

Research Article

Sustainable Water Resources Management and Groundwater Quality Assessment: Case of Karbala, Iraq

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Article Info	Abstract
Article History	Barren lands can be converted into agricultural land through a multidisciplinary approach to water management. This study evaluates the groundwater quality for irrigation in the uncultivated Faddak land (277 km ²) north of Kerbela City, Iraq. Thirty groundwater samples were collected from regional wells and analyzed using GIS, testing, and international standards from the FAO and the Canadian Council of Ministers of the Environment (CCME). A range of physicochemical parameters were tested, including calcium, magnesium, sodium, potassium, sulfate, chloride, total dissolved solids, electrical conductivity, and others. The results showed that most pollutants exceeded permissible limits, with an Irrigation Water Quality Index (IWQI) of 36.28, indicating that the groundwater was unsuitable for irrigation. It is concluded that the water demands of native plants can be met through a combination of rainfall and surface water from the Euphrates River, with a maximum release of 20 m ³ /s required for cotton cultivation in July if 50% of the area is planted.
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1. Introduction

Water management is particularly important in areas that suffer from water scarcity, often due to limited resources or the development of regional water conflicts resulting from groundwater chemical pollution. However, the management of saline or chemically polluted groundwater requires a different approach and must be taken proactively before it is incorporated into an optimal water management program at the regional or local level. This can be achieved by removing the causes of pollution or salinization, or by mitigating and natural purifying groundwater [1].

To achieve sustainable water management, it is essential first to assess the validity of groundwater

for various uses and determine the extent of its biochemical pollution. Conventional evaluation methods compare measured parameters against established guidelines to assess water quality; however, these traditional approaches often fail to provide a comprehensive picture of spatial and temporal trends without extensive seasonal sampling and testing [2]. As climate change intensifies water stress globally and population pressures and urbanization increase demands on groundwater systems, Iraq and similar arid regions face urgent challenges in ensuring sustainable water resource management.

This study focuses on assessing groundwater quality using the Water Quality Index (WQI) and Geographic Information System (GIS) techniques, two widely adopted tools that allow the integration of multiple water quality parameters into a single, interpretable index. By applying these tools to the Faddak region, north of Karbala Province, this research aims to provide new insights into spatial patterns of groundwater quality, identify key areas at risk, and offer actionable recommendations for local water managers. The study involved a physiochemical evaluation of groundwater by testing thirty randomly selected wells across a 277 km² area. Using GIS and IDW interpolation, physiochemical maps of groundwater storage for 2023 were created, and it was concluded that the groundwater was unsuitable for agriculture. As a result, optimal water resource management in the area is based on utilizing monthly rainfall as an uncontrolled source to meet agricultural needs, supplemented by water from the Euphrates River via canals and field pipes. This study highlights that while groundwater can meet the needs of civil, agricultural, industrial, and urban sectors, its chemical composition must remain within permissible limits; otherwise, alternative sources, such as the Tigris and Euphrates rivers, must be relied upon.

2. Literature Review

Various methods and tools have been developed to evaluate groundwater quality across regions. The Water Quality Index (WQI) is one of the most widely used approaches, combining multiple chemical and physical water quality parameters into a single composite score [3]. For example, studies conducted in the Bardarash area of northern Iraq evaluated groundwater used for irrigation and domestic purposes, employing WQI and GIS to assess pH, TDS, NO₃, and other key parameters. Using spatial variation maps generated through the Inverse Distance Weighted (IDW) technique, researchers determined that 8.3% of wells had excellent quality, 75% were of good quality, and 16.7% were of poor quality [2].

At Al-Anbar University, researchers investigated the effects of wastewater, septic tank leaks, and agricultural runoff on groundwater quality. Their analysis combined physical, chemical, and biological tests and assessed treatment options using coagulation and flocculation methods. The optimal conditions achieved a removal efficiency of up to 80.7% using alum, demonstrating effective pathways for groundwater remediation [4]. Similarly, in the Tabriz aquifer in northwest Iran, researchers utilized long-term well monitoring data and indices, including EC, TDS, and SAR, to evaluate groundwater suitability for drinking and irrigation purposes. They noted a decline in water quality over time, which underscored the need for

sustainable management strategies [5].

In China's Loess Plateau, studies employed the entropy-weighted TOPSIS method to evaluate groundwater suitability under the WHO guidelines, revealing that TDS, TH, and SO_4^{2-} were the primary concerns, even though groundwater remained generally suitable for both drinking and irrigation [6]. In Iraq's Hashimiya region, a three-dimensional model tracked total dissolved salts as an indicator of mitigation progress, offering practical insights into salinity management [7].

One method of classifying water quality is to use indices, which allow multiple factors to be combined into a single number. This makes it easier to explain the long lists of indicators that support this categorization. Water quality indices are easy-to-understanding tools that help decision-makers assess water quality and its suitability for irrigation [8]. The Canadian Council of Ministers of the Environment (CCME) is a water quality index that differs from most others by omitting sub-indexing and weighting steps. Instead, it directly calculates the index using parameter measurements within fixed mathematical functions. This unique approach has made it the most popular water quality index, applicable to all water bodies. It also offers several advantages, including its ability to incorporate a wide range of water parameters (from four to many), flexibility in choosing water quality standards, and tolerance for missing data. It is also an easy and effective method for computing water quality indicators [9].

The groundwater quality in the Karbala Governorate, Iraq's Green Belt, was evaluated. The CCME WQI was used for evaluation in this area, and its values ranged between 30-35 using seven parameters, namely pH, CL, Mg, HCO_3 , EC, Na, and Ca for all wells within the study area. Therefore, the water quality is considered poor and must be treated before irrigating perennial trees [10]. A similar study in Ethiopia's Upper Awash Sub-river Basin has been carried out to investigate the hazards of groundwater pollution. Using the CCME, 13.5% of groundwater was designated as a high-risk zone through the application of linear regression, GIS technologies, and water quality indexes. 4.4% of the basin has high pollution levels, affecting 5.64% of the population. The results underscore the need for integrated risk modeling and regulatory actions to protect the health of water and ecosystems [11].

Due to surface water limitations caused by climate change, groundwater has become increasingly crucial for industrial, agricultural, and residential use. The quality and depth of groundwater in Najaf City, Iraq, can be assessed using remote sensing equipment, such as the Aqua detector. Thirty-nine sample sites, spanning 441.23 km², were examined in both rural and urban areas. Five groundwater depth and type spatial models were created using ArcGIS's IDW interpolation technique. The findings indicate that groundwater is available as early as 100 meters below the surface, with depth and quality differences facilitating optimal well placement [12].

Similarly, a chemical study was conducted on groundwater around Babylon City in central Iraq, covering an area of 5119 km². Chemical data were collected for several wells. A geographical information

system (GIS) environment was utilized to create themed maps using the water quality values that were analyzed as an attribute database of different parameters such as EC, CL, bicarbonate (CO_3), Na, and PH to evaluate its suitability for irrigation purposes through a set of indicators such as Kelly's ratio, sodium absorption ratio (SAR), residual sodium carbonate RSC, percentage of dissolved sodium SSP and PI. The study concluded that groundwater cannot be used for irrigation without prior treatment [13].

A hydrochemical study was conducted in an area of 640 km² west of Karbala, Iraq, considered part of the Western Desert. The groundwater flows towards the northeast and is characterized by its alkalinity with PH of 7.03-7.81, TDS of 1693-1852 mg/L, and EC of 2410 $\mu\text{S}/\text{cm}$ [13].

The water quality of the Euphrates River between the provinces of Karbala and Babylon has been evaluated and monitored at eleven locations near industrial discharges, agricultural drainage, and wastewater sources. Monthly samples were gathered and subjected to normal analysis procedures during the dry and wet seasons. PH, EC, BOD, DO, water temperature, TDS, total coliform, and different ions like SO_4 , NO_3 , and CL were among the measured parameters. Water quality was assessed using a new Iraqi Water Quality Index (IWQI) designed specifically for Iraqi aquatic systems [14]. The findings showed that the water quality for freshwater usage ranged from low to very bad. Seasonal variations in suitability for drinking, marine life, and agriculture ranged from favorable to unfit. Dense riverfront populations, industrial enterprises, and wastewater discharge have a significant impact on river water quality.

Despite these advances, many studies remain limited in spatial scope or focus primarily on isolated chemical assessments without integrating broader socio-environmental factors. There is a need for comprehensive, spatially integrated groundwater quality assessments in Iraq that combine WQI, GIS mapping, and robust analytical methods to inform sustainable management practices. This research aims to fill that gap by providing a detailed spatial evaluation of groundwater quality in the selected study area, to support more effective local water resource management strategies.

3. Materials and Methods

3.1. Study Area

The 277 km² study area is north of Kerbela Province and is bounded to the west by Al-Razzazah Lake and east by Babylon. To the north, it is bounded by the Anbar, and to the south, by the agricultural areas of the Karbala's border, as shown in Figure 1. Flat land with elevations between 27 and 64 meters above sea level characterizes the region's topography, as seen in Figure 2, which depicts how the land dips from the southwest to the northeast along the Euphrates River.

3.2. Geological Setting

The geological structures in the study area are the primary cause of groundwater chemical pollution, which in turn plays a crucial role in managing water resources. Geologically, this region is a flat plain

located in the central part of Iraq within the Mesopotamian zone. About 96% of the land is covered by Quaternary deposits (Pleistocene and Holocene), such as Gypcrete, Aeolian, and floodplain deposits. Only 4% of the area comprises the Injana Formation (Upper Miocene) [15-17].

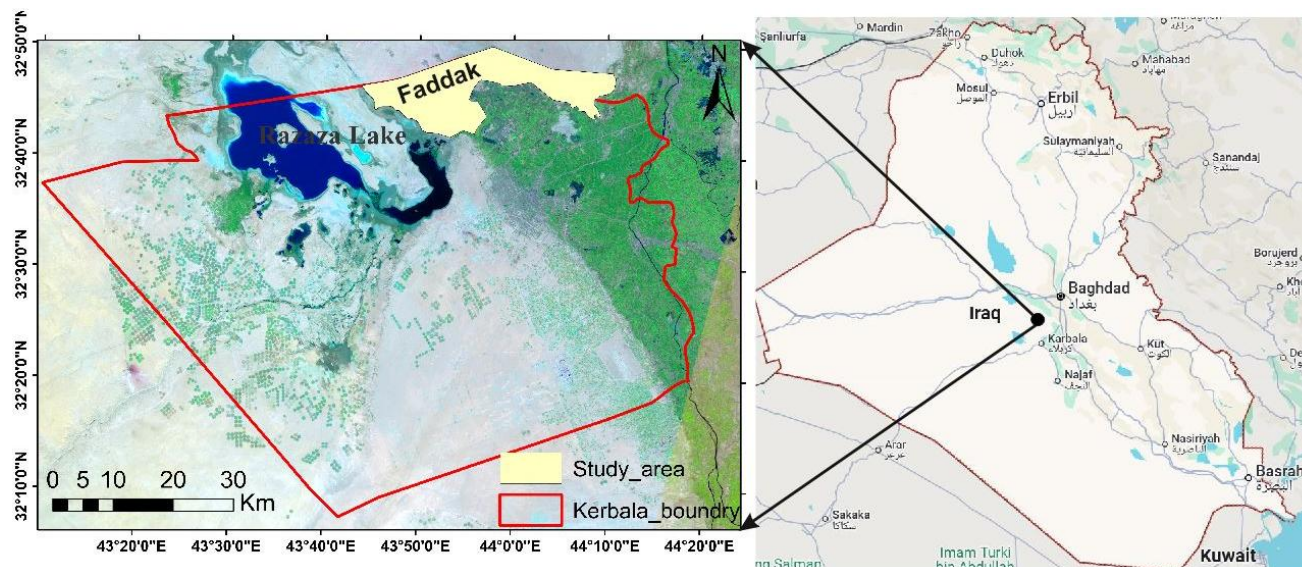


Figure 1. Location map of the study area (Based on GIS and Google Maps of Iraq, 2025)

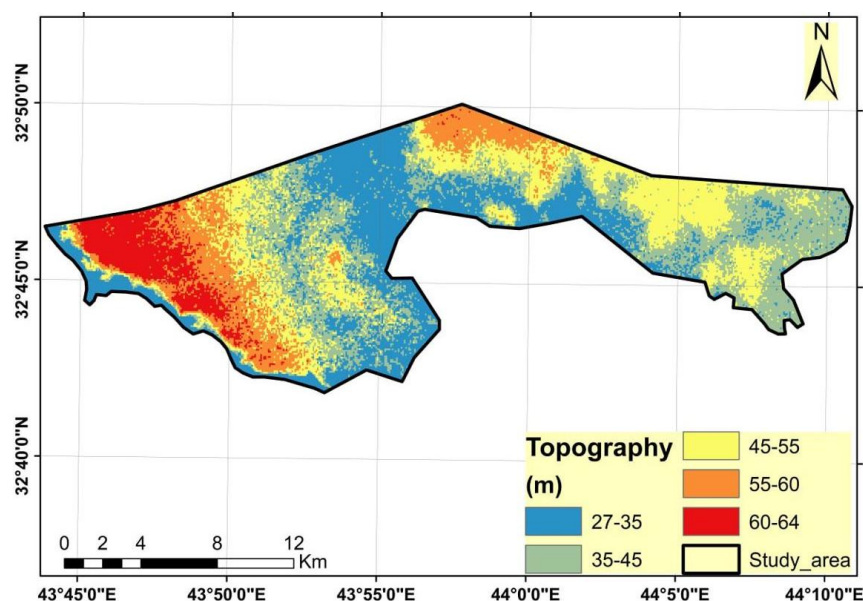


Figure 2. Topographic map (after U.S.G.S. DEMs)

According to the lithological columns of the existing wells [18], the following formations make up the stratigraphic column for the area under consideration, ranked from oldest to newest:

- 1) Nfayil Formation (Middle Miocene): This formation is mostly composed of dolomitic, gypseous, and greenish-reddish marl that is interbedded with calcareous, partially sandy claystone and fossiliferous limestone [17].
- 2) Injana Formation (Late Miocene) is exposed along Al-Razaza Lake's eastern shore. It comprises lenticels of grey, partially greenish silty, brownish, greenish, yellowish sandstone, and sandy calcareous claystone [19].

- 3) Dibdibba Formation (Pliocene–Pleistocene) comprises pebbly sandstone and sandstone with minor claystone, siltstone, and marl connected to secondary gypsum [20].
- 4) Quaternary deposits (Pleistocene - and Holocene):
 - Gypcrete occupies vast areas on the map, representing the basic surficial sediment type northwest of [18]. It is present as an admixture of sand and gravel. It is either exposed directly on the surface or covered by Aeolian deposits. Thickness is up to 2 m. and maybe more.
 - Aeolian or windblown deposits are spread over the map area because of the low precipitation rate. They appear scattered, where these simplest forms start to group. Their thickness is less than a few tens of centimeters and is still discontinuous. The thickness of Aeolian deposits depends on these forms of accumulation; Sand sheets are thicker than 1m. Individual barchans exceptionally exceed 5m [21].

The Euphrates River itself deposited Flood Plain deposits. It consists of silty clays, which comprise the bulk of the floodplain deposits, followed by silt and sand. The floodplain deposits are greatly contaminated by deposits of irrigation channels, which are coarser than those of natural floodplains. Thickness is (12-15 m). The geological formation of the study area is shown in Figure 3.

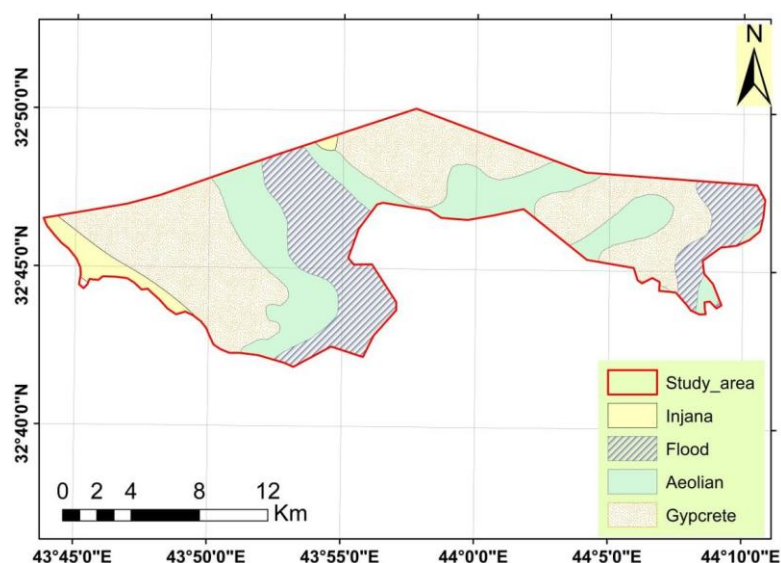


Figure 3. Geologic map

3.3. Groundwater Hydrology

In North Karbala, Iraq, quaternary deposits play a crucial role in groundwater hydrology. These deposits, which are mostly composed of clay, silt, sand, and gravel, create vital aquifers that transport and store groundwater. Rainfall, surface water infiltration, and seepage from the Euphrates River are the main sources of replenishment for the Quaternary aquifer in this area. However, water sustainability is hampered by excessive groundwater extraction and insufficient recharge. Aquifer productivity and groundwater potential in the Karbala plateau have been evaluated through studies employing GIS-based models [22]. Because the aquifer comprises Quaternary deposits, its thickness reaches several meters. The sedimentary aquifer is characterized by its high productivity due to its hydraulic conductivity [23]. The groundwater

storage is fed from two sources: the Euphrates River losses and its tributaries, as well as the deep infiltration of rainwater, despite its scarcity [24]. The deep infiltration in the southwest of the region results from the irrigation network, which is considered the main source of groundwater recharge, as shown in Figure 4.

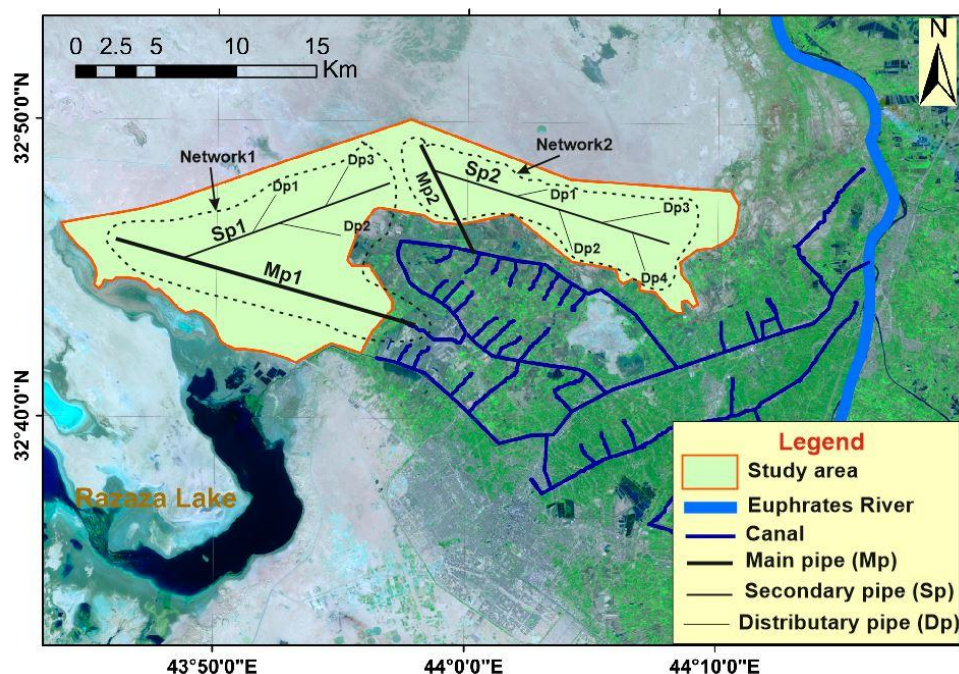


Figure 4. Hydrologic map showing irrigation streams and pipe networks

The main source of groundwater recharge in the unconfined aquifer is the deep infiltration from rainfall and irrigation of agricultural activities, and the water-bearing layer overlays an impermeable layer of several meters in thickness. The quaternary deposits of the Dibdibba and Injana formations consist of consecutive layers of silty clay and clayey silt soils with little permeability and are located at depths from 12m to 20m. The direction of groundwater is unexpectedly greatly affected by the region's topography, and it goes from the southwest to the northeast, as shown in Figure 5.

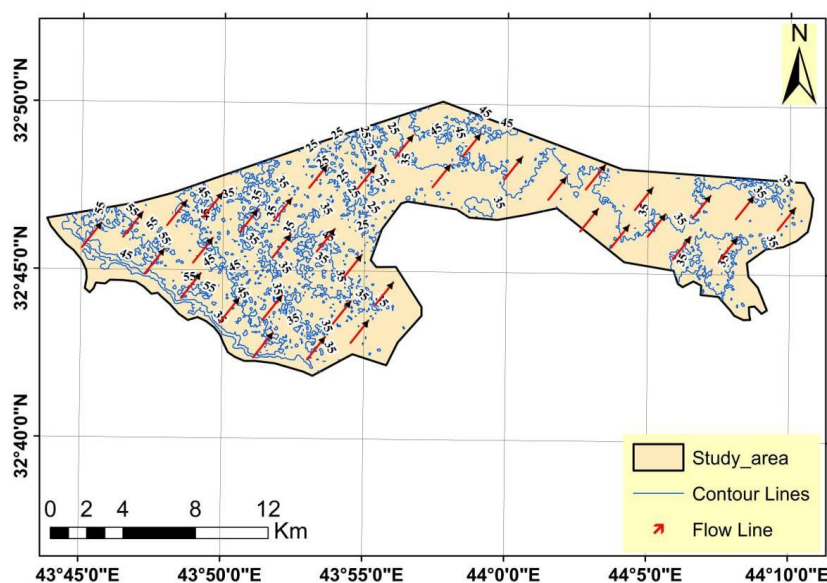


Figure 5. Groundwater flow category

Table 1. Characteristics of the sampling wells

Well No. (Col.1)	X (Col.2)	Y (Col.3)	Ground surface elevation, m.a.s.l (Col.4)	Well depth, m (Col.5)	Static water depth, (d), m (Col.6)	Static water level (SWL), m (Col.7)	Q, L/S (Col.8)
w1	398082	3622390	37	42	4.22	32.78	6
w2	399739	3620213	26	48	3.85	22.15	4
w3	396969	3619183	31	42	4.25	26.75	5
w4	400961	3621480	28	42	3.15	24.85	5
w5	391216	3626115	40	48	4.75	35.25	6
w6	393115	3628613	29	48	3.25	25.75	6
w7	398993	3626104	27	48	5.6	21.4	6
w8	400082	3623720	26	48	5.35	20.65	4
w9	394725	3622464	28	42	3.15	24.85	5
w10	399594	3632073	26	48	3.2	22.8	5
w11	400634	3630206	35	48	6.3	28.7	5
w12	419786	3625129	36	42	4.85	31.15	6
w13	410474	3628209	32	42	5.35	26.65	6
w14	419542	3621600	33	36	4.1	28.9	6
w15	418720	3622304	33	36	3.25	29.75	5
w16	422102	3628180	35	48	5.28	29.72	6
w17	417325	3626773	33	42	3.6	29.4	6
w18	417328	3628270	33	42	3.9	29.1	6
w19	415181	3627534	38	42	6.5	31.5	5
w20	417585	3623533	35	36	6.24	28.76	6
w21	412521	3628461	41	42	6.5	34.5	6
w22	412004	3626128	31	42	2.48	28.52	6
w23	420081	3623248	33	36	2.28	30.72	6
w24	419971	3627249	32	42	3.85	28.15	5
w25	415613	3625510	30	42	3.25	26.75	5
w26	413693	3624964	29	42	2.5	26.5	6
w27	393791	3619700	44	30	3.25	40.75	3
w28	392701	3621264	42	30	3	39	4
w29	394207	3621611	37	48	3.42	33.58	4
w30	393686	3620819	41	30	3.7	37.3	4

3.4. Groundwater Sampling

To investigate the groundwater validity for irrigation purposes, thirty random existing wells were selected throughout the study area to determine the physicochemical characteristics of the groundwater (Figure 6). All the water specimens were collected in special bottles. The bottles were filled, sealed tightly,

and labeled according to the locations of the testing wells. Finally, the sealed sample bottles were put in ice-packed containers and shipped to the laboratory. The groundwater sampling process was conducted on test wells already in the research region. The sampling process begins with determining the well's global coordinates using a GBS. The well's water depth is measured before and after the pumping operation, as seen in Table 1

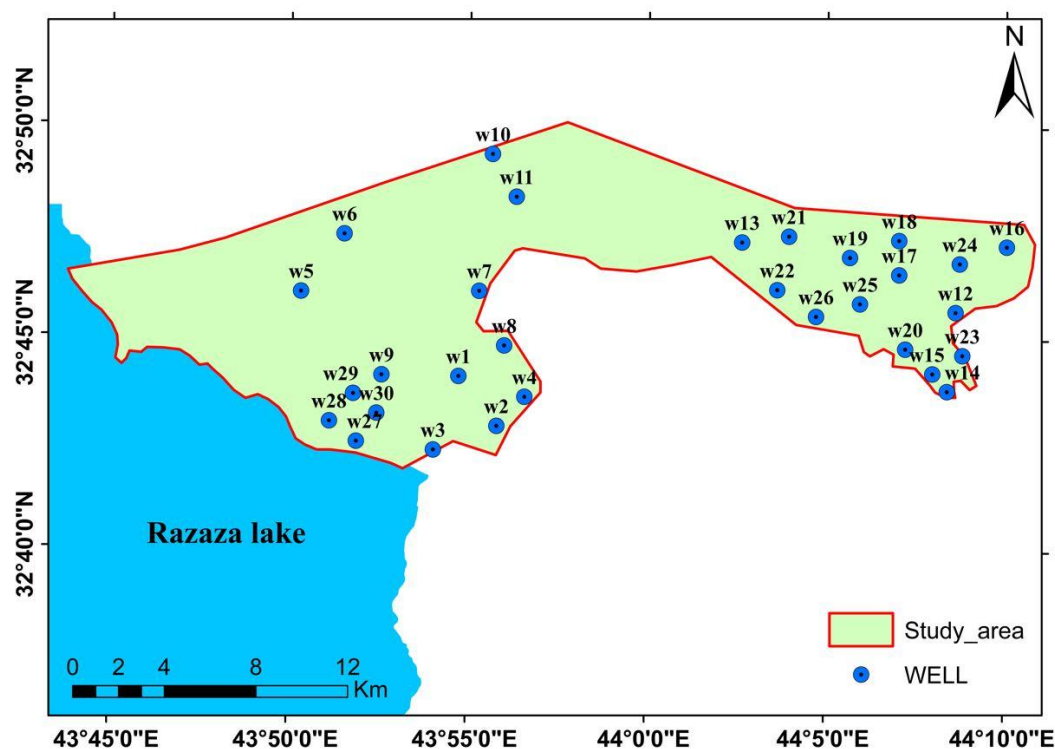


Figure 6. Sampling wells

3.5. Water Quality Evaluation

The Canadian Council of Ministers of the Environment (CCME) and the modified British Water Quality Index (WQI), which takes into account various factors and is applicable in different countries, is available under the abbreviation CCME WQI. This method considers three factors: (a) Scope, which represents the number of variables that do not meet the quality specification; (b) Severity, which represents the degree of impact on the quality specification; and (c) Probability, which represents the likelihood of the variable not meeting the quality specification. The CCME WQI in this method falls between 0 and 100. The worst quality is given ($IWQI = 0$), while the best quality is given ($IWQI = 100$), as indicated in Table 2 [25].

The CCME WQI equations can be listed as follows: F_1 (Scope) represents the ranges and percentages of parameters that do not meet the specification at any point during the relevant period, relative to the total number of parameters.

$$F_1 = \frac{\text{Number of failed parameter}}{\text{Total number of parameters}} * 10 \quad (1)$$

Table 2. CCME WQI standards [26]

Report	Limits	Status
Excellent	95-100	Fully protected with an almost complete lack of threat
good	80-94	Minor threat degree with desirable limits
Fair	65-79	It is occasionally threatened
Marginal	49-64	It is frequently threatened with undesirable limits
poor	0-44	It is usually threatened and departs from desirable limits

F_2 (Frequency): It is the ratio of the failed test to the total number of tests.

$$F_2 = \frac{\text{Numver of failed test}}{\text{Total number of failed test}} * 100 \quad (2)$$

F_3 (Amplitude) refers to a value that fails to meet the required standards. It can be obtained as follows: -

$$F_3 = \frac{es}{0.01es+0.01} \quad (3)$$

where the sum of elusions (es) is estimated by the form: $es = \frac{elusion(1)+elusion(2)}{N}$

When the test values are below the minimum standard objectives, the elusion is obtained as:

$$elusion(1) = \frac{\sum_{i=1}^n \text{failed values}_i}{\sum_{j=1}^n \text{Standard}_j} - 1,$$

elusion (1) means the ratio of failed values to the total number of standard values.

When test values exceed the maximum standard objectives, the elusion may be estimated as:

$$elusion(2) = \frac{\sum_{j=1}^n \text{Standard}_j}{\sum_{i=1}^n \text{failed values}_i} - 1,$$

where: n is the total number of values

Upon calculating the values of F_1 , F_2 and F_3 by using Eq. 1, Eq. 2 and Eq. 3, respectively, then CCME WQI can be calculated by the following form:

$$CCME \ WQI = 100 - \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \quad (4)$$

According to Eq.4, WQI = 0 represents the worst case of water quality, while WQI = 100 represents the best water quality.

3.6. Evapotranspiration and Crop Coefficients

Two important variables in determining how much water is required for effective water resource management in agriculture are evapotranspiration (ET) and the crop coefficient (Kc). Understanding their importance helps enhance agricultural yields, conserve water, and optimize irrigation planning. The combined processes of transpiration (water loss from plants) and evaporation (water loss from soil and water

surfaces) are known as evapotranspiration. To account for different crops' distinct water use characteristics, the reference evapotranspiration (E_o) is modified by a dimensionless variable known as the crop coefficient (K_c). Environmental conditions, crop kind, and development stage are considered [27-29]. To calculate the water requirements in any area, it is necessary to know the crop coefficients of the plants grown in it. The average evapotranspiration and crop coefficient of the crops usually planted in the area are presented in Table 3. This table is essential for estimating the water requirement for each plant crop in a specified area. K_c usually depends on many factors, including crop type, global field location, temperature, etc.

Table 3. Evapotranspiration and crop coefficients (k_c) in Iraq [29]

Month	Evapotranspiration, E_o (mm)	Wheat	Barley	Cotton	Sunflower	Corn	Vegetable and orchard
Oct	168	0.00	0.00	0.00	0.00	0.50	0.70
Nov	82	0.00	0.58	0.00	0.00	0.50	0.70
Dec	52	0.40	0.77	0.00	0.00	0.00	0.50
Jan	41	0.80	1.01	0.00	0.00	0.00	0.50
Feb	55	1.20	1.14	0.00	0.00	0.00	0.60
Mar	101	1.20	1.12	0.60	0.58	0.00	0.80
Apr	154	1.00	0.82	1.00	0.68	0.00	0.80
May	236	0.50	0.00	1.10	0.84	0.00	0.80
Jun	279	0.00	0.00	1.20	1.02	0.00	0.90
Jul	312	0.00	0.00	1.20	0.49	1.00	1.00
Aug	284	0.00	0.00	1.20	0.00	1.00	0.90
Sep	223	0.00	0.00	1.00	0.00	0.80	0.90

The amount of monthly consumptive use in (mm/month) can be estimated by the following equations [27-29].

$$U = E_o k_c \quad (5)$$

In which;

$$E_o = k' f \quad (6)$$

$$k' = 0,0311C^o + 0,24 \quad (7)$$

$$f = P(0,46C^o + 8,14) \quad (8)$$

where P is the yearly percentage of monthly daylight, C^o is the average temperature in degrees centigrade.

By Eq.5, the consumptive use of water (U) in mm/month can be calculated. The evapotranspiration (E_o) in Eq.6 can be estimated by multiplication of the parameters k' which depends on the temperature in (C^o) as presented in Eq.7 and f , which depends on both C^o and P as indicated in Eq.8.

3.7. Geographic Information System (GIS)

Through analyzing spatial data about hydrology, watershed management, and water distribution, GIS is essential to planning water resources. For effective water allocation, rivers, reservoirs, and groundwater sources can be mapped using ArcGIS, a top GIS program. It aids in disaster preparedness and mitigation methods by enabling the visualization of areas vulnerable to flooding. To improve irrigation planning, hydrologists can use ArcGIS to estimate soil moisture levels, rainfall distribution, and surface runoff. The software combines real-time data with satellite photos to track changes in water bodies and identify pollution sources. Locating appropriate sites for drainage systems, pipelines, and dams' aids in decision-making. Watershed management is improved by GIS-based mapping, which examines topography, land use, and climate variables. High-precision maps can be made using ArcGIS technologies [30-32].

4. Results and Discussions

The important physical and chemical characteristics of water, including pH, EC, TDS, TH, Ca, Mg, SO_4 , Cl, Na%, and SAR, were tested for the groundwater samples from all 30 wells. The following theme maps were developed using Arc GIS 10; 7.1, and distribution maps for the measured parameters were generated by using the Arc GIS software of Spatial Analyst. Using the (CCME WQI) model, the water quality of the research region was evaluated for its suitability for irrigation. Table 4 includes the spatial distribution of all these parameters and the IWQI.

4.1. Spatial Distribution of Parameters

The results show that the groundwater is generally brackish based on the TDS classification system developed by Hommadi, et al. [27]. $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ were the major cations trend in the aquifer under consideration, with Na^+ as the dominant cations. The abundance of the major anions is sequenced in order: $SO_4^{2-} > Cl^- > HCO_3^- > NO_3^-$ with SO_4^{2-} as the dominant anions. Concentrations of chloride and bicarbonate are also relatively high. The spatial distribution of these parameters is visualized in the maps in Figure 7.

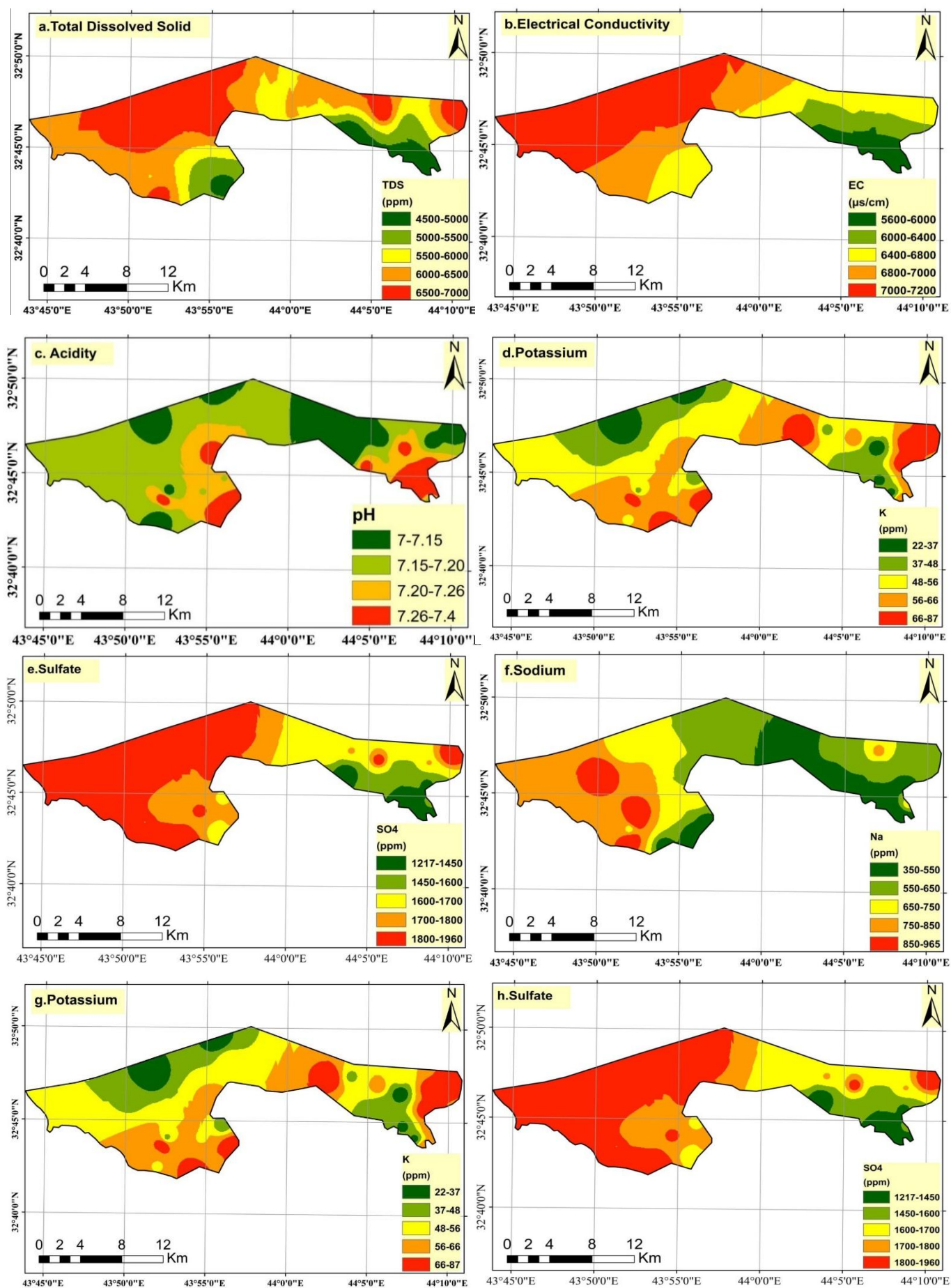
In general, the concentration of calcium ranges between 350-656 Mg/L. The lowest value was in the south of the area, and the highest value was scattered in several northern spots, as shown in Figure 7a. Magnesium values range between 280-522 mg/L, with the highest in the north and the lowest in the south, as shown in Figure 7b. Sodium concentrations ranged between 350-966 mg/L, with the highest values occurring in the west and the lowest in the east, presented in Figure 7c. Potassium ranges between 22-87 Mg/L. The spatial distribution is shown in Figure 7d, and the highest concentrations are found in the eastern south. In contrast, the lowest values are encountered in the eastern-south. Sulfate ions SO_4^{2-} fell in the range 1960-1217 mg/L, spread in the order, highest concentrations covering the area's western part as

indicated in Figure 7e. Chlorine is in the range 1960-899 mg/L; the maximum concentrations were found in the north, and the minimum was encountered in the south.

Table 4. Physicochemical parameters for the water samples

No.	Ca	Mg	Na K	SO4	Cl	TDS	EC	pH	NO3	HCO3	SAR	Na%	TH	IWQI
Standards	≤ 400	≤ 150		≤ 960	≤ 1065	≤ 2000	≤ 3000	6.5-8.5			≤ 15	20-80	≤ 500	0-100
w1	390	280	680 55	1801	1280	5350	6280	7.20	1.7	422	6.44	42.25	2126.9	47.474
w2	480	310	450 65	1620	1206	4950	5950	7.40	2.8	405	3.95	30.11	2475.14	43.497
w3	485	360	480 75	1850	1266	5420	6450	7.20	2.4	550	4.04	29.82	2693.53	43.489
w4	525	389	510 85	1715	1285	5200	6450	7.30	2.6	630	4.13	29.57	2912.83	43.487
w5	510	400	920 44	1870	1455	6890	7152	7.20	1.9	725	7.44	41.43	2920.67	43.476
w6	580	466	680 22	1815	1512	6570	7213	7.10	1.5	755	5.12	31.01	3367.25	43.467
w7	566	485	630 65	1795	1422	6610	7110	7.30	2.1	730	4.71	29.97	3410.53	43.468
w8	500	425	722 38	1688	1410	5890	6680	7.20	1.8	724	5.76	35.16	2998.65	43.480
w9	520	380	914 45	1724	1515	6110	7050	7.10	1.5	788	7.46	41.78	2863.28	43.481
w10	596	489	624 25	1895	1566	6850	7422	7.10	1.2	766	4.61	28.49	3501.91	43.462
w11	523	466	633 55	1840	1620	6280	7115	7.20	1.8	681	4.87	31.07	3224.92	43.471
w12	485	396	517 85	1410	1250	5680	6150	7.30	2.4	726	4.24	30.35	2841.77	43.486
w13	656	516	410 87	1688	1436	6120	6850	7.10	1.4	750	2.92	21.11	3762.92	43.465
w14	426	380	350 66	1355	1105	4755	5360	7.20	2.6	550	2.98	24.42	2628.56	43.497
w15	452	320	455 32	1422	1140	4420	5120	7.40	2.8	530	4.02	29.73	2446.40	43.501
w16	514	465	650 75	1960	1630	6950	7410	7.10	1.6	752	5.02	32.16	3198.33	43.468
w17	452	316	625 22	1455	1150	5314	5920	7.30	2.2	480	5.54	36.45	2429.93	43.498
w18	480	325	799 52	1687	1355	5780	6520	7.20	1.8	425	6.93	41.67	2536.91	43.490
w19	610	522	644 65	1866	1590	6900	7552	7.10	2.5	788	4.64	28.86	3672.77	43.459
w20	422	310	460 33	1233	1025	4650	5210	7.30	2.8	520	4.16	31.01	2330.31	47.477
w21	458	386	650 45	1720	1422	6150	6720	7.10	2.6	690	5.43	35.09	2733.17	43.486
w22	350	280	480 56	1217	899	4400	5080	7.00	2.4	520	4.66	35.60	2026.99	51.097
w23	386	285	714 65	1452	1180	5120	5890	7.30	2.2	360	6.75	43.46	2137.47	47.477
w24	480	410	621 75	1714	1435	6100	6700	7.10	1.9	650	5.05	33.48	2886.94	43.484
w25	466	360	552 38	1560	1302	5620	6150	7.20	2.1	466	4.69	32.16	2646.08	43.490
w26	422	310	450 40	1457	1295	4890	5680	7.30	1.2	389	4.07	30.74	2330.31	43.500
w27	416	362	966 53	1856	1595	6650	7150	7.00	1.4	725	8.39	46.27	2529.47	43.484
w28	460	380	804 62	1785	1422	6050	6530	7.20	1.9	695	6.74	40.35	2713.46	43.489
w29	435	338	962 82	1775	1366	6310	6780	7.40	1.3	652	8.44	47.10	2478.08	43.492
w30	558	420	699 62	1835	1412	6200	7100	7.16	1.2	590	5.46	33.97	3122.89	43.480
Max	656	522	966 87	1960	1630	6950	7552	7.40	2.8	788	8.44	47.10	3762.92	51.097
Min	350	280	350 22	1217	899	4400	5080	7.00	1.2	360	2.92	21.11	2026.99	43.459
Ave.	488	385	636 56	1664	1346	5798	6481	7.20	2	612	5.31	34.15	2804.32	

* Ec in (μs/cm), SAR in (meq/L) and all other parameters in (ppm).



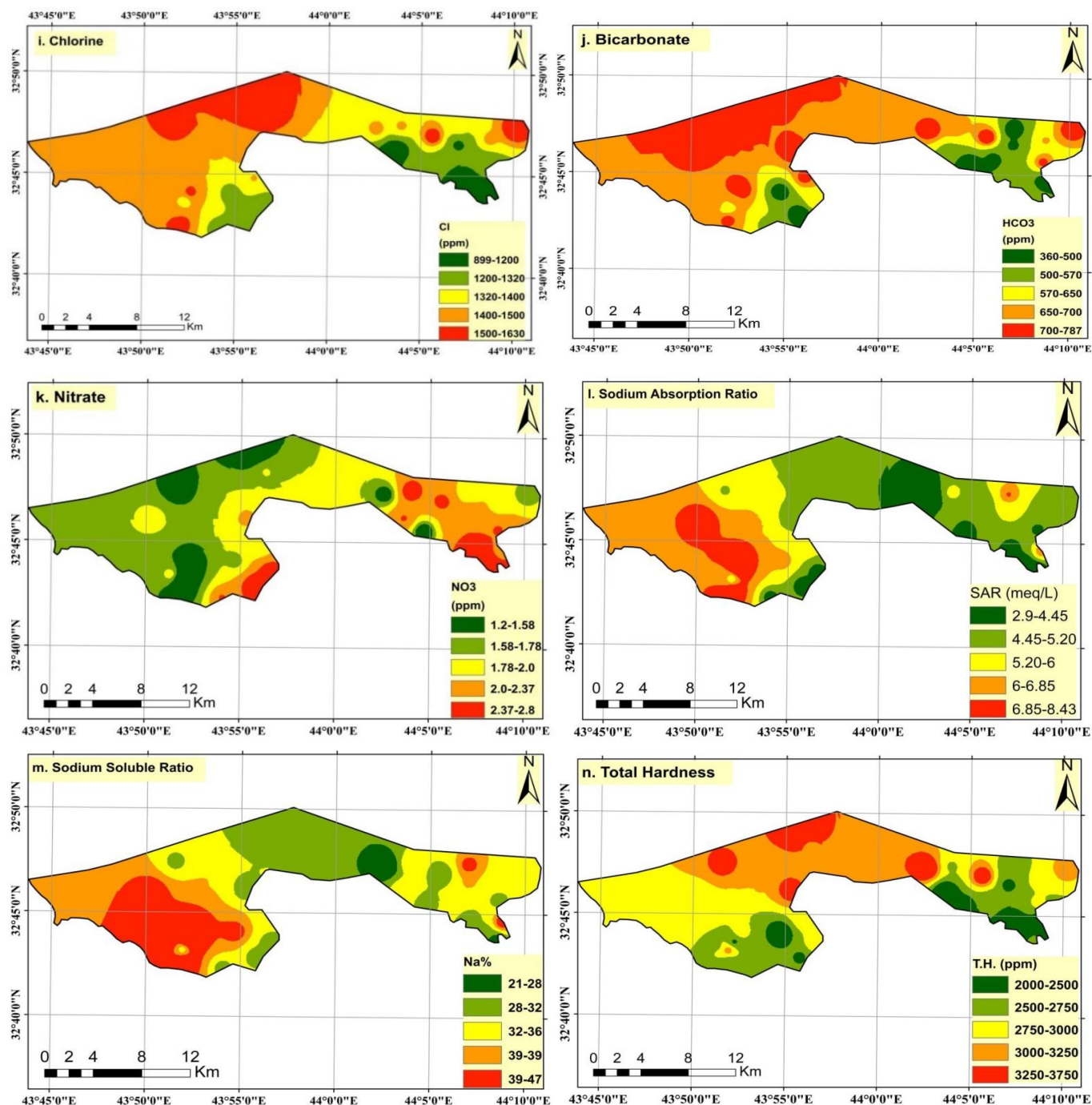


Figure 7. Spatial distribution of physiochemical parameters

This is demonstrated in Figure 7f. The TDS is anticipated to be very high for agricultural purposes. It ranges between 4400-6950 mg/L. From spatial distribution, most of groundwater storage's western and northern parts are salinized to 6950 Mg/l, while the lower concentration is found in the southern part, as shown in Figure 7g. The electrical conductivity is fallen in the range of 5080-7552 $\mu\text{S}/\text{cm}$. It is very coincidental to the distribution of the TDS. Most of the values of the TDS in Table 4 were checked according to the relationship ($\text{TDS} < 0.7 * \text{EC}$), and most of them were found to be less than EC, as presented in Figure 7h. The groundwater of pH in the considered area is fallen in the range of 7.0-7.4, which is the middle range of FAO and WHO specification 6.5-8.5. The maximum and minimum acidity are encountered

in the south and north, respectively, as shown in Figure 7i. The nitrate ions NO_3 range between 1.2-2.8 mg/L with maximum values focused in the south and eastern-south as in Figure 7j. The Bicarbonate groundwater concentrations range between 360-788 mg/L. Their spatial distribution is shown in Figure 7k. Their maximum ion concentrations are dominant in the west and northern-east. The sodium adsorption ratio, which is a key indicator of water quality for irrigation [19], this parameter decreases from southwest to northeast, following the aquifer's flow direction, as shown in Figure 7L. Total hardness TH in groundwater ranges between 2027 and 3763 mg/L. The spatial distribution reveals that the maximum concentrations are found north of the area, as represented graphically in Figure 7n.

The high salinity value of the water sample of the wells is due to:

- 1) The presence of dissolved minerals such as calcium, magnesium, sodium, and potassium can originate from the geology of the aquifer and get dissolved into the groundwater as it moves through rock formations.
- 2) Due to the groundwater flow direction of Figure 5, using fertilizers from the southern irrigated area certainly increases groundwater salinity due to a hydraulic connection between groundwater and surface water in recent deposits.
- 3) Due to the network roads found in the area, stormwater runoff from paved surfaces can carry pollutants and salts into the groundwater because of a high existing permeable layer in the geology column of the study area, which raises the salinity levels (TDS and EC), especially when there is a hydraulic connection between surface water (river) and groundwater as is mentioned above.
- 4) The presence of dissolved minerals, calcium and magnesium ions, in the groundwater originates from the aquifer's geological composition and dissolves into the groundwater as it interacts with soil.
- 5) Leaching of Minerals: Water passing through mineral-rich layers can dissolve minerals and increase the hardness of the groundwater.
- 6) Since the area is in an arid region, evaporation is surely the main reason for high calcium limits in shallow groundwater. When water evaporates from the surface, it leaves behind dissolved minerals, including calcium, which can become more concentrated over time, particularly in areas with limited rainfall or high evaporation rates.

All the parameters are shown in Table 4. According to the United Nations Food and Agriculture Organization (FAO), their allowable limits are also included for comparison purposes. It was found that all concentrations of minerals exceeded the allowable limits except PH, Na%, and SAR.

4.2. Water Quality Criterion in CCME WQI

4.2.1. Spatial Distribution of IWQI

The spatial distribution of IWQI in each well was calculated and listed in Table 4. The highest value

was 51.097, encountered in well 22, and the lowest was 43.459, which occurred in well 19. The graphical representation is in Figure 8.

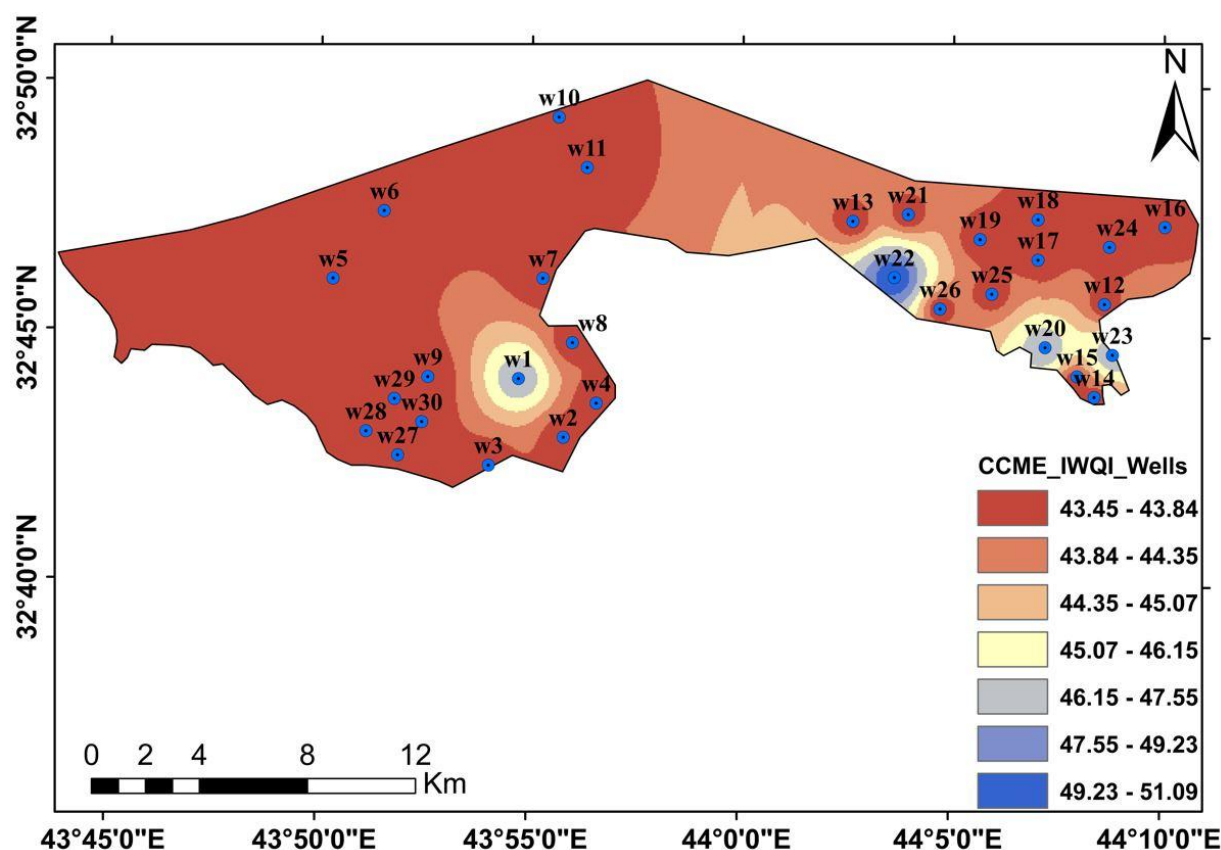


Figure 8. Spatial distribution of IWQI

4.2.2. Determination of the Irrigation Water Quality Index (IWQI)

The Irrigation Water Quality Index (IWQI) will be determined based on specific water quality parameters. This index provides a single figure representing the overall water quality for a particular time and place, indicating the water's condition. In this regard, water quality characteristics can be represented as geographical distribution maps using GIS, allowing for the introduction of comparative analysis. The IWQI's collective quality characteristics can be used to determine if groundwater irrigation is suitable for a given usage. The United Nations Food and Agriculture Organization (FAO) recommended irrigation water quality standards, adopted by the University of California Committee of Consultants in 1974, which were applied to the measured data for the study area. These values served as the objective values for calculating the WQIs. The ten water quality parameters were considered: pH, EC, TDS, TH, Ca²⁺, Mg²⁺, SO₄²⁻, Cl⁻, Na⁺%, and SAR.

Based on the laboratory output of values of the elements in Table 1 and the specification provided in Table 2, the CCME WQI value was estimated to be 36.28, hence deeming the water quality poor. This suggests that the water quality in the current study area is unsuitable for irrigation use and is often at risk of contamination, with values frequently differing from the natural or preferred status. Hence, this water

cannot be utilized for irrigation purposes. This is attributed to the formation of the area of soluble salt materials under consideration.

4.3. Qualified Water for Sustainable Management

Since groundwater is not suitable for irrigation purposes, water resources management in the area requires searching for alternative resources such as rainfall and surface water. The unique solution to overcome this difficulty is to utilize surface water from the nearest stream to the study area, which is located 15 km to the south. After consuming the rainfall in winter, the farmer can consume the surface water using modern and economical irrigation systems. Sprinkler and drip irrigation systems are suitable for lands planted with seasonal crops and orchard and forest lands, respectively. The water should be transferred from the stream to the land through a network of pipes, as shown in Figure 4. Two sets of pipes are suggested to cover the land, which takes water from the southern Euphrates streams. The pipes are coded as: - Main pipe (MP), Secondary pipe (SP), Distributary pipe (DP), Secondary pipe in network No.1 (Sp1), and Secondary pipe in network No.2 (Sp2). The network consists of two networks of pipes due to the land's morphology. The water is pumped from the streams toward the highest land by MP and then distributed toward the agricultural areas by SP. Finally, the water reaches the fields by the DP. Accordingly, for instance, the final distributary pipe in network No. 2 is coded as MP2-SP2-DP4.

The optimum water resources management proposed to estimate the amount of water needed in the area and assess the average annual rainfall. The amount of rainfall will be subtracted from the total water needed to obtain the water quantity to be supplied by the waters of the Euphrates River through the proposed pipeline network. The estimated water needs for different crops are listed in Table 5.

Table 5. Monthly water requirement for each crop and rainfall (mm/month)

Month	Wheat	Barely	Cotton	Sunflower	Corn	Vegetable and orchard	Rainfall
Oct	0	0	0	0	84	117.6	13
Nov	0	47.56	0	0	41	57.4	27
Dec	20.8	40.04	0	0	0	26	35
Jan	32.8	41.41	0	0	0	20.5	76
Feb	66	62.7	0	0	0	33	40
Mar	121.2	113.12	60.6	58.58	0	80.8	25
Apr	154	126.28	154	104.72	0	123.2	14
May	118	0	259.6	198.24	0	188.8	12
Jun	0	0	334.8	284.58	0	251.1	0
Jul	0	0	374.4	152.88	312	312	0
Aug	0	0	340.8	0	284	255.6	0
Sep	0	0	223	0	178.4	200.7	0

The rainfall values are the average values of Karbala meteorological station for the period from (2010-2023)

The net water requirement can be obtained by subtracting the rainfall in Table 6 from the total water need for each land crop; the rest of the obtained water requirements are listed in Table 6. For instance, the total need for wheat in March is 121.2 mm. By subtracting the average rainfall of 25mm, the required surface water of 96.2mm has been obtained and should be recovered from the Euphrates network.

Table 6. Net monthly WD (mm/month)

Month	Wheat	Barely	Cotton	Sunflower	Corn	Vegetable and orchard
Oct					71	104.6
Nov		٢٠,٥٦			14	30.4
Dec		٥,٠٤				
Jan						
Feb	26	22.7				
Mar	96.2	88.12	35.6	33.58		55.8
Apr	140	112.28	140	90.72		109.2
May	106		247.6	186.24		176.8
Jun	0	0	334.8	284.58	0	251.1
Jul	0	0	374.4	152.88	312	312
Aug	0	0	340.8	0	284	255.6
Sep	0	0	223	0	178.4	200.7

4.3.1. Cultivation Intensity and Water Supply

The term *cultivation intensity* refers to the percentage of cultivated land in the total area. Because the total area considered for the study is irregular and its shape is longitudinal, as shown in the figure, it is preferable to use two main systems of pipes, namely MP1 and MP2, to supply it with necessary water allocation. Since the total considered area is 277 km², each pipe system irrigates 138.5 km². The water releases required to be pumped through each network based on Table 6 are indicated in Table 7.

Table 7. Water releases through MP1 and MP2, (m³/s)

Month	Wheat	Barely	Cotton	Sunflower	Corn	Vegetable and orchard
Oct	0	0	0	0	3.8	5.5
Nov	0	1.1	0	0	0.7	1.6
Dec	0	0.27	0	0	0	0
Jan	0	0	0	0	0	0
Feb	1.4	1.2	0	0	0	0
Mar	5.1	4.7	1.9	1.8	0	3
Apr	7.5	6	7.5	4.8	0	5.8
May	5.6	0	13.2	9.9	0	9.4
Jun	0	0	17.8	15.2	0	13.4
Jul	0	0	20	8.1	16.6	16.6
Aug	0	0	18.2	0	15.1	13.6
Sep	0	0	11.9	0	9.5	10.7

The results of Table 7 are based on 100% *Cultivation intensity*. It is observed that the maximum pumping rates occurred in July, reaching 20 m³/s for cotton crops. These pumping rates may be reduced if partial intensive cultivation is used and the unsuitable areas for agriculture are excluded.

5. Conclusions

Water scarcity has long plagued the Faddak Barren Lands, making cultivation impossible. The area's proximity to the Western Desert, lack of surface water, and poor groundwater quality are the primary causes. Based on the CCME IWQI standard, the groundwater quality is categorized as poor, with an IWQI of 36.28. The water-yielding geological formations in the region primarily determine the quality of groundwater. Cotton farming requires 20 m³/s of water annually, with peak agricultural demands in July. In this arid region, agriculture must rely on sustainable water resource management. Maximizing rainfall collection during the winter months should be a key objective.

Additionally, utilizing water from the Euphrates River's tributaries is crucial. Expanding pipe networks to distribute water efficiently is also necessary. Implementing sustainable water resource management in the Faddak area will enable the cultivation of all crops listed in Tables 5-7 at 50% crop density.

The suggested irrigation plan and new groundwater desalination process require a seasonal evaluation and monitoring program to track groundwater levels and quality.

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