects affect the groundwater quality of Salah Al-Din. Sedimentary formations with a more complex hydrogeological structure characterize the geology of the region and influence the mineral composition of groundwater. Constituents, like most iron, manganese, and sulfates, may be released during the dissolution process in rock-water aquifers through natural elements [6]. Most importantly, human activities contribute significantly to environmental issues. The unregulated use of chemical fertilizers and pesticides in agriculture has led to increased levels of nitrates and phosphates in groundwater. Likewise, the release of untreated sewage and solid waste, together with leaching from septic tanks, has contributed to microbial pollutants and heavy metals in ecosystems [7]. Numerous hydrogeological and land use factors relate to the differences in groundwater quality observed in Salah Al-Din. Shallow aquifers, which are at high risk of pollution due to their proximity to agricultural land and populated areas, are concentrated particularly in southern and central areas of the governorate. Shallower aquifers, however, provide more protection but are also far less expensive to access and monitor [8]. In addition, the absence of advanced wastewater treatment infrastructure in the majority of Salah Al-Din has resulted in the release of pollutants directly or indirectly into the subsurface, an action that threatens the safety of groundwater intended for drinking purposes. Beyond anthropogenic pressures, climate change has increased the risk to groundwater in Salah Al-Din.

Over the last 20 years, Iraq has experienced a significant rise in temperature and a decline in yearly precipitation, both of which have contributed to the decrease in renewable water resources and an increased reliance on non-renewable or slowly recharged aquifers [9]. Longer spells of drought have resulted in low recharge and increased the dissolved constituent's concentration due to lack of dilution and have had an adverse impact on water quality [10]. Such climatic conditions, together with over-abstraction, jeopardize the long-term viability of the region's aquifers. Beyond agricultural runoff and domestic wastewater, industrial activities in Salah Al-Din are a new relevant source of groundwater pollution. Several oil refineries, chemical plants, and manufacturing facilities are in the governorate, and most of them do not have wastewater treatment infrastructure. Hydrocarbons, heavy metals, and toxic solvents from industrial effluents are commonly discharged straight into the environment or indirectly infiltrate groundwater systems via unlined waste pits and poorly managed disposal sites [11]. The hospital wastewater poured into the public network ends up in the central wastewater treatment plants. Some of the treated effluents are injected into the groundwater, and some of them are released into the Tigris River [12].

Water scarcity in the semi-arid area is a critical issue for local citizens. Water scarcity is an expected and challenging issue in Iraq. The phenomenon is correlated to the construction of new dams on the wellsprings of the two main rivers of Iraq (Euphrates and Tigris), which in turn reduces the recharging process of the two main rivers [13]. As illustrated, the total of these discharges, and therefore long-term aquifer contamination, is most harmful in regions with high industrial density like Baiji, potentially triggering irreparable ecological damage and public health risks. Salah Al-Din Governorate is geographically in the middle of the Iraqi Tigris River basin, which is the geographical center of Iraq's agricultural and economic activities. Long drought durations, the unevenness of surface water, and the deterioration of river systems as a result of upstream damming and contamination have rendered the wetland areas of Salah Al-Din historically dependent on groundwater resources for its citizens and industries [14]. Recent investigations warn that the deleterious effect of hydro-climatic variations on natural groundwater quality could exceed that of anthropogenic pollution [15]. Particularly, this trend has intensified the strain on overexploited aquifer systems, many of which are exhibiting signs of declining quality and quantity.

Salinity, as expressed in total dissolved solids (TDS), is the most important parameter in groundwater hydrochemical studies, where the salinity of the groundwater changes by location, time within the hydrogeological basin, and water depth in the aquifer. Salinity is the first element in determining the validity of groundwater use for Resources, Environment, and Information Engineering. The geological and topographical conditions play an important role in changing salinity due to the effects of exposed geological formations, quality of recharged water, and the topography of the basin [16]. Investigations indicate that the groundwater of the Al-Alam district in Salah Al-Din (Figure 1) has high values of TDS ranging between 1000 and 1930 mg/l, which exceed the allowable limit described by the Water Health Organization (WHO) and for Iraqi standards [17]. The recorded electrical conductivity (EC) data indicated that values can reach up to 3940 µS/cm. This was as a result of the dissolution of evaporite minerals like gypsum and halite [17]. Groundwater in the Al-Alam district is also very dense and has a total hardness (TH) of more than 180 mg/l. Mahmood et al. [18] showed that 62% of the groundwater samples were found above the acceptable limits of EC, Sodium Adsorption Ratio (SAR), and sodium (Na) for irrigation purposes. They placed some of the groundwater levels under doubt for agricultural purposes in the Al-Alam district. Microbial pollution had been discovered in all tested wells, with coliform bacteria density at 3240 cells/100 ml in a study on coliform bacteria presence in well water. The most contaminated samples were from Al-Alam in November, which imposed health risks on the consumers [19]. Al-Saadi et al. [20] conducted some physicochemical studies of groundwater in the Balad district in Salah Al-Din. They found that soil EC was in the range of 590–3492 µS/cm, which indicated the different levels of soil solution salts. The pH values were between 7.02 and 7.85, which were close to natural. Furthermore, it was noted that sulfate concentration (SO_4) had a wide range of difference, from 49.67 to 796.28 mg/l, and TDS difference from 753 to 3,614 mg/l, which also exceeded the standard in some areas [20]. Heavy metals were the source of worry in groundwater quality. Mahmoud & Hassan [21] also reported lead levels of 0.355 to 0.509 mg/l, which is above the standards of WHO. Zinc concentrations ranged from 0.033 to 3.841 mg/l, and some of the samples exceeded safe levels. Heavy metals indicate industrial and agricultural runoff could be the sources of contamination [16].

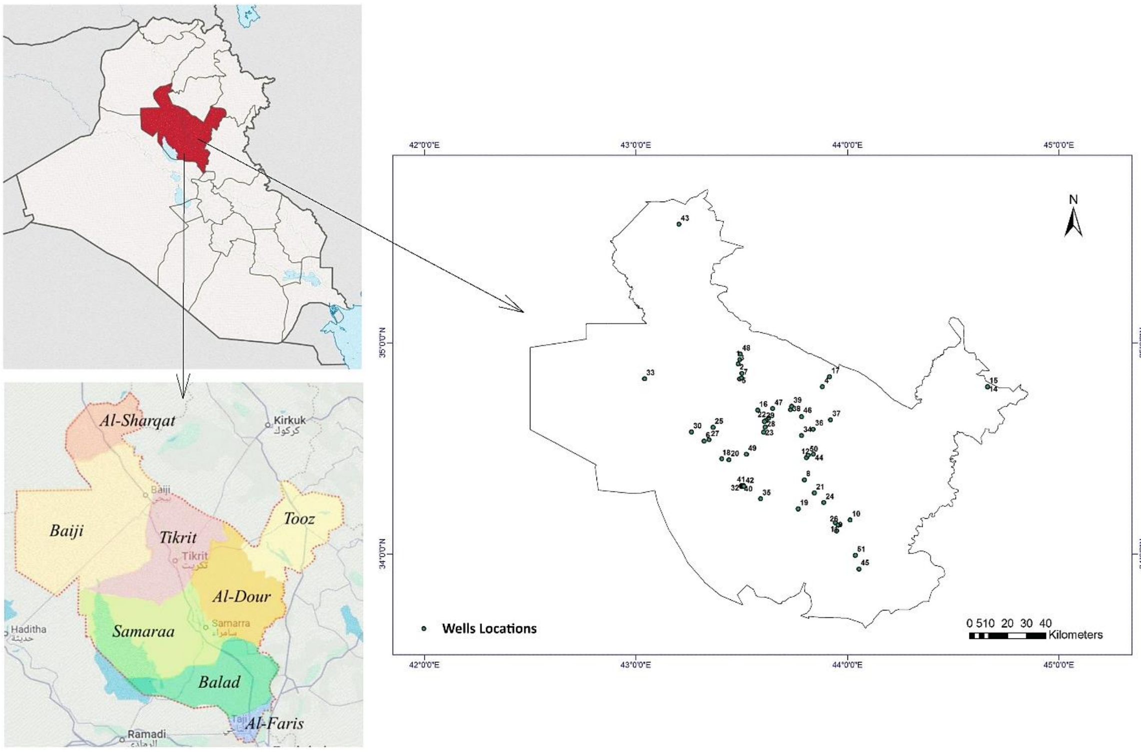


Figure 1. Study area of Salah Al-Din Governorate showing the districts of the governorate and well locations

Furthermore, Al-Tameemi et al. [22] showed that the groundwater in the Samarra district in Salah Al-Din has vast hydrochemical fluctuations. They reported that EC varies between 650 and 4,200 µS/cm, reflecting different salinities. The pH ranges from 7.1 to 8.0. Nevertheless, the values of TDS are approaching the limits for water hardness and usability, ranging between 800 and 4,500 mg/l. Heavy metal pollution in the groundwater of Samara is a significant concern. Hamza & Younis [23] reported lead levels varying from 0.25 to 0.65 mg/l, which is above the WHO drinking water guidelines. Arsenic and cadmium concentrations were similarly detected in trace levels but exceeded permissible levels in some locations, probably as a result of industrial and agricultural waste. Biological Quality Contamination by microorganisms is a significant issue that must be addressed to ensure groundwater safety. Khalaf [24] tested 20 wells from Samarra city for coliform bacteria, which was detected in 40% of samples, suggesting a possible fecal contamination. These results suggest that public health is at risk and further effective disinfection is needed prior to use for personal remedies against diseases.

Research work carried out by Jassim & Al-Ani [25] assessed the quality of irrigation water indices and observed that more than 50% of the tested samples possessed high salinity and SAR, and were not suitable for direct agricultural utilization. Soil management and dilution are also required to reduce these effects. Several indices, such as SAR, Na%, and RSC (Residual Sodium Carbonate), have been used to evaluate the efficiency of groundwater for irrigation. It is pointed out that most of the soil samples of the Tikrit district in Salah Al-Din were found to be in the "non-suitable" category as a result of severe salinity and sodicity threats [26]. Aquifers of the Al-Dour district in Salah Al-Din indicate high levels of salinity, hardness, and mixture with some heavy metals. These are problems that are not only harmful to human health but also damage agricultural productivity. Local water treatment such as reverse osmosis should be adopted, in addition, awareness of water quality should be raised among the general public, and periodic programs for groundwater monitoring should be established [27, 28]. In Al-Dour, the pH of the groundwater samples ranged from 6.4 to 8.4, falling within WHO standards. However, the TDS values were from 1380 to 1903 mg/l, and the TH values were from 1843 to 2357 mg/l. These values indicated that the water is very dense and mineralized. Sulfate concentrations exceeded 2000 mg/l in some samples, far beyond the WHO limit of 250 mg/l. Additionally, heavy metals such as iron and cadmium were detected above permissible levels, potentially due to corrosion of distribution pipes or geochemical sources [29, 30].

Previous research did not comprehensively cover the groundwater quality for the entire area of Salah Al-Din Governorate for irrigation use. These studies were concentrated on some water quality parameters and in some specific areas or districts. Investigating the physicochemical properties of groundwater in Salah Al-Din Governorate is important to identify the suitable wells for irrigation and to determine the regions required for agricultural use. Therefore, this research aims to estimate the physicochemical properties of groundwater in Salah Al-Din Governorate via analysis of essential water quality parameters, which include EC, TDS, pH, chloride (Cl^-), Na^+, potassium (K^+), nitrate (NO_3^-), bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), SO_4^{2-}, calcium (Ca^{2+}), and magnesium (Mg^{2+}), and to assess the spatial patterns and inhomogeneity of groundwater quality using the kriging technique via GIS methods. The SAR, RSC, TH, and Water Quality Index (WQI) were also calculated to determine the suitable wells for irrigation and determine the required regions for agricultural use. Figure 2 presents the flowchart of the methodology in this research.

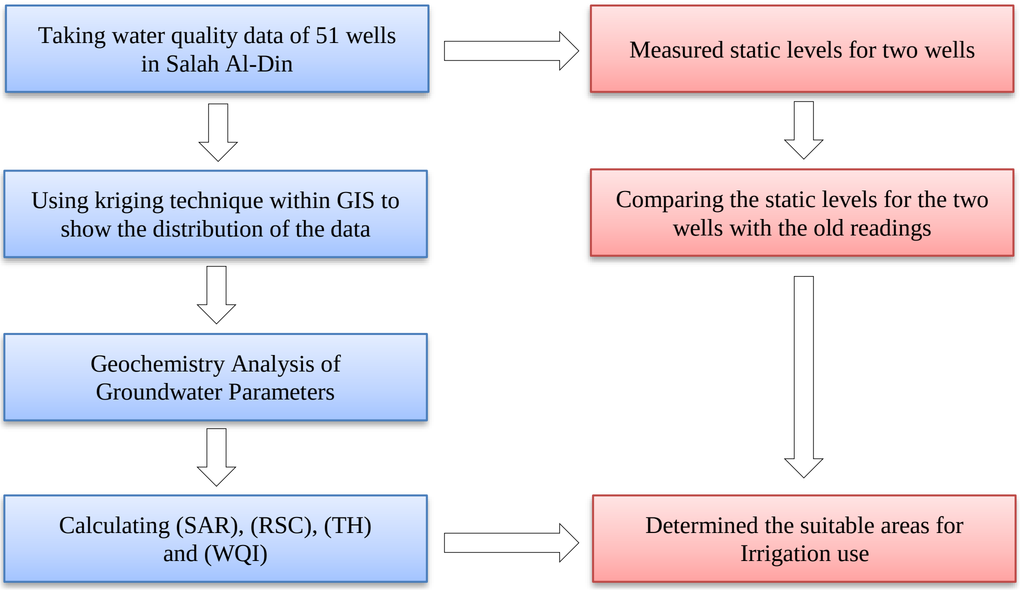


Figure 2. Flowchart details of the methodology process in this study

2. Materials and Methods

2.1. Study Area

Salah Al-Din Governorate, located in the north-central region of Iraq (Figure 1), is geologically diverse, with formations that significantly influence the availability and movement of groundwater. The region is primarily composed of sedimentary rocks from the Tertiary and Quaternary periods, which include limestone, marl, gypsum, and alluvial deposits [31]. The western part of Salah Al-Din is characterized by the presence of the Al-Fatha Formation, predominantly composed of alternating layers of limestone, marl, and gypsum. This formation is highly fractured and karstified in some areas, creating favorable conditions for groundwater storage and movement. Karst features such as sinkholes and underground channels allow for significant groundwater recharge and flow [32]. Toward the east, the Injana Formation dominates, consisting mainly of sandstone, siltstone, and claystone. This formation generally acts as a semi-confined aquifer, with groundwater mostly stored in sandstone layers. However, the clayey layers reduce permeability, making groundwater movement slower compared to karstified zones [33]. In the river valleys, especially along the Tigris River, Quaternary alluvial deposits provide important shallow unconfined aquifers. These deposits, composed of sand, gravel, and silt, offer high permeability and substantial groundwater yields, making them crucial for agriculture and domestic water supply [31].

2.2. Sampling of Water Quality Parameters

The data for fifty-one wells were taken from the General Commission for Groundwater, Ministry of Water Resources, in Iraq. The wells were chosen near the Tigris River, where agriculture is successful, and some were on the city's outskirts (Figure 1). The data was collected and tested between 2023 and 2024, as shown in Table 1. It is noticed that the maximum well depth was 144 m at wells 4 and 14, while the minimum well depth was 54 m at well 45. The discharge of these wells ranges from 3 to 7 l/s (Table 1). The details of the water quality parameters of EC, TDS, pH, Cl^-, Na^+, K^+, NO_3^-, HCO_3^-, CO_3^{2-}, SO_4^{2-}, Ca^{2+}, and Mg^{2+} for the 51 wells were presented in Table 2. It observed that EC ranges from 1000 to 18000 µs/cm, TDS ranges from 700 to 11000 ppm, and pH was in the same range for all wells (see Table 2).

Table 1. Information about the wells in Salah Al-Din Governorate, Iraq

No.	Well Name	Depth of Well, m	Date of Drilling	Static water level, m	Dynamic water level, m	Discharge Rate, l/s	District
1	Baiji District Council	84	8/27/2024	16.5	37.22	5	Baiji
2	Al-Hajjaj District Stadium	102	8/27/2024	39.15	72.2	3	Baiji
3	Baiji Municipality/Middle Island	84	8/24/2024	16.32	36.85	5	Baiji
4	Al-Ma'abdi Area/Seihat Al-Milh	144	8/24/2024	68.2	82.15	4	Tikrit
5	New Al-Bu Tamah Village	114	8/17/2024	39.15	72.2	4	Baiji
6	Abu Al-Khudayb Elementary School	132	7/23/2024	32.85	78.56	4	Tikrit
7	Al-Mahdiya/Al-Hajjaj Village	114	7/16/2024	36.2	68.75	4	Baiji
8	Al-Qamishli Mixed Elementary School	72	7/9/2024	22.15	32.68	5	Samarra
9	Al-Hadeel Elementary School	72	5/31/2024	7.45	32.3	5	Samarra
10	Al-Yarmouk School	63	5/24/2024	8.35	32.2	5	Samarra
11	Hadarat Al-Iraq Elementary School	78	5/18/2024	30.5	45.25	5	Samarra
12	Al-Sahaba Al-Karam Mosque	72	3/9/2024	30.2	48.75	5	Aldour
13	Al-Ayyubi Elementary School	120	2/12/2024	48.6	78.75	4	Tikrit
14	Suleiman Water Supply unit/2	144	2/8/2024	37.85	60.3	6	Tooz
15	Suleiman Water Supply unit/1	138	2/2/2024	37.9	60.35	6	Tooz
16	Artillery Directorate / Heavy Machinery	90	11/27/2023	34.25	78.46	3	Tikrit
17	Al-Janawar Village	90	11/26/2023	28.45	48.2	5	Tikrit
18	Awad Al-Saleh Village	132	11/24/2023	35.82	88.35	3	Samarra
19	Shield Control 1	114	11/20/2023	38.35	82.2	3	Samarra
20	Al-Bu Issa Village	120	11/13/2023	38.75	76.8	4	Samarra
21	Camp L16 F4 S3 / No. 1	60	11/13/2023	15.42	27.3	6	Samarra
22	Al-Bu Mukhlif Al-Saleh Village	112	11/9/2023	35.2	78.82	3	Tikrit
23	Al-Malik Mixed Elementary School	120	11/5/2023	37.25	79.2	3	Tikrit
24	Headquarters of the Fourth Regiment 1	72	11/5/2023	16.36	28.12	6	Samarra
25	Al-Raishan Mixed Elementary School	120	11/4/2023	22.15	82.35	3	Tikrit
26	Headquarters of the Third Regiment 1	72	11/2/2023	18.35	38.65	6	Samarra
27	Ibn Al-Faqih Mixed Elementary School	120	11/1/2023	20.35	82.25	3	Tikrit
28	Al-Janabin Village	120	11/1/2023	38.4	72.35	4	Tikrit
29	Hamed Al-Ma'id Village	120	10/30/2023	36.75	59.2	5	Tikrit
30	Al-Karfat Village	108	10/29/2023	19.72	82.45	3	Tikrit
31	Rasool Mazhar Ahmed /2	120	10/6/2023	40.3	72.15	5	Samarra
32	Rasool Mazhar Ahmed /1	120	10/3/2023	40.35	72.2	5	Samarra
33	95th Brigade / 1st Regiment Headquarters	90	10/1/2023	9.5	78.42	3	Baiji
34	Nahr al-Hadid (Juma'a Khader /1)	120	9/30/2023	32.2	56.87	5	Tikrit
35	Amru al-Qais Mixed Elementary School	132	9/7/2023	36.2	82.35	3	Samarra
36	Al-Bu Najm Village	114	9/3/2023	42.4	60.32	5	Tikrit
37	Brigade / Al-Ghufran Mosque	102	9/3/2023	35.2	68.75	4	Tikrit
38	Al-Basit Mosque	120	9/2/2023	49.3	82.6	4	Tikrit
39	Martyr Naji Jabara Village	96	7/30/2023	38.2	62.54	4	Tikrit
40	Abdullah Abbas Alwan	99	7/24/2023	36.3	74.4	4	Samarra
41	Entesar Khalil Asoud /2	99	7/19/2023	36.4	74.5	4	Samarra
42	Entesar Khalil Asoud /1	99	7/17/2023	36.2	74.35	4	Samarra
43	Shukran al-Manar Village	60	6/14/2023	21.1	52.64	2	Alsharqat
44	Abdul Ghani Wahib Latif	84	5/31/2023	28.65	52.4	5	Aldour
45	Daw Al-Haq Elementary School	54	5/26/2023	14.2	28.36	5	Balad
46	Al-Majra and Tal Ar-Rujum 10 / Sayyid Ahmed Saleh Al-Naimi Village	108	5/24/2023	32.45	59.84	5	Tikrit
47	Al-Khazamiah Village / 28	102	4/15/2023	18.2	40.35	6	Tikrit
48	Sand Dune Stabilization Project / Baiji	80	4/14/2023	4.6	28.35	7	Baiji
49	Medical Clinic in Al-Farajiah Village	132	3/3/2023	36.75	75.4	5	Samarra
50	Technical Institute in Al-Dour / Dormitory Building / 3	66	3/2/2023	22.8	40.35	6	Aldour
51	Al-Qanat Elementary School / 1	66	3/2/2023	9.2	28.15	6	Balad

Table 2. Water quality parameters values for the 51 wells that located in Salah Al-Din Governorate, Iraq

Well No.	pH	EC, µs/cm	TDS, ppm	K, ppm	Na, ppm	Mg, ppm	Ca, ppm	Cl, ppm	SO_4, ppm	HCO_3, ppm	NO_3, ppm
1	7.22	2920	1890	14	253	110	169	583	538	199	0.6
2	7.25	2380	1545	10	243	63	179	296	585	145	0.1
3	7.24	3250	2108	12	299	156	214	569	586	241	0.8
4	7.28	1203	789	2	133	63	83	223	213	51	0.3
5	7.22	2430	1580	12	247	67	183	300	591	153	0.1
6	7.22	4390	2850	29	439	170	329	645	684	512	0.1
7	7.25	2820	1830	7	271	126	195	423	542	239	0.2
8	7.2	4010	2602	15	480	135	200	590	1021	122	1.2
9	7.19	5110	3318	6	529	242	322	684	1112	372	1.1
10	7.22	4150	2698	15	495	150	215	605	1037	136	1.3
11	7.2	3100	2016	14	274	131	190	604	553	215	0.8
12	7.2	3400	2210	12	369	109	198	409	639	384	0.3
13	7.2	3470	2250	7	337	90	293	339	708	444	1.3
14	7.25	1385	904	2	141	71	91	257	240	81	0.5
15	7.2	2780	1805	9	267	122	191	419	532	237	0.4
16	7.25	2340	1520	6	258	83	148	222	576	202	1.1
17	7.12	10380	6730	130	934	494	674	1510	2112	786	0.9
18	7.2	5980	3888	62	645	243	347	719	1213	595	1.2
19	7.2	3090	2010	15	271	128	196	601	556	207	1.3
20	7.2	3510	2275	10	229	158	271	557	807	211	1.2
21	7.24	3030	1970	12	250	106	165	577	639	187	0.8
22	7.23	3150	2040	12	342	82	171	382	666	358	1.1
23	7.2	2330	1515	7	258	83	148	222	570	200	1.2
24	7.19	3080	2005	13	270	127	195	601	554	207	1.1
25	7.15	5070	3297	90	624	174	194	564	970	625	1.6
26	7.18	3090	2013	15	270	129	195	602	555	208	1.2
27	7.12	9780	6340	68	1034	449	634	1258	1997	816	1.2
28	7.19	2420	1575	5	245	66	182	299	590	159	1.1
29	7.23	3160	2060	15	344	84	173	384	669	351	0.1
30	7.25	3960	2573	35	472	127	192	582	1012	112	0.2
31	7.2	3470	2250	10	224	156	266	552	800	213	0.4
32	7.25	3120	2028	13	286	143	201	556	571	224	0.7
33	7.14	18590	11984	200	1768	829	1177	2648	3913	1316	0.4
34	7.22	2310	1500	7	261	88	153	229	533	204	0.6
35	7.22	3070	1994	12	280	137	195	550	565	223	0.8
36	7.14	6130	3960	62	659	256	361	738	1233	611	1.1
37	7.27	4500	2922	18	456	138	306	641	822	497	0.1
38	7.12	6740	4370	128	506	286	436	809	1608	538	1.2
39	7.19	3410	2216	12	370	109	198	412	693	385	1.4
40	7.15	5850	3796	18	629	200	366	739	1261	529	0.3
41	7.16	5820	3775	13	626	198	364	737	1257	527	0.4
42	7.14	5810	3764	11	626	197	363	736	1255	527	0.6
43	7.25	1399	914	6	93	76	116	109	443	49	0.9
44	7.19	4280	2760	22	398	129	288	604	658	635	1.1
45	7.22	3070	1997	12	270	126	185	597	560	212	0.8
46	7.16	6610	4296	128	494	274	424	799	1584	594	1.4
47	7.25	2780	1800	7	266	121	190	418	536	238	1.1
48	7.19	3780	2457	10	256	185	298	584	838	245	1.3
49	7.19	2290	1490	15	166	118	158	292	607	106	0.7
50	7.2	2310	1500	6	261	88	153	229	529	209	1.3
51	7.22	2080	1352	13	145	98	140	274	578	80	0.6

The elevations of two wells in Al-Alam District, Tikrit, Salah Al-Din Governorate, Iraq, were taken in 2025 to compare the values of them with the elevation observed in 2014 using a water level sounder or electric tape (Table 3). These wells were 102 and 72 m in depth, 23.15 and 36.82 m in static water level, and 3 and 5 l/s in flow rate, respectively. The device measured the depth from a known reference point (usually the top of a well casing) to the water table. Calculation of groundwater elevation was performed using the following formula [34]:

$$GE = EM - DW \tag{1}$$

where; GE is groundwater elevation, EM is elevation of measuring point, and DW is depth of water.

Table 3. Well properties and locations that tested by level sounder in 2025 for Tikrit/Al-Alam District, Salah Al-Din Governorate, Iraq

Well Location	Well Depth, m	Drilling Date	Static water level, m	Dynamic water level, m	Well Discharge l/s	District
Eastern Khazamiyah / 15	102	3/8/2014	23.15	86.36	3	Tikrit / Al-Alam
Al-Saiha / Dhiyab Saleh Muhammad No. / 3	72	1/23/2008	36.82	45.72	5	Tikrit / Al-Alam

The elevation of the measuring point is the known elevation (usually in meters or feet above sea level) of the wellhead or reference point. Depth to water is measured using a sounder; it is the vertical distance from the measuring point to the water surface in the well. The measurement was done by employees working in the General Commission for Groundwater, Ministry of Water Resources, Salah Al-Din, Iraq. The collected data was analyzed according to the classification of water quality parameters for irrigation standards according to Food and Agriculture Organization (FAO) classifications for each parameter, and all data units were converted to the units of the table for correct compression (see Table 4).

Table 4. Classification of water quality parameters for irrigation purposes according to FAO standards [35]

Parameter	Value	Suitability for Irrigation	Relative Weight	Remarks
EC (dS/m)	< 0.7 0.7 – 3.0 3.0 – 5.0 > 5.0	No restriction Slight restriction Moderate restriction Severe restriction	5	Ideal for most crops and soils with minimal salinity risk. Suitable for most crops with moderate tolerance to salinity. Tolerant crops can be used, but watch for salt accumulation in soil. Risk of reduced crop yield and poor soil conditions. Only salt-tolerant crops recommended.
TDS (mg/L)	<500 500 – 1000 1000 – 2000 > 2,000	No restriction Slight restriction Moderate restriction Severe restriction	4	Excellent for irrigation with minimal risk of salinity accumulation. Safe for most crops; may require management of salt build-up over time. Crops may experience reduced yield; requires proper drainage. Suitable only for salt-tolerant crops; requires careful soil and water management.
pH	6.0 –8.5 5.5 – 6.0 8.5 – 9.0 < 5.5 > 9.0	No restriction Slight restriction Moderate restriction Severe restriction Severe restriction	3	Optimal for most crops and soils Safe for most crops; may affect some sensitive crops, especially in soils with low buffering capacity May affect certain crops and soil chemistry, especially in alkaline soils Harmful to most crops; high acidity may cause nutrient imbalances and soil erosion Alkalinity could lead to soil salinity, nutrient lockout, and toxicity
Cl^- (me/L)	< 4 4 – 10 > 10	No restriction on use Slight to moderate restriction Severe restriction	3	Safe for all crops and most soils Sensitive crops may show injury Only tolerant crops should be used; may harm soil
Na^+(me/L)	< 3 3 – 9 > 9	No restriction on use Slight to moderate restriction Severe restriction	3	Safe for nearly all soils and crops Sensitive crops or poorly drained soils may be affected Use only on well-drained soils with sodium-tolerant crops
K^+ (me/L)	< 2 2 – 5 > 5	Safe for all crops and soils Generally safe, may affect nutrient balance in sensitive crops May cause issues in sensitive soils or crops; monitor soil fertility	3	Safe for all crops and soils Generally safe, may affect nutrient balance in sensitive crops May cause issues in sensitive soils or crops; monitor soil fertility
NO_3^- (mg/L)	< 22 22 – 130 > 130	No restriction Slight to moderate restriction Severe restriction	2	Safe for all crops and soils May be beneficial as a nitrogen source; monitor for over-fertilization May cause excessive vegetative growth, nitrate leaching, or crop toxicity
HCO_3^- (me/L)	< 1.5 1.5 – 8.5 > 8.5	No restriction Slight to moderate restriction Severe restriction	2	Safe for most soils and crops May reduce availability of Ca^{2+} and Mg^{2+} ; potential soil sodicity Can precipitate Ca^{2+} /Mg^{2+} , increase SAR, and reduce soil permeability
CO_3^{2-} (me/L)	0 < 1.0 > 1.0	No restriction Slight to moderate restriction Severe restriction	2	Most irrigation water contains no CO_3 ²□ May affect water quality, especially in high pH and low Ca^{2+} /Mg^{2+} waters precipitate Ca^{2+} and Mg^{2+} , increase SAR and RSC, reduce infiltration
SO_4^{2-} (me/L)	< 5 5 – 20 > 20	No restriction Slight to moderate restriction Severe restriction	2	Safe for most soils and crops May affect very sensitive crops or contribute to salinity May harm crops and contribute significantly to total salinity hazard
Ca^{2+}(me/L)	< 2 2 – 4 > 4	No restriction Slight to moderate restriction Severe restriction	2	Safe for all crops and soils May start contributing to salinity on poorly drained soils Can contribute to salinity and affect nutrient balance
Mg^{2+} (me/L)	< 2 2 – 5 > 5	No restriction Slight to moderate restriction Severe restriction	2	Safe for most crops and soils May contribute to salinity or interfere with Ca^{2+} /K^+ uptake in some soils Can cause soil structure issues, especially if Ca^{2+} /Mg^{2+} ratio is low

2.3. Calculations of SAR, RSC, TH and WQI

2.3.1. Sodium Adsorption Ratio (SAR)

The Sodium Adsorption Ratio (SAR) is used to assess the relative concentration of sodium (Na^+) to calcium (Ca^{2+}) and magnesium (Mg^{2+}) in irrigation water. It is a crucial indicator of the potential for sodium to negatively impact soil structure [35, 36]. In water with high SAR, displacement of calcium and magnesium ions can occur on the surface of soil particles, resulting in soil dispersion, crusting, lower permeability, and poor infiltration [35]. These conditions can severely affect plant root growth and water availability. The calcifications of SAR for irrigation water were mentioned in Table 5. Sodium Adsorption Ratio (SAR) was calculated using the following equation [37]:

$$\mathrm{SAR} = \frac{Na}{\sqrt{(Ca+Mg)/2}} \tag{2}$$

2.3.2. Residual Sodium Carbonate (RSC)

The RSC measures the ratio of carbonate and bicarbonate ions versus calcium and magnesium ions. High levels of carbonate and bicarbonate in comparison to calcium and magnesium could lead to the precipitation of calcium and magnesium. This process negatively affects the combined relative sodium, soil dispersion, infiltration, and soil structure. High RSC waters will lead to the addition of sodium in soil, which has negative influences on soil permeability and crop yield. The problem is major in dry land areas where the leaching effect is less and irrigation is an integral part of agriculture. The calcifications of RSC for irrigation water were mentioned in Table 5. Residual Sodium Carbonate (RSC) was calculated by using the following equation [37]:

$$\mathrm{RSC} = (CO_3^{2-} + HCO_3^{-}) - (Ca^{2+} + Mg^{2+}) \tag{3}$$

where all ionic concentrations are expressed in ppm (mg/l).

Table 5. The SAR, RSC, TH, and WQI Classifications for Irrigation Water according to FAO standards [35]

Parameter	Value	Suitability for Irrigation	Remarks
SAR	< 3	No restriction	Safe for most crops and soils. No significant sodium hazard.
	3 – 6	Slight restriction	Most crops can tolerate, but may affect some soils with poor drainage.
	6 – 9	Moderate restriction	Potential to affect crops sensitive to sodium and soils with poor structure.
	> 9	Severe restriction	High risk of soil dispersion and poor soil permeability. Only sodium-tolerant crops can be used.
RSC (meq/L)	< 1.25	Safe	
	1.25 – 2.5	Marginally suitable	
	> 2.5	Unsuitable	
TH in (mg/L) as $CaCO_3$	<50	Soft	
	50-150	Moderately hard	
	150 – 300	Hard	
	> 300	Very hard	
WQI			Excellent quality; suitable for all types of crops and soils.
	< 25	Excellent	Good quality; suitable for most crops and soils.
	25–50	Good	Marginally suitable; sensitive crops may be affected.
	50–75	Poor	Unsuitable for long-term use; needs treatment or management.
			Not suitable for irrigation without significant improvement.

2.3.3. Total Hardness (TH)

Total hardness (TH) in irrigation water is the sum of divalent metal cations (Ca^{2+} and Mg^{2+}) in water. It is usually reported as milligrams per liter (mg/l) of equivalent calcium carbonate ($CaCO_3$). It's not typically hardness by itself that begins to affect crops negatively, and in fact calcium and magnesium are among the plant's required nutrients. But excessive hardness may cause scaling in irrigation equipment and impact soil texture over several years. Soil permeability and infiltration can also be influenced by water hardness. High hardness can lead to precipitation of minerals in irrigation systems, especially where you have a drip or sprinkler type of system, which can lead to clogging of emitters and pipes. Moreover, in the case of concomitant use of very high hardness and high sodium water, soil structure may be destroyed, deteriorating water infiltration and aeration needed for healthy plants [35]. The total hardness of water is commonly expressed in terms of equivalent calcium carbonate ($CaCO_3$) concentration and is calculated using the concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. The formula is expressed as [38]:

$$\mathrm{TH} = 2.5\, Ca^{+2} + 4.1 Mg^{+2} \tag{4}$$

where; Ca^{+2} and Mg^{+2} are in mg/l. Multiplication factors 2.5 and 4.1 convert calcium and magnesium to $CaCO_3$ equivalents. The calcifications of TH for irrigation water were mentioned in Table 5.

2.3.4. Water Quality Index (WQI)

The Water Quality Index (WQI) for agricultural use is an important indicator for assessing the suitability of the groundwater for irrigation. The index is based on the analysis of selected physiochemical properties that influence soil structure and crop health as well as long-term agricultural productivity. It usually involved measurements of EC, SAR, RSC, TDS, chlorides, nitrates, and boron. High EC and TDS of water would cause soil salinity problems, while high SAR and RSC would destabilize soil structure and reduce its permeability, resulting in unsuitable water for crop growing. Thus, evaluation of the WQI is significant to the farmers and planners for safer irrigation water and also to make rectifications, if need be. WQI is a single-value summary of complex water quality data in water resource management for agriculture, which is easy to interpret and suitable for decision-making. The water quality index is a significant issue in sustainable agriculture, especially in places where there is contamination of groundwater or overextraction [39]. The calcifications of WQI for irrigation water were mentioned in Table 5. The WQI was calculated to define the arable areas by the following formula [28, 40, 41]:

$$\mathrm{WQI} = \frac{\sum Qn \times Wn}{\sum Wn} \tag{5}$$

where; *Qn* is the quality rating for the n-th parameter, and *Wn* is the weight of the n-th parameter (importance factor), *n* is the number of parameters used. The *Qn* is expressed as:

$$Qn = \frac{(Vn - V\ ideal)}{(Sn - Videal)} \times 100 \tag{6}$$

where; *Vn* is the measured concentration of the n-th parameter, *Sn* is the standard permissible limit of the n-th parameter for irrigation, and *Videal* is the ideal value of n-th parameter for irrigation.

2.4. Kriging Analysis

In the ArcMap 10.3 software, the Arc Toolbox refers to the toolkit used in this study for analysis. This feature helps us to perform multiple analyses on our attribute table and data. In this case, it implies the Kriging (spatial analyst interpolation tool) is responsible for this. We generate a prediction over the entire map based on this data. Format-wise, Kriging methods vary from each other, but all of them are based on the very basic concept of ordinary least squares regression [42]. Kriging is an advanced geostatistical method that generates an interpolation surface from a collection of points in space, each of which has z-values. First of all, unlike the other interpolation methods in the Interpolation toolset, the Kriging tool requires the experimentalist to explore the distributional tendencies of the event represented by the z-values before choosing the most suitable approximation method for producing the surface map. There are two types of interpolation methods. The first one is the deterministic interpolation method: These types of interpolation methods are derived directly from nearby observations (IDW, spline interpolation tools) or are based on mathematically determined smoothness of the resulting surface.

The second family of interpolation methods, which are based on statistical models like autoregression (for example, kriging), is particularly useful for their intended applications. Therefore, Geostatistical methods are not only useful for developing prediction surfaces, but they also offer an assessment of the confidence of those predictions. Kriging is a suitable method for spatial variation across a surface, as it is based on the premise of a spatial autocorrelation that can be used for prediction whereby the distance and direction between sample points have a relation. Kriging is a mathematical function fit to some of the sample points, or all sample points but to a certain distance, to estimate what the values at non-sample points would be. Kriging can be considered as a multi-step process including exploratory statistical analysis of the dataset, variogram modeling, surface interpolation, and (optionally) prediction variance assessment. This approach is especially appropriate if spatial gradients or directional tendencies are recognized in the data. Kriging is popular in Earth science disciplines like soil science and geology [43]. Kriging behaves analogously to IDW in that it weights the measured values surrounding an unmeasured location and predicts its value accordingly. Both interpolators use the general formula in the following way, as a weighted sum of the data:

$$Z(\mathrm{s}0) = \sum_{i=1}^{N} \lambda i\, Z\,(si) \tag{7}$$

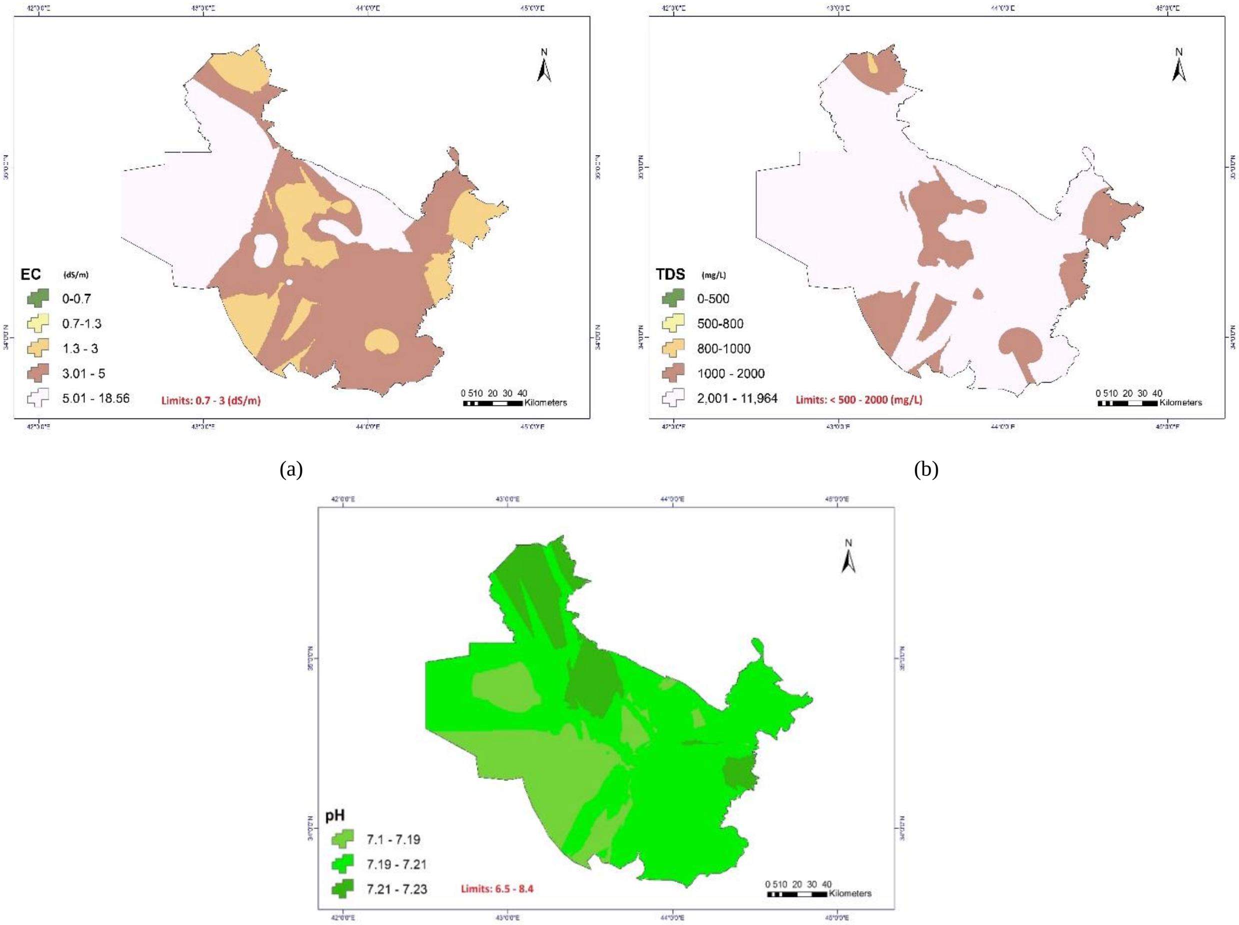
where; $Z(si)$ is the observed value at the i^{th} point, λi is an unknown weighting corresponding to the observed value at the i^{th} location, s_0 is the prediction location and N is number of observed values.

Kriging has a different approach to weighting than, for instance, Inverse Distance Weighting (IDW), where the weight λi only accounts for the distance to the prediction location. Kriging enables the use of both distance and the spatial layout of sampled points, i.e., the weight given to each measurement point is dependent on autocorrelation in space, which needs to be first assessed. In particular, in ordinary kriging, the weight λi is found through a model fit to the sample data that considers the distance to the prediction location and the spatial relationships among neighbors of the sampled values [43]. Previous research has validated the use of the kriging technique in monitoring the groundwater quality parameters [44-46].

3. Results and Discussion

3.1. Kriging Interpolation of Groundwater Quality Parameters

According to Figure 3-a, natural and anthropogenic causes are responsible for the high EC values of groundwater in Salah Al-Din. The primary natural agent is dissolution of salts from sedimentary rocks; thus, groundwater in the Balad district could be influenced by interactions with formations that are rich in dissolved chloride elements, sulfate, calcium, magnesium, and sodium [47]. Moreover, evaporation in arid and semi-arid regions, such as the Al-Jallam desert, increases salinity by reducing water bodies and retaining ions, particularly in groundwater recharge zones [48]. Unsustainable agricultural practices are another major contributor to the problem, as the pollution caused by the excessive use of fertilizers and inefficient irrigation systems results in secondary salinization and salt-rich water being refilled into aquifers [49]. Seasonal variability also plays a role; EC values during the wet season are lower than during the dry season, as dry periods are associated with less groundwater recharge in addition to higher evaporation rates due to high evapotranspiration rates [50]. Finally, geophysical studies in various areas of Salah Al-Din, particularly in Balad, suggest that geo-electrical conductivity associated with high salinity zones proves that the geological structure and water chemistry have a contribution in raising the EC value [51]. The map in Figure 3-b shows that most of the lands have high values of TDS due to the same causes of high EC, and the result map for pH values, as shown in Figure 3-c, shows that all of the area has groundwater with an acceptable value of pH for irrigation purposes.



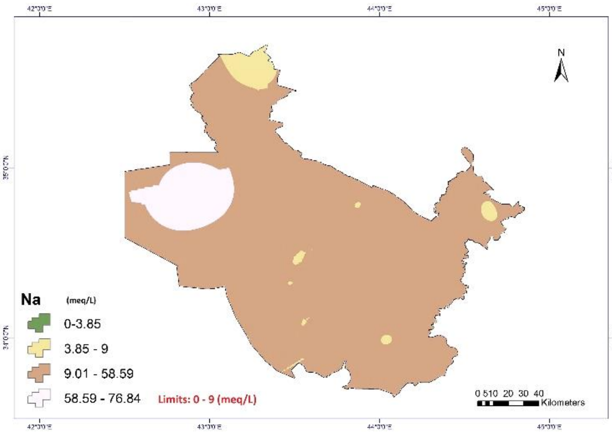
(a) (b)

(c)

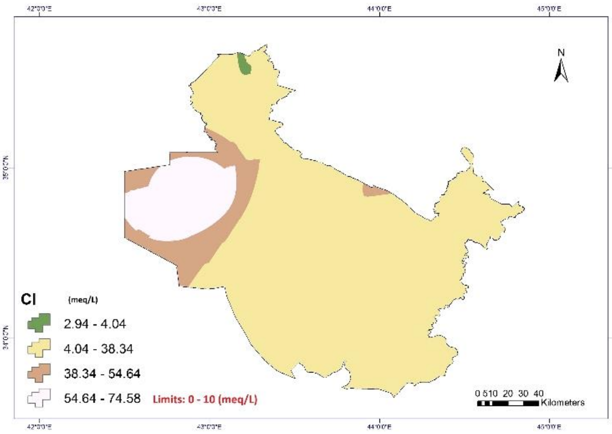
Figure 3. Kriging Analysis of a) EC, b) TDS, and c) pH of 51 wells in Salah Al-Din Governorate, Iraq

In Tikrit, Hussain et al. [17] reported that the EC was higher than 3940 µS/cm and the TDS ranged from 1000 to 1930 mg/l. In the present study, EC ranged from 2000 to 11000 µS/cm, while TDS ranged from 2000 to 7000 mg/l. Al-Saadi et al. [20] discovered that the TDS levels in Balad ranged from 753 to 3,614 mg/l, while the soil EC was between 590 and 3,492 µS/cm. On the other hand, two wells in Balad in the present investigation had TDS values of 1352 mg/l and 1997, respectively, and EC values were 3070 and 2080 µS/cm. Additionally, it was demonstrated by Al-Tameemi et al. [22] that the groundwater in the Samarra district had EC values ranging from 650 to 4,200 µS/cm, which indicates varying salinity. TDS concentrations range from 800 to 4,500 mg/L. The TDS values in the present study ranged from 1000 to 4000 mg/l, while the EC values in Samarra ranged from 2000 to 6000 µS/cm. TDS readings at Al-Dour ranged from 1380 to 1903 mg/l, according to Daoud et al. [29], whereas the TDS for the three wells in the present study were 2210, 2760, and 1500 mg/l. Compared to earlier research, this study generally revealed an increase in salinity.

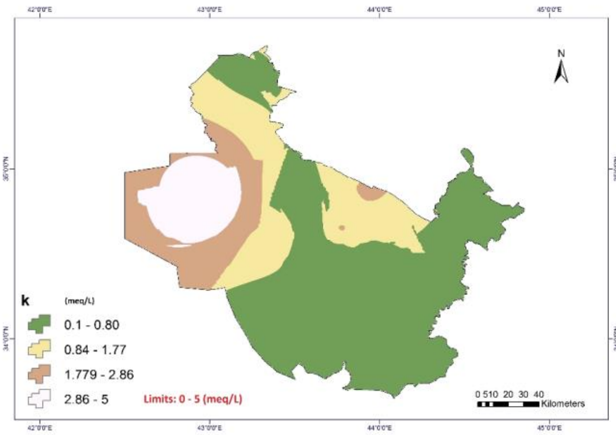
The concentration of Na in the groundwater of Salah Al Din is high and harmful to crops as well as the parameter Cl (Figures 4-a and 4-b). Groundwater in Salah Al-Din Governorate is characterized by relatively high concentrations of chloride (Cl^-) and sodium (Na^+). These are the most common ions associated with natural and anthropogenic processes. Of course, the leaching of evaporitic minerals such as halite (NaCl) from the rock contributes substantially to the high concentration of these ions. Furthermore, dry to semiarid climates speed up evaporation, so there is more salt in soil and groundwater. Salinization can be aggravated by agriculture (over-application of chemical fertilizers, irrigation reaching aquifers, etc.). High Cl^- and Na^+ concentrations are hazardous to soil structure, crop productivity, and the potential of groundwater for irrigation [52].



(a)



(b)

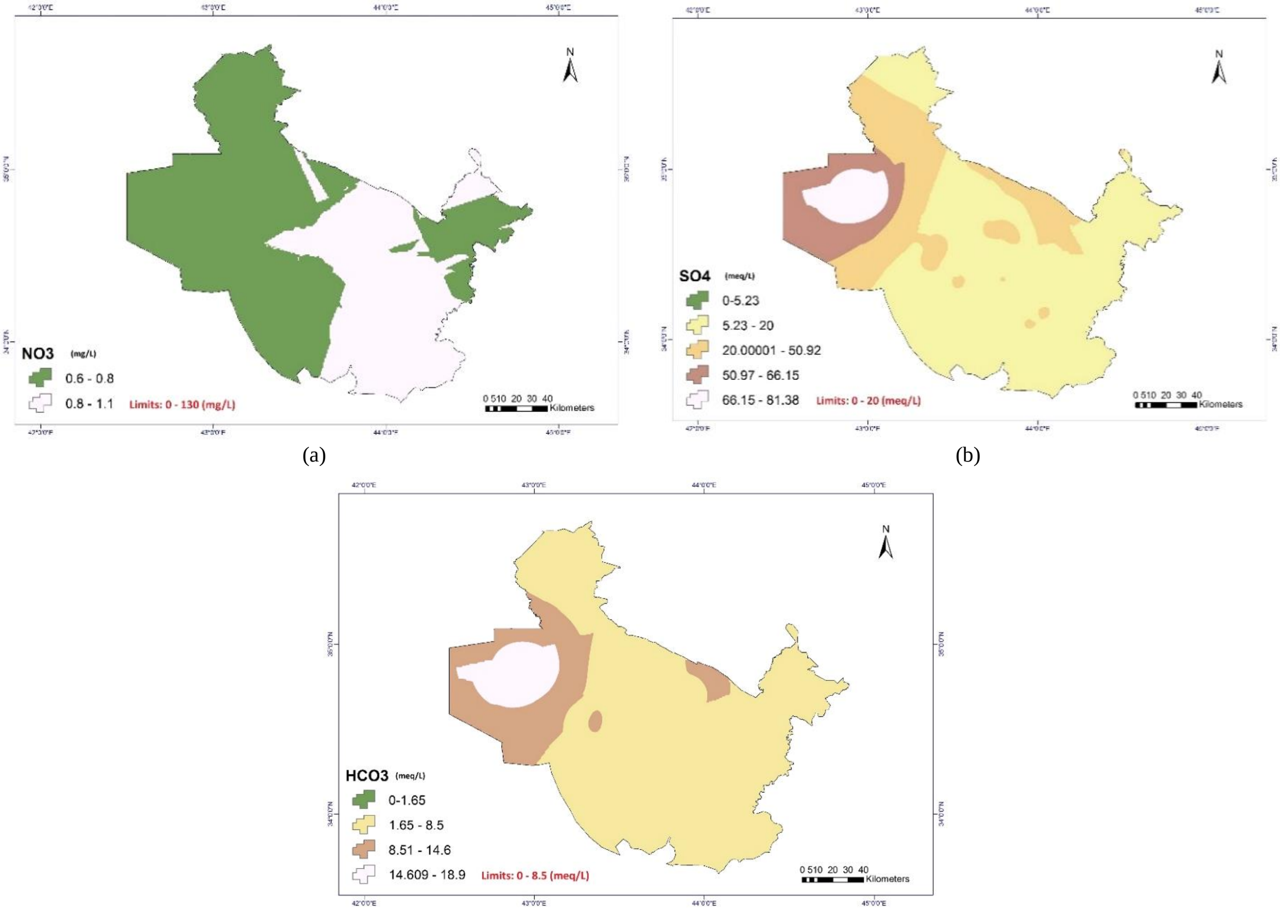


(c)

Figure 4. Kriging Analysis of a) Na, b) Cl, and c) k of 51 wells in Salah Al-Din Governorate, Iraq

Figure 4-c indicated that the concentration of K in Salah Al Din groundwater is reasonable. Potassium is not a very mobile cation within aquifers and does not play a major role in the ionic balance of groundwater. This could be attributed to potassium having a high ability to be adsorbed onto clay minerals and soil particles. Potassium is usually present at a minimal level in groundwater of Salah Al Din, within the acceptable limit for irrigation and domestic use. Concentrations of less than 2 mg/l in irrigation water are more acceptable because they prevent the nutrient imbalance and soil structural problems that occur at these higher levels [52].

The acceptable concentration of NO_3 in Salah Al-Din groundwater wells was observed in Figure 5-a. The modest nitrate pollution is attributed to comparatively low fertilizer use in conventional agriculture, coupled with moderate aquifer permeability, which can diffuse nitrate infiltration. Combined, these factors keep nitrate at concentrations that are typically acceptable for drinking water and irrigation [53]. The SO_4 in the groundwater of most areas in Salah Al-Din is acceptable (Figure 5-b). The local geology and hydrogeological conditions are key in the suitable concentration range. Groundwater moving through sedimentary rocks in the region has moderate amounts of sulfate-bearing minerals like gypsum ($CaSO_4 \cdot 2H_2O$) and anhydrite ($CaSO_4$). These minerals gradually dissolve, continuously liberating sulfate ions into the water, but at a relatively low rate. Furthermore, the semi-arid climate reduces leaching and the over-accumulation of sulfate. Natural drainage and mixture with recharge water also assist in keeping sulfate concentrations low (< 180 mg/l) [54].



(a) (b)

(c)

Figure 5. Kriging Analysis of a) NO_3, b) SO_4, and c) HCO_3 of 51 wells in Salah Al-Din Governorate, Iraq

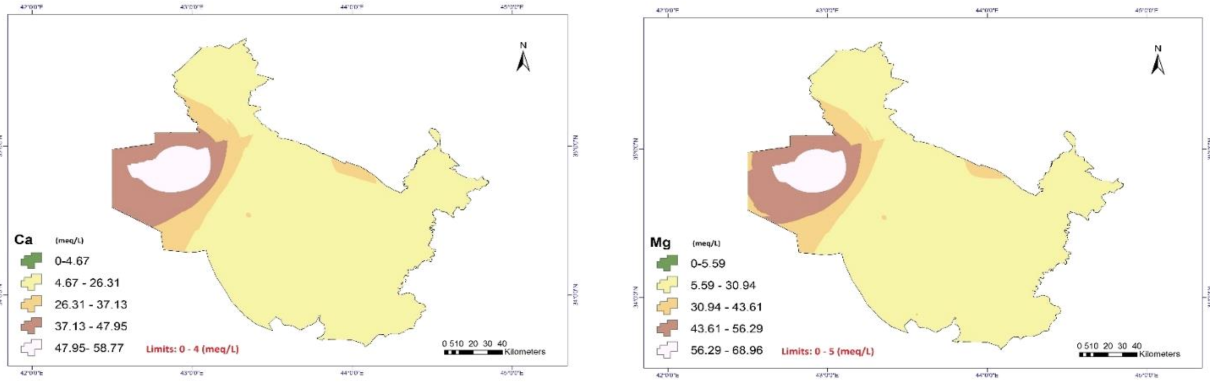
Figure 5-c shows that the HCO_3 concentrations in the groundwater of the majority of areas in Salah Al Din are within an acceptable range. This high value of bicarbonate (HCO_3^-) ions in groundwater of Salah Al-Din Governorate could be attributed to the geological and hydrogeochemical nature of the area. Aquifers in the study area are mainly carbonate reservoirs (i.e., limestone, dolomite), which release bicarbonate when groundwater interacts with carbonate minerals. This process keeps the water slightly alkaline, i.e., it buffers the water against extreme swings in pH and helps to maintain a neutral to slightly alkaline pH value ideal for drinking and irrigation. In addition, the lack of major industrial contamination and the average agricultural pressure limit the accumulation of bicarbonate. Therefore, the concentrations of HCO_3^- in most groundwater samples fall within permissible limits, indicating that these water resources can be used sustainably [55].

The concentration of CO_3 in the groundwater of Salah Al Din is equal to zero, as reported in this study. The reason for this phenomenon is largely attributed to the natural pH of groundwater, which is mostly neutral to slightly alkaline (approximately pH 6.5–8.5). At this pH interval, most of the dissolved inorganic carbon is bicarbonate ions (HCO_3^-), not carbonate ions (CO_3^{2-}). From a chemical perspective, carbonate ions are stable only at elevated pH (above pH 10 in general). The cations bicarbonate forms at low pH levels with carbonate ions are:

$$CO_3^{-2} + H^+ \rightarrow HCO_3^- \tag{8}$$

Under such conditions, CO_3^{2-} is less important and bicarbonate is formed in Salah Al-Din groundwater instead. This is a common phenomenon in many natural groundwater systems with moderate alkalinity and depends on the buffering of carbonate minerals and equilibrium with dissolved CO_2 [54].

The high calcium concentration (Figure 6-a) is mainly due to the solubilization of carbonate minerals, including calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$], which are abundant in the sedimentary formations of the region. When groundwater comes into contact with these rocks, the minerals dissolve, releasing calcium ions into the water. The high content of magnesium (Figure 6-b) ions in the groundwater of Salah Al-Din Governorate refers to natural geochemical processes and regional hydrogeological conditions. This increase is predominantly due to the decomposition of carbonate minerals, notably dolomite [$CaMg(CO_3)_2$] and magnesite, widely present in the sedimentary rock formations of the area. In reaction with these carbonate-bearing rocks, groundwater releases magnesium in the solution, thus increasing its concentration in the aquifer. Furthermore, its semi-arid climate encourages high rates of evaporation that enrich shallow groundwater with dissolved ions such as magnesium. In addition, ion exchange processes are involved: calcium being precipitated or exchanged, but magnesium could stay in solution or even increase [56, 57].

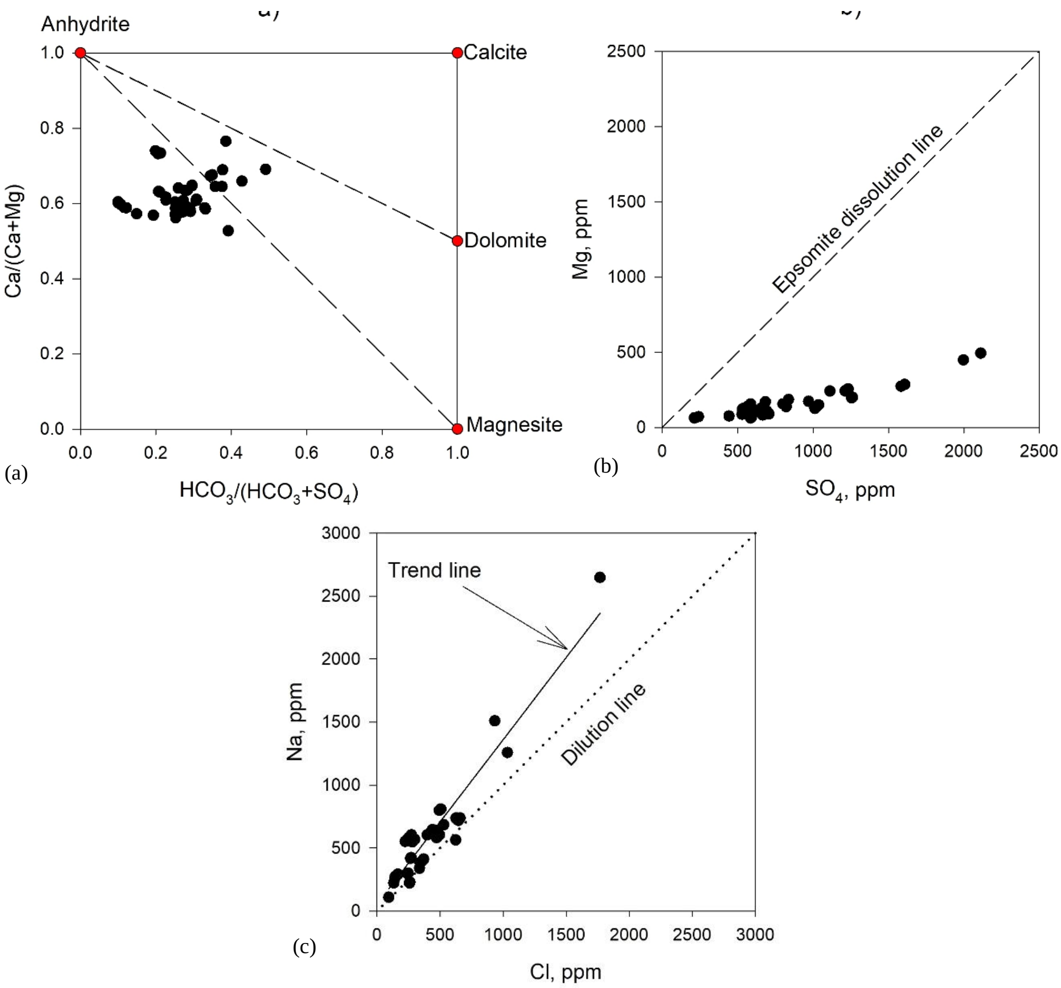


(a) (b)

Figure 6. Kriging Analysis of a) Ca and b) Mg of 51 wells in Salah Al-Din Governorate, Iraq

3.2. Geochemistry Analysis of Groundwater Parameters

Figure 7-a shows that some of the well data fall within the dolomite stability field, exhibiting a compositional trend towards calcite; however, none reach pure calcite conditions. This implies that the predominant controlling process of carbonate species in the groundwater is probably dolomite dissolution rather than calcite dissolution exclusively. The majority of wells's data are situated in the magnesite range. The moderate concentration of HCO_3^- indicates that carbonate minerals are being weathered and releasing Ca^{2+} and Mg^{2+} into solution. The lower HCO_3^- compared to SO_4^{2-} also suggests another potential SO_4^{2-} source, presumably evaporated minerals. Figure 7-b shows that the gypsum (or anhydrite) dissolution line plotted reflects the stoichiometric relationship expected between SO_4^{2-} and Ca^{2+}, assuming both are derived from dissolution of these evaporates. Groundwater samples are below this line, reflecting an excess of SO_4^{2-} compared to Mg^{2+}. The result indicates that SO_4^{2-} is predominantly derived from gypsum or anhydrite dissolution, whereas Mg^{2+} is more affected by carbonate minerals (i.e., dolomite). This symbol denotes a dual control on the chemistry of groundwater (evaporating minerals releasing SO_4^{2-} and Ca^{2+} and dolomite adding Mg^{2+}).



(a) (b) (c)

Figure 7. Binary diagrams: a) Ca/(Ca + Mg) vs. HCO_3/(HCO_3 + SO_4), b) Mg vs. SO_4, and c) Correlation diagrams of Na vs. Cl, for 51 wells in Salah Al-Din Governorate, Iraq

The dilution line indicates a conservative mixing trend that would be derived primarily from halite dissolution or from mixing with a saline source (Figure 7-c). The dashed line for the actual data represents the trend line, and most samples plot just above the dilution line, indicating Na^{+} enrichment relative to Cl^{-} . Part of this excess Na^{+} can be attributed to cation exchange reactions (where Ca^{2+} in solution is exchanged for Na^{+} on clay minerals) or to silicate weathering (e.g., dissolution of albite). As a result, ion exchange and silicate weathering—both hydrogeochemical processes that modify the conservative behavior of ions—are confirmed by the observed departure from the dilution line. Because most data points follow a positive linear trend, this indicates that halite dissolution or conservative mixing is the dominant mechanism controlling groundwater salinity.

Groundwater pH and alkalinity are buffered by carbonate weathering (mainly dolomite), which is responsible for one of the main sources of Ca^{2+} and Mg^{2+}. A solution of gypsum/anhydrite greatly increases its salinity and hardness from SO_4^{2-}. The elevated Na^{+} concentrations that exceeded what could result from halite, due to ion exchange and silicate weathering, suggest interaction of the water with rock and clays and feldspars. The trends in this mixing imply that this groundwater is chemically evolved through both mineral dissolution and geochemical reactions during subsurface flow processes. Overall, the two plots demonstrate the main components of groundwater chemistry in the study area, which are carbonate and evaporite mineral dissolution and secondary contributions by ion exchange and silicate weathering. It suggests that the hydrogeochemical system is affected simultaneously by the lithology and the patterns of groundwater flow [58]. These hydrogeochemical patterns are consistent with previous studies conducted in similar semi-arid regions of Iraq and neighboring areas. For example, Al-Ansari et al. [57] and Mahmood et al. [56] also reported that groundwater chemistry in the region is predominantly controlled by the dissolution of carbonate and evaporate minerals, with dolomite playing a more significant role than calcite in controlling Mg^{2+} levels. Similarly, Jassas et al. [59] noted that sulfate enrichment is mainly sourced from gypsum and anhydrite layers within the sedimentary sequence, aligning with the trends observed in the current study. Moreover, the excess sodium relative to chloride has been highlighted by Ismail et al. [54], who attributed it to active cation exchange and prolonged interaction with clay minerals and feldspar-rich formations. This is consistent with the departure of data points from the conservative dilution line shown in Figure 7-c. Overall, these results reinforce existing knowledge about the dominant geochemical processes shaping groundwater quality in Salah Al-Din and surrounding districts: mineral dissolution (carbonates and evaporites), ion exchange, and silicate weathering. However, the current study provides updated and site-specific evidence confirming that dolomite dissolution and gypsum/anhydrite weathering remain the primary contributors to groundwater hardness and salinity, while sodium enrichment continues to pose challenges for domestic and agricultural use under declining recharge conditions and increasing abstraction pressures.

The clear positive linear trend in Figure 8-a indicated that SO_4^{2-} comes from the dissolution of evaporite minerals (e.g., gypsum/anhydrite). The ions Cl^{-} and HCO_3^{-} indicate mixing and carbonate mineral dissolution [58]. A near-linear relationship indicates that as SO_4^{2-} increases in the vicinity of gypsum dissolution, Cl^{-} and HCO_3^{-} may also increase proportionally due in part to mixing with more mineralized groundwater or through longer water–rock interaction pathways [60]. A scatter plot of magnesium (Mg) and calcium (Ca) concentrations in groundwater samples is shown in Figure 8-b. The two ions are the most common constituents of natural groundwater, and their relative abundances are important indicators of water–rock interaction processes. The data points falling very closely around the trend line clearly show a strong positive linear correlation between Ca and Mg. According to Hem [60], based on their presence, both the ions are primarily derived from dissolving carbonate minerals, especially from groundwater weathering of limestone (calcite, $CaCO_3$) and dolomite [$CaMg(CO_3)_2$] within the aquifer. The near-linear trend indicates homogeneous geochemical conditions existing through the groundwater system with a moderate scatter likely due to localized lithological variation or cation exchange processes.

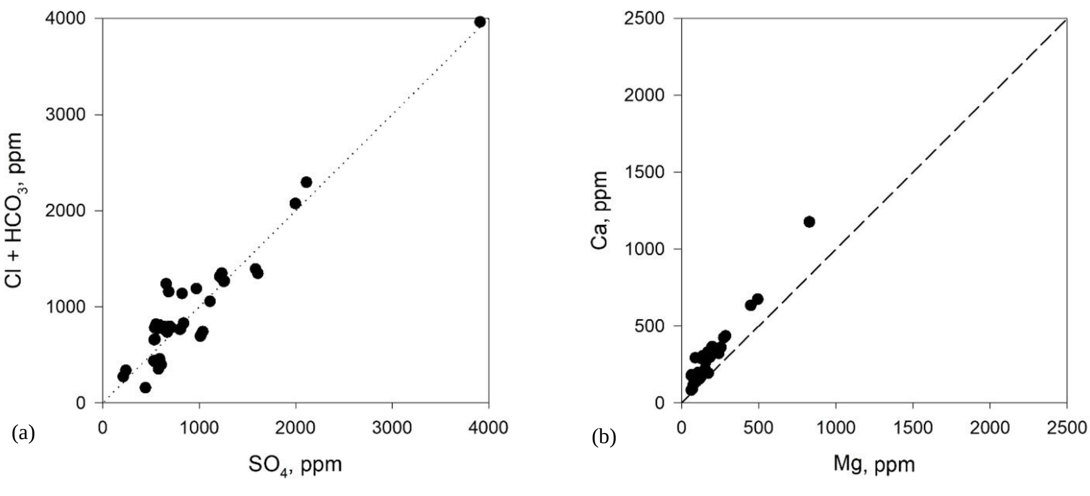


Figure 8. Correlation diagrams of a) SO_4 vs. HCO_3 + Cl and b) Mg vs Ca showing the groundwater samples 51 wells in Salah Al-Din Governorate, Iraq

Major ion concentrations in groundwater samples from 51 wells are plotted as a stacked bar chart (Figure 9). Bars correspond to wells, and colors are used to show the proportion of Cl^{-} + NO_3^{-} (dark blue), Na^{+} + K^{+} (red), CO_3^{2-} + HCO_3^{-} (green), SO_4^{2-} (purple), Mg^{2+} (light blue), and Ca^{2+} (orange). Total ion concentrations vary greatly from well to well, suggesting different water–rock interactions, residence times, or anthropogenic influences. Several of the wells (particularly Well 17, Well 27, and Well 33) have very high TDS, indicative of nearby contamination sources, intense mineral dissolution, or longer flow paths. Most samples yield dominant anion patterns of chloride plus nitrate and carbonate plus bicarbonate, which aligns with the expected cation–anion relationship in sedimentary basins [60]. Gypsum dissolution or dolomitic rock effects are indicated by elevated sulfate, magnesium, and calcium in some wells. The detected ionic species is representative of the geochemical processes groundwater experiences when interacting with aquifer material, although some wells may be influenced by anthropogenic contributions (e.g., fertilizers for nitrate or irrigation return flow for chloride). In general, the patterns of major ions agree with the norms of hydrogeochemical processes described by Saleh et al. [31].

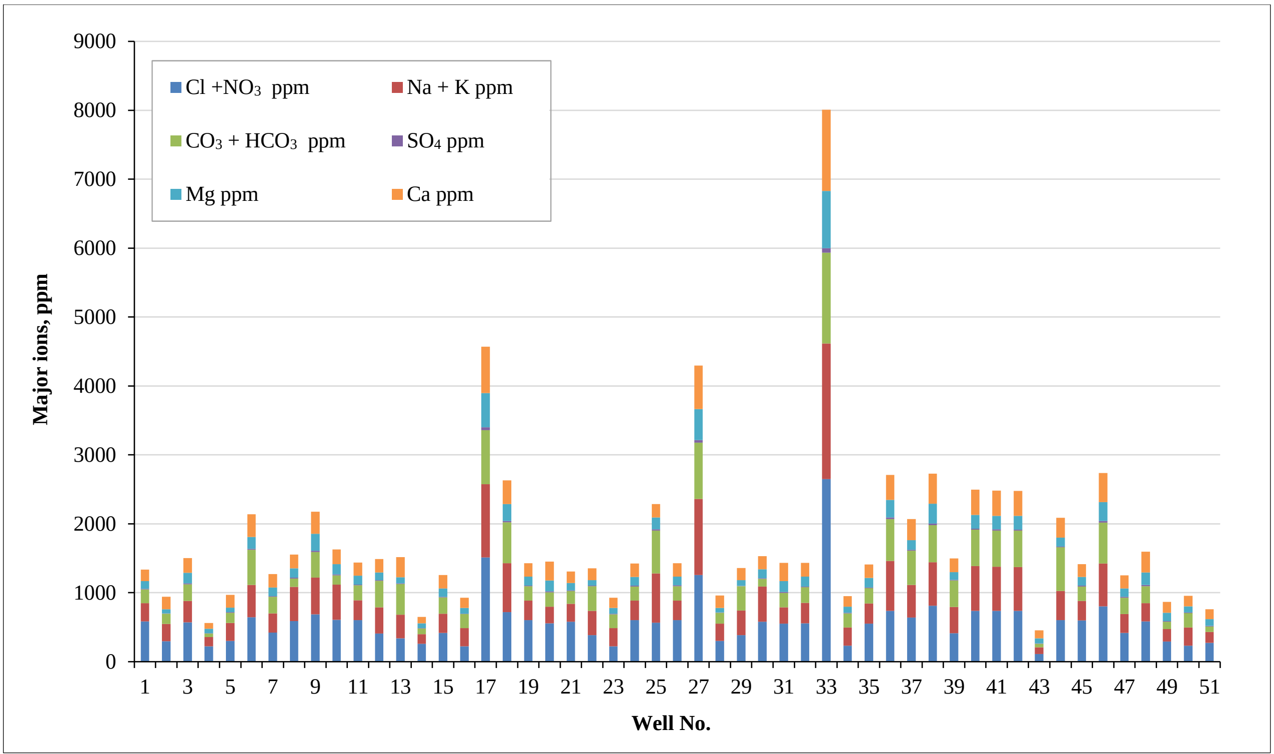


Figure 9. The concentrations of major ions in groundwater samples from 51 wells in Salah Al-Din Governorate, Iraq

3.3. Analysis of SAR, RSC, TH, and WQI

As shown in Figure 10-a, the SAR does not exceed the acceptable level throughout the area. Low SAR values imply a balanced status of Na with respect to Ca and Mg in the water, which is preferred for good soil structure and permeability. Water with a low sodium adsorption ratio (SAR $\leq$ 10) exerts minimal risk of sodium accumulation in the ground. Soil sodicity is the excessive sodium that can disrupt the stability of soil particles, decreasing infiltration, causing poor aeration, and reducing yield potential. Thus, irrigation water with a low SAR value is effective in maintaining soil fertility and the growth of healthy plants [35]. Since CO_3 and HCO_3 are less than Mg and Ca values, all RSC values are in minus (Figure 10-b). In the same way, the RSC is also acceptable in the entire area of the study, as shown in Figure 10-b. Low or negative RSC values are desirable, as this confirms the calcium and magnesium ions are present in adequate proportions to offset precipitation as slaked products to enhance sodium hazard and soil dispersion [35]. Figure 10-c shows that all of the study area has a very high total hardness according to the high concentrations of Ca and Mg as discussed above.

Figure 10-d shows that a small area of Salah Al-Din has groundwater with a good WQI (dark green) for irrigation in distribution associated with the values of SAR, EC, RSC, TDS, pH, Cl, Na, NO_3 , HCO_3 , Ca, and Mg for the region. The groundwater quality in the Tikrit, Al-Alam, and Baiji districts, based on WQI and kriging analysis, is more at risk from degradation, resulting in impacts on agriculture and food production and food security, starting from a short-term scale to a long-run environmental sustainability high risk.

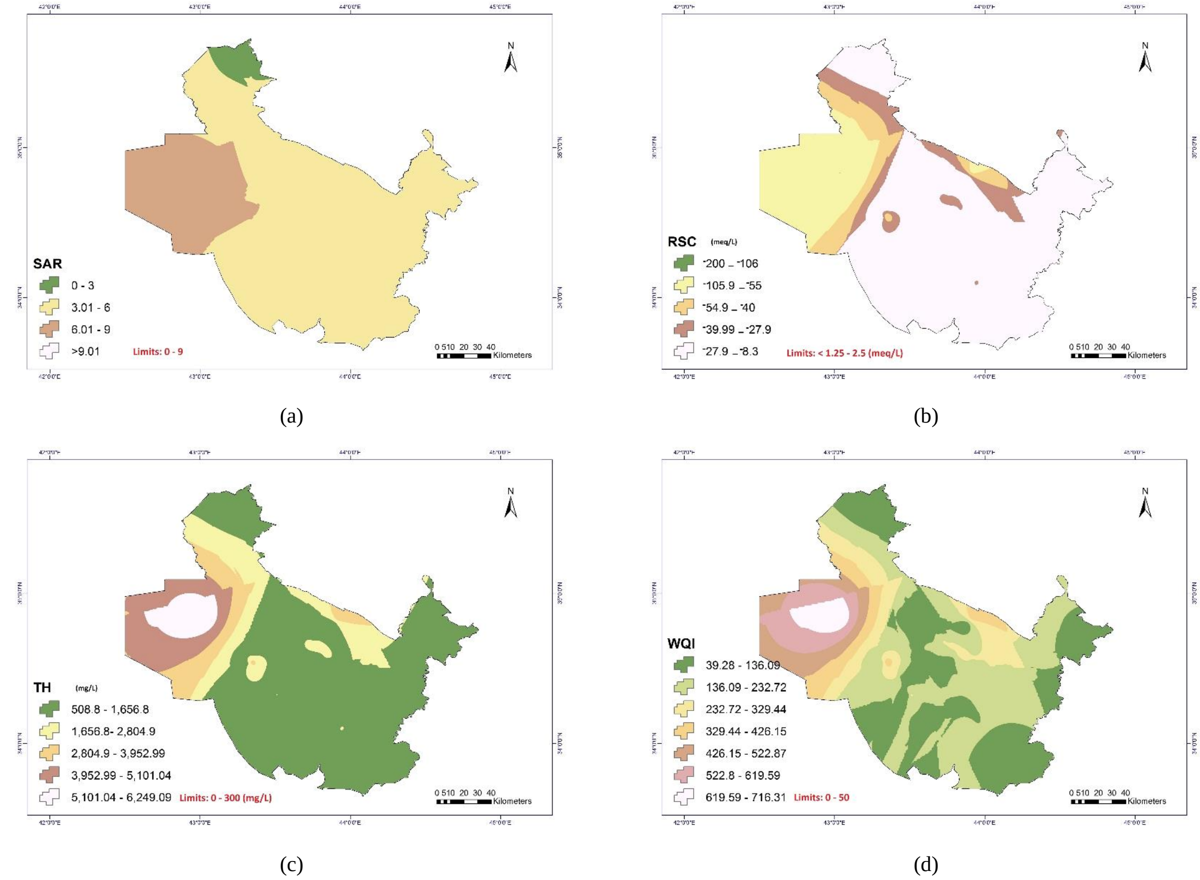


Figure 10. Kriging Analysis of a) SAR, b) RSC, c) TH, and d) WQI of 51 wells in Salah Al-Din Governorate, Iraq

In the Al-Alam District, groundwater levels have shown a noticeable decline in recent years. For instance, the static water level at the Eastern Khazamiyah well (which had been read by a level sounder) dropped from 23.15 meters in 2014 to 75.5 meters in 2025. Similarly, the static level at the Al-Tefouf well increased from 46.35 meters to 88.5 meters over the same period. This trend is largely attributed to rising agricultural water demand, reduced annual rainfall, upstream water extractions, and prolonged drought conditions linked to climate change. Additionally, the proliferation of unregulated wells has further intensified pressure on the aquifer. Together, these factors have contributed to groundwater withdrawals exceeding the aquifer's natural recharge capacity [56, 57, 59].

4. Conclusion

The research indicated high groundwater salinity, as observed by the high values of EC and TDS in most of the Salah Al-Din Governorate regions. In many of the wells, there were also relatively high concentrations of sodium and SAR that exceeded the standard level, which may harm soil structure and permeability, particularly in poorly drained soils. The RSC values at most of the locations indicated the precipitation potential of calcium and magnesium, which aggravated sodium hazards and reduced the infiltration capacity of the soils. This study's analysis revealed that the groundwater in Al-Alam (primarily well 17), Tikrit (primarily well 27), and Baiji (primarily well 33) is at a higher risk of degradation, which negatively impacts agriculture, food production, and food security, ranging from short-term effects to long-term risks for environmental sustainability. Groundwater quality monitored via well data among the seasons indicated substantial degradation with regard to groundwater quality during summer months, which was attributed to minimal recharge, a substantial increase in evaporation, and an increase in agricultural water demand. The comparative analysis of static water level between the two measurement wells for 2014 and 2025 indicated the groundwater elevation depletion due to overextraction of groundwater and poor replenishment in some areas. Groundwater quality in Salah Al-Din is mostly controlled by natural hydrogeological formations; however, considerable anthropogenic impacts associated with unregulated use of fertilizers, industrial discharges, and untreated sewage infiltration determine an additional component of this variable source of data. This study emphasizes the urgent requirement for groundwater conservation through an integrated approach in resource management. Some areas of Salah Al-Din are still suitable for groundwater irrigation based on the current water quality, while most vegetable-growing regions are either unsuitable or will soon become unsuitable. It is essential to urgently define scientific monitoring, implement policy changes, and mobilize the community; otherwise, further groundwater degradation will soon lead to irreversible impacts on agriculture and human health in the region.

5. Declarations

5.1. Author Contributions

Conceptualization, N.R. and A.A.; methodology, N.R. and A.A.; software, N.R. and D.S.; validation, N.R. and D.S.; formal analysis, N.R. and A.A.; investigation, N.R.; resources, N.R. and D.S.; data curation, N.R.; writing—original draft preparation, N.R.; writing—review and editing, A.A.; visualization, D.S.; supervision, A.A.; project administration, A.A.; funding acquisition, N.R. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding and Acknowledgments

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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