

Research Article

Groundwater Quality and Irrigation Suitability in Carbonate Aquifers of Semi-Arid Regions: A Case Study from the Dammam Aquifer, Southern Iraq

Saad H. Hadi ^{1,*} , Husam H. Alwan ² , Fadhil M. Al-Mohammed ³ 

¹ Department of Civil Engineering, College of Engineering, Kerbala University, Karbala, 56001, Iraq

² Department of Civil Engineering, College of Engineering, Al-Safwa University, Karbala, 56001, Iraq

³ Department of Building and Construction Engineering, Karbala Polytechnic College, Al-Furat Al-Awsat Technical University, Karbala, 56001, Iraq

*Corresponding Author: Saad H. Hadi, E-mail: saad.h@s.uokerbala.edu.iq

Article Info	Abstract
Article History	Groundwater serves as the primary source of freshwater in arid and semi-arid rural regions due
Received Sep 04, 2025	to low precipitation, limited surface water, and growing socio-economic activities.
Revised Nov 15, 2025	Understanding the hydrogeochemical processes that influence groundwater quality is essential
Accepted Nov 21, 2025	for effective management and long-term sustainability. This study evaluates the
Keywords	hydrogeochemical characteristics of groundwater within the Dammam Formation in the Samawa
Hydrogeochemistry	region of southern Iraq based on data from 30 wells. Laboratory analyses include measuring pH,
Groundwater Quality Index (GWQI)	EC, TDS, total hardness (TH), major cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+), and anions (SO_4^{2-} , Cl^- , NO_3^- , HCO_3^-).
Dammam Aquifer	Groundwater suitability for human consumption was assessed using the Groundwater
Groundwater sustainability	Quality Index (GWQI) according to World Health Organization (WHO) standards. In contrast,
Samawa	irrigation suitability was evaluated using sodium percentage (%Na), sodium adsorption ratio (SAR), permeability index (PI), magnesium hazard (MH), and Wilcox and USSSL classification charts. GWQI results showed that 6.67% of samples were "excellent," 6.67% were "good," 66.67% were "poor," 6.67% were "very poor," and 13.33% were "unfit for drinking." Piper diagram analysis indicated 87% of samples in the Ca-Cl field and 13% in the Ca-Mg-Cl field. Wilcox's results revealed 70% of samples were unsuitable for irrigation and 30% of uncertain use. PI results showed 93.33% in class II, suitable for irrigation, and 63.33% with no magnesium hazard. The study recommends desalination with monitoring of sodium, chloride, and sulfate to improve groundwater quality.



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1. Introduction

The deterioration of water quality is a significant environmental and public health issue in Iraq, as both surface and groundwater resources are under increasing pressure from human activity [1]. The rapid increase in population, industrialisation, and urban development has increased demand for groundwater, leading to overexploitation and deterioration in both supply and quality [2]. Concerns over long-term

sustainability have been raised by the careless dumping of household, commercial, and agricultural solid waste, which has exacerbated groundwater contamination [3]. Numerous studies have used multivariate statistical techniques to evaluate the geographical and temporal fluctuations in water quality across different river systems, including the Tigris [4, 5] and the Euphrates [6]. The assessment of physicochemical and biological factors is crucial for determining water quality, highlighting the need for ongoing monitoring and evaluation [7]. Several studies in Iraq have underscored the need for a bioindicator-based methodology to ensure water safety [8-11].

The groundwater quality index (GWQI) has been widely used as a standardised method for assessing and communicating water quality status globally, including in Iraq [12-14]. It provides a mathematical framework for evaluating multiple water quality parameters, facilitating the comprehension of complex datasets [15]. GWQI applications in Iraq have been crucial for evaluating water quality in many areas, including Kirkuk [16], the Nineveh Plain [17], Kalar in the Kurdistan Region [18], and Muthanna Governorate [19]. The development of GWQI in Iraq is primarily directed by the WHO, guaranteeing adherence to regulatory standards. Geochemical and statistical analyses, including Piper's diagram, Gibbs' diagram, principal component analysis (PCA), and cluster analysis, indicated that both natural processes (rock weathering, silicate dissolution) and anthropogenic activities (agriculture, sewage discharge) affect water quality [20, 21]. In recent years, the evaluation and surveillance of groundwater quality using GIS methodologies have garnered considerable interest [22].

This study comprehensively assesses groundwater quality in the Dammam aquifer in the Samawa region of southern Iraq by characterising the physical and chemical properties of 30 water samples collected from open wells and hand pumps. The evaluation employs the GWQI approach to analyse the data and compare the results with the international human consumption standards set by the WHO. The study's specific objectives are to (a) analyse the spatial variability of essential groundwater quality parameters within the study area, (b) develop and implement the GWQI methodology based on field observations to provide a comprehensive evaluation of groundwater suitability for drinking purposes, and (c) evaluate the feasibility of groundwater for irrigation by utilising the USSL and Wilcox classification diagrams. (d) Use the Piper diagram to categorise groundwater types and explain the mechanisms that influence groundwater composition. Ultimately, the study seeks to enhance the debate on groundwater quality management by providing policymakers, stakeholders, and resource managers with significant insights to develop

sustainable water management strategies.

2. Literature Review

The Dammam aquifer in Iraq has been the subject of intensive study of water quality and the identification of significant pollution sources, prompting discussions of mitigation techniques.

Al-Sheikh and Al-Shamma'a [23] studied water wells in the Dammam aquifer during both the rainy and dry seasons in 2019. The results indicated that the (EC) varied from 2260 to 5500 $\mu\text{S}/\text{cm}$ during the dry season and from 2540 to 5630 $\mu\text{S}/\text{cm}$ during the rainy season. The TDS varied from 1289 to 3582 ppm during the dry season and from 1710 to 3960 ppm during the rainy season. The higher EC and TDS values during the rainy season compared to the dry season may be attributed to higher evaporation rates in the study area. According to the Iraqi Meteorological Organisation [24], evaporation ranges from 100.8 mm in January to 765.6 mm in July. This evaporation leaves salts on the surface soil, and when it rains, these salts are washed into the groundwater, increasing EC and TDS values. The pH varied from 7.11 to 7.3 across the dry and rainy seasons. The hydrochemical classification via the Piper diagram identified three water types (sulfate type $\text{Ca}^{2+} - \text{Mg}^{2+} - \text{Cl}^- - \text{SO}_4^{2-}$, sulfate type $\text{Ca}^{2+} - \text{Mg}^{2+} - \text{Cl}^- - \text{SO}_4^{2-}$, NaCl), whereas the Chadha diagram indicated two water types (sulfate $\text{Ca}^{2+} - \text{Mg}^{2+} - \text{Cl}^- - \text{SO}_4^{2-}$, $\text{Na}^+ - \text{Cl}^-$).

A study of groundwater in the Dammam aquifer in the Najaf Desert was conducted by Alikhan et al. [25]. Five wells were utilised. Upon evaluating the results, they concluded that pH was within the excellent range, while EC was noted as unsuitable. The sulfate and TDS were determined to be in the inferior category. The calcium, magnesium, sodium, potassium, and chloride were categorised as poor according to the identical water quality categorisation. Moreover, the total average (WQI) score was classified as poor, adversely affecting human social, economic, and health conditions.

Al-Khafaji et al. [26] reported that the hydrochemical assessment of water from the Dammam aquifer in Muthanna Governorate, southern Iraq, showed considerable mineralisation and significant hardness. The concentrations of the principal ions were as follows: $\text{SO}_4 > \text{Cl} > \text{HCO}_3 > \text{NO}_3$ and $\text{Na} > \text{Ca} > \text{Mg} > \text{K}$. The dominant groundwater facies were sodium sulfate type. The analysed well water was deemed unfit for human consumption. According to TDS and EC readings, most water samples fell within the moderate salinity range for irrigation purposes.

There are many previous studies evaluating groundwater in the Dammam aquifer [27, 28]. Research on emerging contaminants has highlighted the need to address substances that pose a threat to human

consumption safety. Similarly, research assessing the Dammam aquifer has yielded insights into its water quality status in southern Iraq.

3. Methodology

This study employs a comprehensive approach to evaluate groundwater quality in the Samawa region of Iraq, combining field data collection, laboratory analysis, geographic information systems (GIS), and index-based assessment. Groundwater samples were collected from representative wells and analysed for key physical and chemical parameters to characterise contamination levels. GIS was used to map the spatial distribution of water quality, while the Groundwater Quality Index (GWQI) was applied to assess suitability for human consumption. For irrigation suitability, Wilcox and US Salinity Laboratory (USSL) diagrams were used alongside indices such as SAR, %Na, PI, MH, and RSC. Hydrochemical facies and groundwater types were interpreted using Piper diagrams, which display the relative proportions of major cations and anions. Together, these methods provide an integrated understanding of groundwater quality dynamics and support data-driven decision-making for sustainable groundwater management in Samawa and similar hydrogeological settings.

3.1. Study Area

The study area is located in Samawa City, southern Iraq, within the Muthanna Governorate. The area extends from latitudes 3243827 to 3435923 N and longitudes 422784 to 571055 E, covering roughly 27,185 km² and forming part of the Western Desert. It is bounded to the east by the Mesopotamian alluvial plain, to the west by the Umm al-Radhuma aquifer, and to the south by the Iraqi-Saudi border. The region has an arid environment, with an average annual precipitation of 110.80 mm and an average annual temperature of 25.23°C [29]. Soils are crucial in hydrological studies as they influence surface runoff and groundwater retention.

Water infiltration rates depend on soil properties, including particle-size distribution, colloidal matter content, moisture content, and permeability. The region's soils are classified as Aridisols, with four main types: desert gypsum soils, desert stony soils, dune soils, and floodplain and wadi soils. The soils are arid, sandy, lacking in organic matter, and exhibit low moisture content, reflecting the region's arid and semi-arid climate. In specific soil classification systems, topsoil is identified as Clacisol CL [30]; however, in alternative systems, it is classified as Calcic Yermosols [31]. Groundwater is the primary resource for

irrigation, household, and industrial applications in the region. However, increasing demand, coupled with pollution from industrial discharges and agricultural runoff, poses significant challenges to effective water management. Assessing the quality of groundwater in Samawa, particularly within the Dammam aquifer, is essential for maintaining a sustainable water supply and reducing the risks of depletion and contamination.

3.2. Collection of Samples

Field surveys were executed to obtain groundwater samples from several locations. Sampling sites were selected based on hydrogeological parameters, land-use classifications, and potential contamination threats to ensure a representative evaluation of groundwater quality.

The sampling sites were chosen based on multiple criteria. For example, wells (15, 16, and 26) in the Al-Salman district, adjacent to Modern Village, were included because they are actively used for drinking and domestic purposes, rendering them essential for assessing water quality from a public health perspective. Wells (19 - 22) were chosen because they supply water to the Al-Salman Water Project, thereby directly affecting a larger population. Conversely, the other wells in the research region are used for agricultural irrigation or as experimental/test wells, facilitating comparisons across various water-use settings.

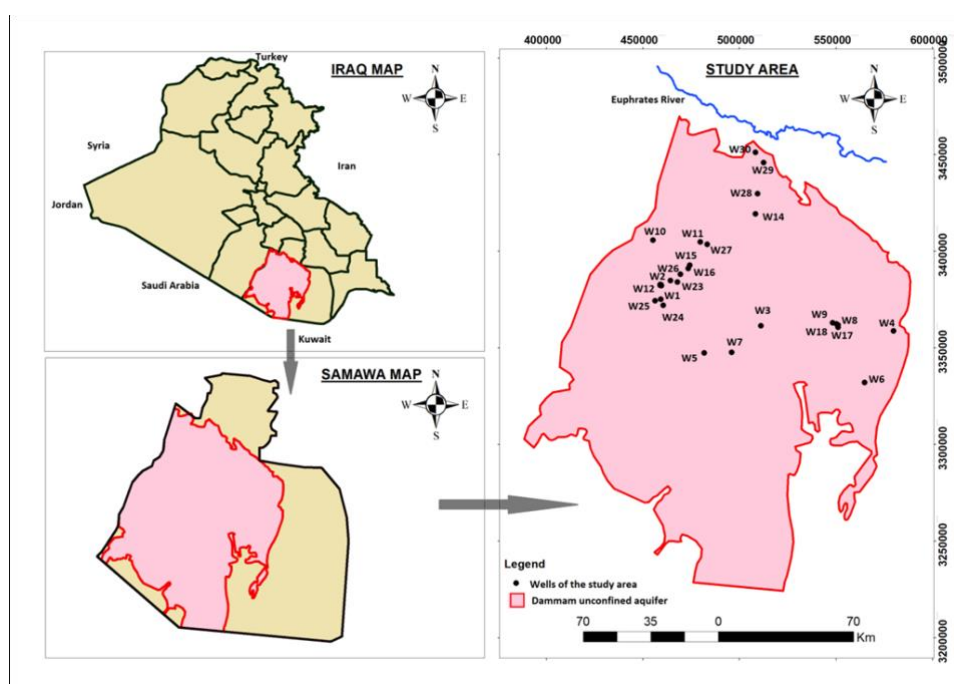


Figure 1. The study area and the positions of the chosen wells

Thirty groundwater samples were obtained from artesian wells and hand pumps to assess source type

and consumption variations, each sample from a different well. All samples were preserved in high-grade polypropylene containers and maintained at 4°C to prevent chemical or biological modification before laboratory analysis. Sampling coordinates were documented and mapped utilising ArcGIS 10.8.1 (see Figure 1). Certain areas were inaccessible owing to challenging terrain or logistical limitations. The geographic distribution of wells was essential for comprehending regional disparities and pinpointing regions with potential. Although there are 30 water samples in total, wells W13, W19, W20, W21, and W22 are located near well W12 in the Salman area, which serves as the primary source of domestic water supply. Due to their proximity, these wells overlap in the map representation and cannot be distinguished in the Figure 1. Therefore, these wells are included in the sampling process, but their individual locations were not visually represented in the figure.

3.3. Hydro-Geochemical Analysis

Field samples were pre-treated by filtration to ensure accurate, consistent results before laboratory analysis. To ensure accurate measurements of water parameters, hand pumps were operated for a sufficient period before sample collection, thereby contributing to reliable pH and Electrical conductivity (EC) measurements. Nitrate (NO_3^-) and sulfate (SO_4^{2-}) ion concentrations were accurately determined using a spectrophotometer, while Chlorine (Cl^-) ions were evaluated using the Mohr titration method with Silver nitrate (AgNO_3). Bicarbonate (HCO_3^-) concentrations were calculated. Magnesium (Mg^+), Calcium (Ca^{2+}), Sodium (Na^+), and Potassium (K^+) ions were determined by titration and flame photometry. pH and TDS were measured using a digital multi-parameter meter.

To ensure the reliability of the hydrogeochemical analysis results, the ion balance was validated, with an error of between (± 5 to ± 10) % for all samples, which increased data acceptance. Ion balance calculations for the major ions were performed to verify the accuracy of the study, using Equation (1) [32]:

$$\text{Ion Balance} = \left[\frac{\sum \text{Cations} - \sum \text{Anions}}{\sum \text{Cations} + \sum \text{Anions}} \right] * 100 \quad (1)$$

4. Assessment of Groundwater Quality in the Dammam Aquifer

4.1. Groundwater Quality Index for Human Consumption

The (GWQI) is a quantitative metric employed to assess the appropriateness of groundwater for human consumption. The process entails consolidating several water quality attributes into a singular index by mathematical summation [33, 34, 35]. It is employed to clarify trends in water quality over time. The

methodology has achieved global recognition and has been used to evaluate the suitability of groundwater for potable use across diverse areas [36].

The calculation of the (GWQI) entails four primary steps: assigning weights to each groundwater quality parameter, calculating relative weights, determining the water quality rating scale for each parameter, and computing the sub-index and the overall (GWQI) as follows:

Weights (w_i) were assigned to different groundwater quality criteria based on their significance for human consumption [36]. Nitrates received the highest weight of 5 due to their crucial role in assessing groundwater quality and their substantial effects on human health [35, 37]. Sodium and potassium were assigned minimal importance due to their lesser significance in groundwater quality evaluation. Table 1 delineates the weights allocated to each groundwater quality metric.

Table 1. Parameters of groundwater quality utilised for the calculation of the (GWQI) [38]

Parameters	Unit	WHO [38]	Weight (w_i) [36, 39]	Relative Weight (W_i)
pH	-	6.6 - 8.5	4	0.103
K ⁺	mg /L	12	2	0.051
Na ⁺	mg /L	200	2	0.051
Mg ⁺²	mg /L	150	3	0.077
Ca ⁺²	mg /L	200	3	0.077
Cl ⁻¹	mg /L	250	4	0.103
SO ₄ ⁻²	mg /L	250	3	0.077
HCO ₃ ⁻	mg /L	500	3	0.077
CO ₃ ⁻	mg /L	30	2	0.051
NO ₃ ⁻	mg /L	50	5	0.128
EC	μS /cm	1500	3	0.077
TDS	mg /L	1000	5	0.128
			Σ w_i =39	Σ W_i = 1.000

The relative weight (W_i) was computed using Equation (2) below:

$$W_i = \frac{w_i}{\sum_i^n w_i} \quad (2)$$

where W_i represents the relative weight, w_i signifies the weights allocated to each parameter, n indicates the total number of quality parameters, and i refers to the i th parameter.

The q_i for all parameters was calculated using Equation (3).

$$q_i = \frac{c_i}{s_i} * 100 \quad (3)$$

where (q_i) represents the quality rating, (c_i) signifies the concentration of each groundwater quality parameter in mg/L, and (S_i) is the WHO recommendation value for each parameter.

Calculation of sub-index and groundwater quality index: The sub-index (SI_i) for each parameter and the overall (GWQI) were computed using Equations (4) and (5):

$$SI_i = W_i * q_i \quad (4)$$

$$GWQI = \sum_{i=1}^n SI_i \quad (5)$$

where (SI_i) represents the sub-index of the (i th) water quality parameter, (q_i) signifies the quality rating of the (i th) parameter, (n) denotes the total number of water quality parameters, and (GWQI) refers to the groundwater quality index. In Table 2, groundwater was categorised by potability and GWQI classification.

Table 2. Classification of groundwater according to GWQI [40]

GWQI range	Type of water	Number of samples	% of samples
< 50	Excellent	2	6.67
50 - 100	Good	2	6.67
100 - 200	Poor	20	66.67
200 - 300	Very Poor	2	6.67
> 300	Unsuitable for drinking	4	13.33
	Total	$\Sigma 30$	$\Sigma 100$

4.2. Groundwater Quality for Irrigation

The suitability of irrigation water depends on the concentration of dissolved salts and undesirable substances. This is determined by analysing the physical and chemical properties of the water, including pH, EC, TDS, major ions, and trace elements [41]. This section provides various calculations to assess water for irrigation. The SAR ascertains the risk of salt associated with Ca^{+2} and Mg^{+2} levels. Elevated water salinity can adversely affect soil characteristics and reduce soil permeability [42]. Equation (6) is employed to calculate SAR [41]:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (6)$$

The sodium percentage (%Na) and magnesium hazard (MH) are frequently utilised to assess the suitability of water for agricultural purposes. An increased concentration of soluble salts in irrigation water diminishes permeability. The elevated concentration of Mg^{2+} ions in water adversely affects soil quality, rendering the soil alkaline and reducing crop yields, as calculated by Equations (7) and (8) [43].

$$Na\% = \frac{(Na^{+} + K^{+}) * 100}{(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+})} \quad (7)$$

$$Magnesium\ hazard\ (MH) = \frac{(Mg^{2+} * 100)}{(Ca^{2+} + Mg^{2+})} \quad (8)$$

The sufficiency of irrigation water is assessed by the permeability index, or "PI." Excessive Ca^{2+} , Mg^{2+} , and bicarbonate levels can cause reduced soil permeability. Equations calculate the index (9) [44]:

$$PI = \frac{(Na + \sqrt{HCO_3}) * 100}{(Ca + Mg + Na)} \quad (9)$$

This is the equation for determining the quantity of residual sodium carbonate (RSC) in groundwater [45, 46]

$$RSC = (HCO_3^{-} + CO_3^{2-}) - (Ca^{2+} + Mg^{2+}) \quad (10)$$

All ionic concentrations in Equations (6)-(10) are expressed in Millequivalents Per Liter (mEq/L). The aforementioned irrigation water quality indicators have diverse implications and may affect decisions. Consequently, the variables EC, %Na, PI, SAR, RSC, and MH were established to address this deficiency. See Table 3.

Table 3. Parameters and acceptable limits for irrigation [46]

Parameter	Unit	Suitable limit for irrigation
MH	No unit	50
%Na	%	60
SAR	No unit	18
EC	$\mu S/cm$	2250
PI	No unit	85
RSC	mEq/L	< 1.25 (Safe) 1.25 -2.5 (Fair quality) > 2.5 (Unsuitable)

5. Results and Discussion

5.1. Hydrochemical Characteristics of Groundwater

The summary of the physicochemical features of the analysed groundwater samples reveals significant variability among the specific parameters presented in Table 4.

Electrical conductivity (EC) values range from 1,013 to 9,410 $\mu S/cm$. Compared with the WHO guideline value of 1,500 $\mu S/cm$, most samples are unsuitable for direct drinking without treatment [47]. Only wells with EC close to 1,000–1,500 $\mu S/cm$ may be acceptable for drinking, and even these require careful monitoring (see Figure 2a).

Table 4. The physicochemical in situ measurement results for 30 sampling locations within the Dammam Aquifer

Well No.	Parameters (mg/L)										TDS	EC $\mu\text{S/cm}$
	pH	K	Na	Mg	Ca	Cl	SO4	HCO3	CO3	NO3		
W1	7.12	2	122	50	70	210	204	38	0	0.3	710	1092
W2	7.16	14	391	131	220	432	590	250	0	0.6	2052	3170
W3	7.2	35	478	138	203	593	1028	127	0	1.2	2652	4070
W4	7.2	13	153	105	145	278	592	93	0	0.8	1404	2160
W5	7.25	5	271	93	208	327	606	184	0	1.3	1720	2650
W6	7.22	29	381	121	347	663	704	537	0	0.3	2824	4350
W7	7.19	71	942	276	564	1212	2096	857	0	1.1	6100	9410
W8	7.19	29	434	164	324	640	683	813	0	0.3	2831	4360
W9	7.2	35	489	144	209	599	1032	132	0	1.1	2682	4130
W10	7.26	2.3	441	105	198	465	806.4	494	0	1.8	3240	4960
W11	7.26	2.08	299	56	161	355	548	245	0	42	1810	2660
W12	8.38	6.64	102	25	42	88	195	133	0	-	700	1013
W13	8.08	10.16	161	60.8	80.1	178	384.2	183	0	-	1200	1802
W14	7.29	110	459	141	290	620	1140	478	0	2	3663	4240
W15	7.73	78	411	126	361	548	1003	451	0	5	3085	4430
W16	7.11	24	359	108	154	507	785	99	0	3.5	2980	4140
W17	7.22	14	473	128	193	583	1013	115	0	1.3	2561	3940
W18	7.2	15	245	174	286	573	825	234	0	1.2	2390	3690
W19	7.22	12	246	103	162	576	539	189	0	0.6	1852	2860
W20	7.2	14	276	203	213	517	727	198	0	0.3	2182	3360
W21	7.23	11	282	209	219	523	741	207	0	1.1	2230	3430
W22	7.21	9	271	198	208	512	730	194	0	1.1	2160	3320
W23	7.16	7	257	112	181	409	523	223	0	1.2	1740	2680
W24	7.17	11.96	140.43	156.16	488	401.8	1267.93	128	0	0.444	1898	2920
W25	7.14	30.48	230.02	195.2	600	460.6	1686.43	154	0	0.099	2476.5	3810
W26	7.46	13.48	547.21	107.36	256	1019.2	810.19	46	0	2.41	2554.5	3930
W27	7.37	18.7	673.12	204.96	592	1097.6	1621.04	76	0	1.256	3815.5	5870
W28	7.15	20.55	728.81	190.32	664	1362.2	2885.27	118	0	1.216	4147	6380
W29	7.31	29.3	903.14	273.28	640	1764	3138.12	100	0	0.054	5122	7880
W30	7.21	34.86	1038.74	292.8	648	2214.8	3247.1	108	0	0.032	6116.5	9410

Total dissolved solids (TDS) values range from 700 to 6,116.5 ppm in the sampled wells. According to WHO guidelines (1,000 mg/L), most groundwater in the study area exceeds the recommended limit and

therefore requires treatment or blending before it can be used safely for drinking, as shown in Figure 2b. This water can be treated to reduce TDS using technologies such as desalination and reverse osmosis, which remove dissolved salts and minerals, bringing the TDS to safe levels [28].

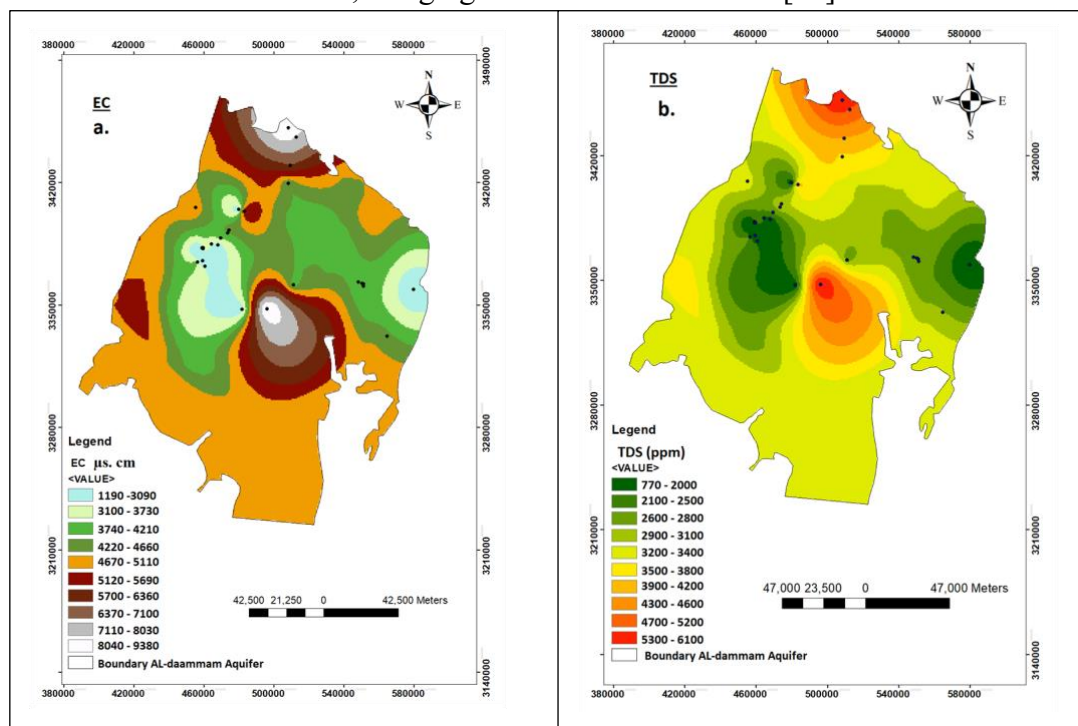


Figure 2. Spatial distribution maps of EC and TDS value

Most pH values fall between 7.1 and 7.3, indicating a broadly balanced distribution and weakly alkaline nature of the groundwater [48], which is normal for groundwater as it interacts with rocks and minerals. Higher values (such as W12 = 8.38 and W13 = 8.08) indicate higher than normal alkalinity, which may be due to the influence of carbonate rocks (such as limestone) or low calcium and magnesium concentrations. Slightly lower values (such as W16 = 7.11 and W1 = 7.12) indicate nearly neutral water, which may have limited influence from organic acids or dissolved carbon dioxide. It is concluded that there is no excessive acidity, and the water is generally stable in terms of pH, but some alkaline samples may require additional testing to ensure there are no undesirable geological influences or chemical contamination.

Magnesium (Mg) in most wells exceeded the WHO limit (150 ppm), indicating that the water may be hard. The highest Mg value was in well W7 (564 ppm), and the lowest was in well W12 (25 ppm; see Figure 3a). For calcium (Ca), several wells exceeded the limit (200 ppm), with well W7 recording the highest value at 1212 ppm, while the lowest was in well W12 (42 ppm). Calcium and magnesium originate from the breakdown of carbonate and ferromagnesian minerals in igneous and metamorphic rocks, as well

as from magnesium carbonate (dolomite) in sedimentary rocks [49], see Figure 3b.

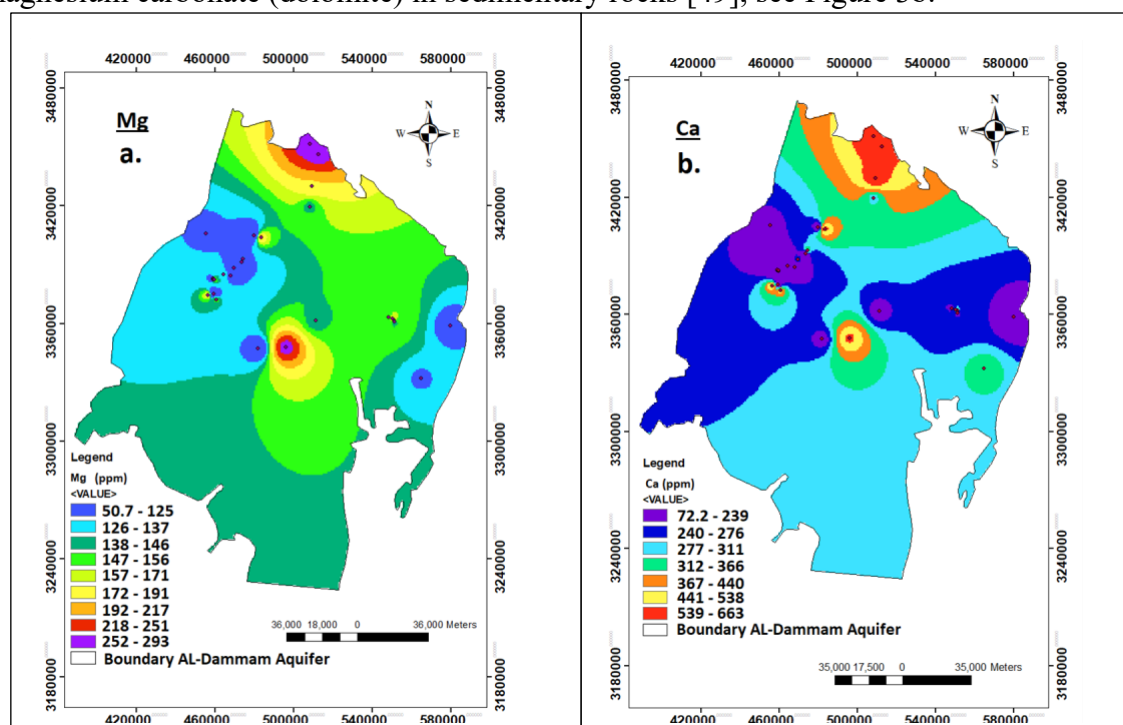


Figure 3. Spatial distribution maps of Mg and Ca values

Bicarbonate (HCO_3) concentration in most samples was within the WHO limit (500 ppm), except for wells W7 and W8, which recorded 857 and 813 ppm, respectively. This may lead to increased water hardness and sediment buildup in these two wells. The lowest bicarbonate value was recorded in well W3 (127 ppm), as shown in Figure 4a. As for carbonate (CO_3), all wells were within the permissible limit (30 ppm) and did not pose a health risk.

Some wells contain high levels of chloride (Cl^-) that exceed the permissible limit (250 ppm), such as well W30 (2214.8 ppm), which can affect taste and cause pipe corrosion. The lowest value recorded in well W12 (88 ppm) is within the safe limit. High chloride levels in some wells indicate potential contamination or exposure to saltwater sources [48]. This water may require treatment, such as reverse osmosis, to reduce the chloride concentration (see Figure 4b).

Groundwater hardness is mainly controlled by water–rock interaction, cation exchange, evaporation, and, in some settings, seawater intrusion, with local geology and human activities influencing spatial variability [50, 51]. Total hardness (TH) in the study area is primarily due to elevated concentrations of dissolved Ca^{2+} and Mg^{2+} derived from the dissolution of limestone and dolomite along the flow paths. As groundwater infiltrates these formations, it acquires minerals that increase hardness. TH values range from 67 to 940.8 mg/L; wells W7, W24, W25, W27, W28, W29, and W30 exceed the WHO guideline value of

500 mg/L and therefore require treatment, such as ion exchange or reverse osmosis, before use. In contrast, wells W1, W11, W12, and W13 exhibit moderate hardness and are more suitable for domestic use. Regular monitoring of water hardness is recommended to ensure compliance with health regulations.

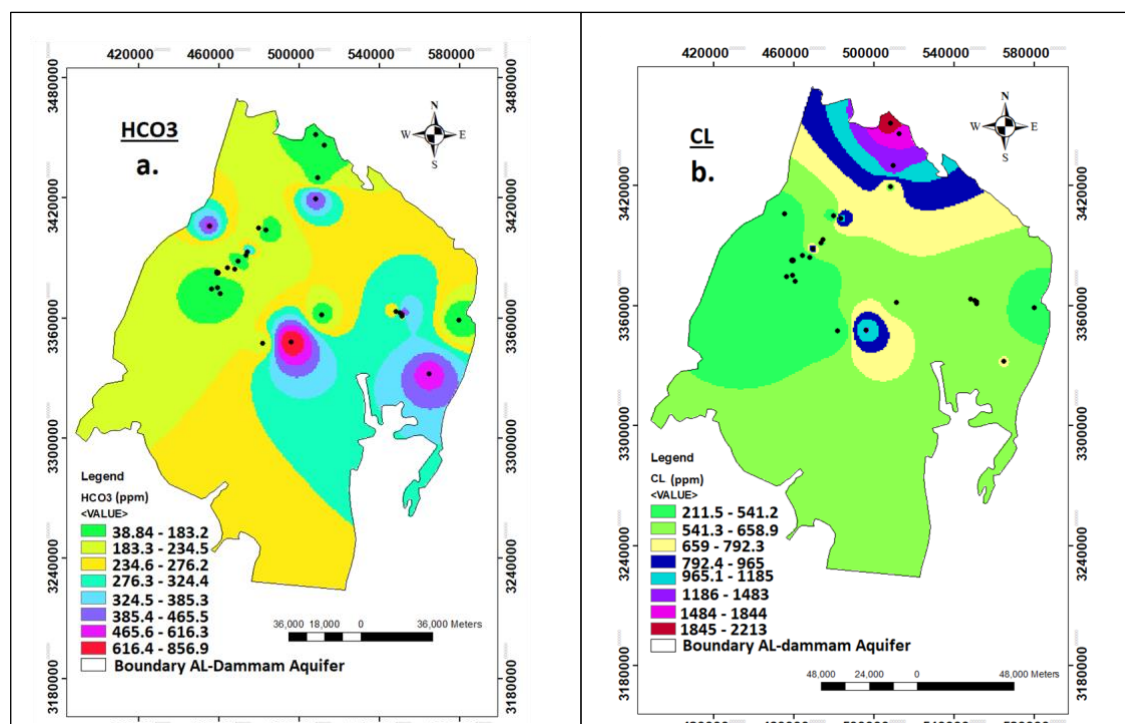


Figure 4. Spatial distribution maps of HCO₃ and CL values

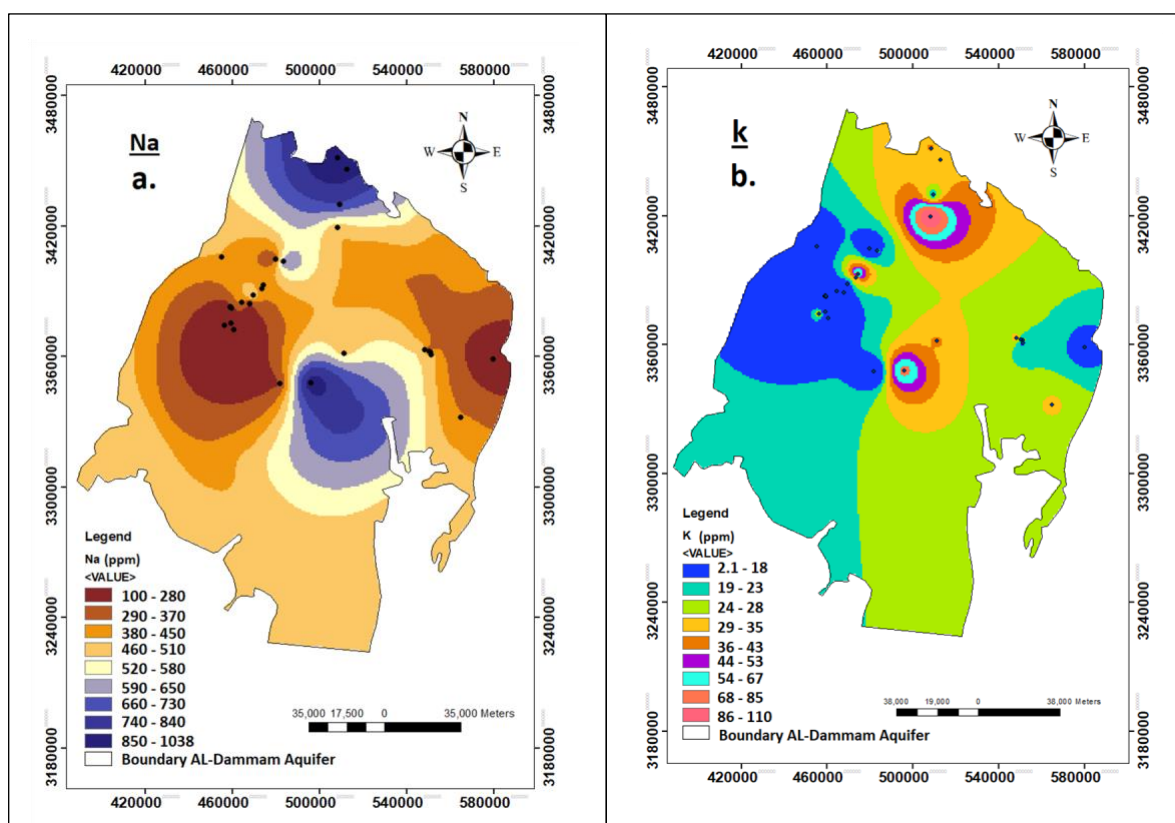


Figure 5. Spatial distribution maps of Na and K values

Sodium (Na) levels in many wells exceed the WHO limit (200 ppm), including well W30, which recorded 1038.74 ppm, indicating that some water contains unhealthy levels of sodium. The lowest sodium value was in well W1 (122 ppm; see Figure 5a).

Potassium (K^+) levels in many wells exceed the limit (12 ppm), including well W30, which recorded 34.86 ppm. The lowest potassium value was in well W1 (2 ppm; see Figure 5b). The modification of silicate minerals is the primary source of Na^+ and K^+ concentrations [52]. These ions are benign at normal concentrations, but when they surpass permissible thresholds, they may adversely affect human health, leading to conditions such as hypertension, cardiovascular disease, or renal issues.

Nitrate (NO_3) levels in the Well results ranged between 0 and 42 ppm, which is below the WHO maximum permissible limit of 50 ppm. All wells are considered safe in terms of nitrate levels, and none of the waters contained nitrates exceeding the permissible limit. According to international standards, the nitrates in these waters do not pose a health risk. Therefore, no special treatment is required for the nitrate levels in these wells. Nitrate is a key indicator of groundwater pollution caused by human activities [53]. See Figure 6a.

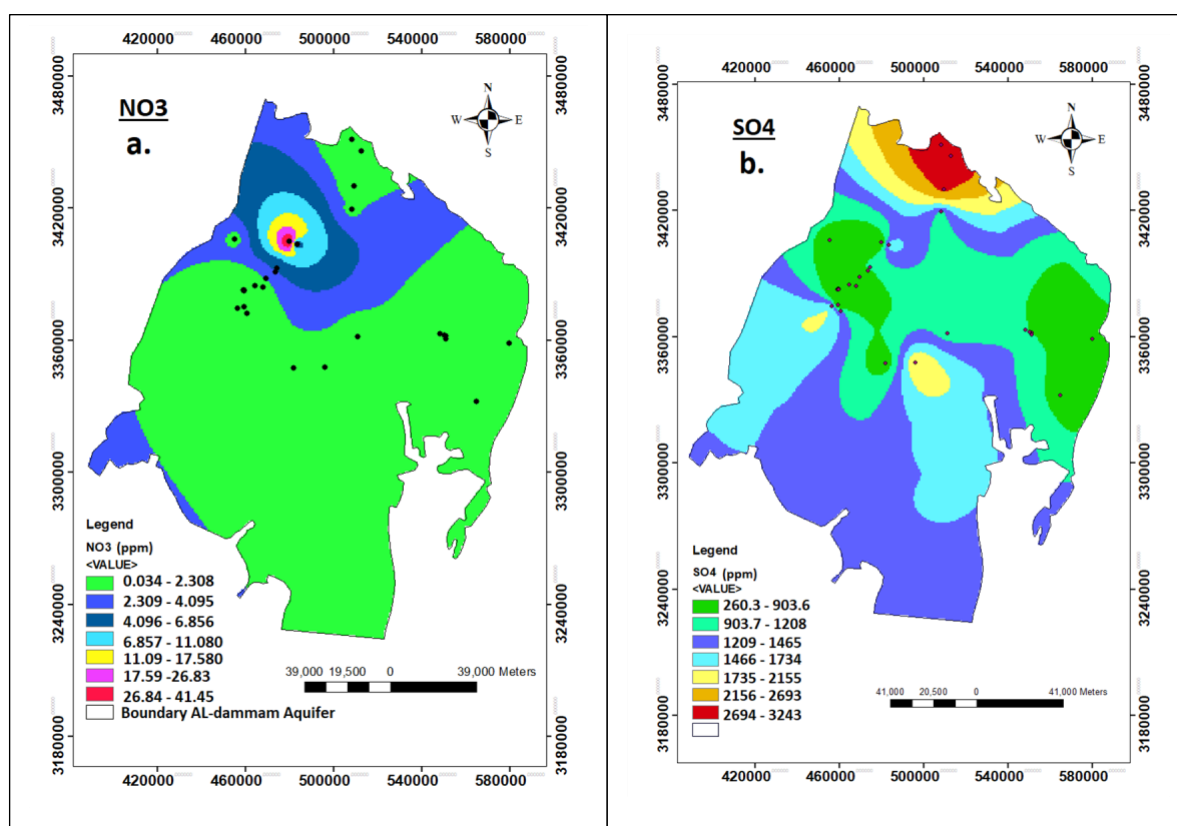


Figure 6. Spatial distribution maps of NO_3 , and SO_4 value

Many wells contain high levels of sulfate (SO_4) that exceed the permissible limit (250 ppm), such as

well W30 (3247.1 ppm), which can affect taste and cause health problems. The lowest value recorded was well W12 (195 ppm), which is within the safe limit. High sulfate levels in some wells can cause adverse effects, such as diarrhoea and an unpleasant taste. This water may require treatment, such as reverse osmosis or dilution with other water, to make it safe to drink. The primary source of sulfates is the dissolution of gypsum. No evidence of oxidised sulfides was found in the study area [47], as shown in Figure 6b.

5.2. Hydrochemical Evolution and Groundwater Types

Hydrochemical data were analysed using the methodologies proposed by M. Piper in 1944 [54] to enhance comprehension of the geochemical mechanisms influencing water quality. Employing analytical data from the primary parameters of chemical analysis (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , NO_3^- , HCO_3^- , CO_3^{2-} , SO_4^{2-}), Piper's trilinear diagram was utilised to delineate the geochemical facies and groundwater types within the Dammam aquifer and their interactions with adjacent rocks.

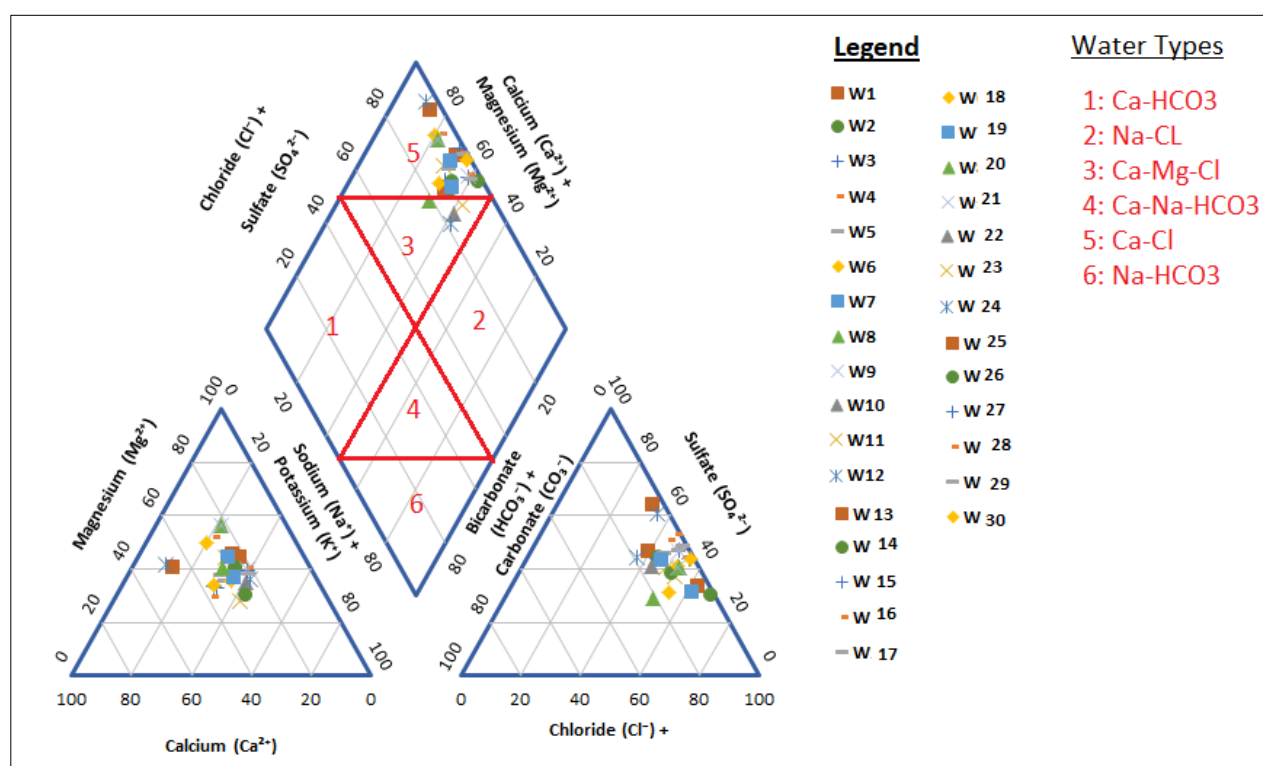


Figure 7. Piper diagram showing the type of groundwater samples

Analysis of the Piper ternary plot reveals that most samples (87%) fall into the Ca-Cl range, indicating that calcium and chloride dominate the water chemistry. A few other samples (13%) fall into the Ca-Mg-Cl range, indicating the influence of magnesium alongside calcium and chloride. This distribution reflects geological influences. The presence of calcium and chloride indicates the potential for water interaction with sedimentary rocks. Increased magnesium levels may be due to ion-exchange processes or to specific

geological sources. Thus, Piper analysis helps determine the nature of water chemistry and interpret its sources and environmental impacts (see Figure 7).

5.3. Groundwater Quality Index (GWQI)

Table 2 shows the quality classification of 30 samples using the GWQI. 66.67% of samples fall into the "poor water" category, indicating the need for treatment before consumption. Another 20% fall into the "very poor" or "non-potable" category, requiring intensive treatment. Only 13.34% of samples fall into the "excellent" or "good" categories, meaning that most of the water tested suffers from problems. Regular quality monitoring is recommended in accordance with the GWQI standards. Improving treatment can help reduce health risks and ensure that water is safe to drink, as shown in Figure 8.

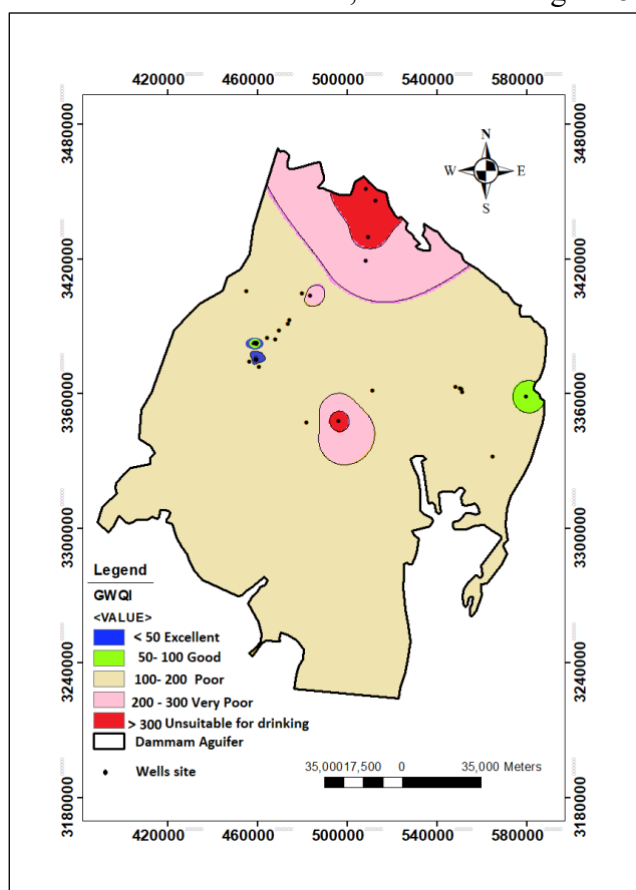


Figure 8. The GWQI results for all studied areas in the Samawa district

Previous research in the study area has shown increased salinity and a prevalence of sulfate- and chloride-dominated water types, both of which are unsuitable for human consumption. The study attributes groundwater chemistry to geological processes, including the dissolution of carbonates, sulfates, and halite, as well as cation exchange. All studies conclude that water is predominantly unsuitable for human consumption according to GWQI and WHO standards. All research agrees on the primary

hydrogeochemical challenges, salinity, sulfate predominance, and geological influence, yet this study offers the most thorough and policy-relevant examination [12, 14, 15, 25, 55].

5.4. Evaluation of Irrigation Water Quality

Evaluating groundwater suitability for irrigation is essential to determine the impact of its salinity and elemental content on plants and soil. High salinity and toxic elements contribute to reduced water uptake and inhibited growth by elevating osmotic pressure or exerting toxic effects. The evaluation includes indicators such as EC, sodium content, and pH. The same applies to soil structure, permeability, and aeration.

Table 5 shows the test results for the criteria for five risk groups: EC, %Na, SAR, PI, and MH [56]. To assess irrigation compatibility, all previous regional studies used criteria such as SAR, %Na, PI, EC, and other irrigation parameters. The results showed that most samples fell into the high salinity categories, making them unsuitable for agricultural use without treatment [12, 14, 15, 25, 55].

5.4.1. USSL Diagram

The US Salinity Laboratory (USSL) has developed a flowchart to categorise irrigation water based on electrical conductivity (EC) as a measure of salinity risk and sodium adsorption ratio (SAR) as a measure of sodium risk, see Fig. 9. Salinity is categorised into four zones based on the concentration of dissolved salts: C1 (low), C2 (medium), C3 (high), and C4 (very high) [57].

As the salinity of irrigation water increases, the osmotic pressure of the soil solution rises, diminishing the pressure gradient between the interior and exterior of root cells and hindering the plant's water uptake [58]. Wilcox (1955) states that groundwater classified as C1, indicating a minimal salinity risk, is often suitable for irrigating a wide range of crops and soil types. In circumstances of moderate leaching, class C2 water, which presents a moderate salinity risk, may be deemed suitable for irrigation. Water with elevated salinity (class C3) can be used for salt-tolerant crops; however, it is unsuitable for standard irrigation methods, especially in soils with limited drainage capacity. Class C4 water, distinguished by elevated salinity, is considered unsuitable for application on soils with drainage constraints [59].

Analysis of the samples from this study area revealed that all samples were categorised as high-salinity water (C3) to very-high-salinity water (C5), with electrical conductivity values ranging from 1013 to 9410 $\mu\text{S}/\text{cm}$ (see Figure 9 and Table 6).

Table 5. Calculated irrigation water quality parameters for Samawa groundwater samples

Sample	SAR	%Na	MH	PI	RSC	EC ($\mu\text{S}/\text{cm}$)
W1	2.72	41.30	54.07	47.18	-6.98	1092.00
W2	5.15	44.36	49.53	49.07	-17.66	3170.00
W3	6.34	50.21	52.84	52.57	-19.40	4070.00
W4	2.36	30.55	54.41	35.00	-14.35	2160.00
W5	3.92	39.76	42.42	45.33	-15.02	2650.00
W6	4.48	38.81	36.49	44.54	-18.48	4350.00
W7	8.12	45.67	44.64	48.68	-36.81	9410.00
W8	4.90	39.79	45.48	46.39	-16.35	4360.00
W9	6.37	49.85	53.17	52.20	-20.11	4130.00
W10	6.30	50.93	46.64	58.40	-10.43	4960.00
W11	5.17	50.78	36.44	58.50	-8.63	2660.00
W12	3.08	52.57	49.52	68.82	-1.97	1013.00
W13	3.30	44.64	55.57	54.56	-6.00	1802.00
W14	5.52	46.61	44.48	49.42	-18.24	4240.00
W15	4.74	41.16	36.52	44.50	-20.99	4430.00
W16	5.42	49.46	53.61	52.45	-14.95	4140.00
W17	6.47	50.91	52.22	53.85	-18.27	3940.00
W18	2.82	27.84	50.07	32.12	-24.75	3690.00
W19	3.71	39.91	51.17	45.69	-13.46	2860.00
W20	3.24	31.13	61.10	35.08	-24.08	3360.00
W21	3.27	30.83	61.13	34.91	-24.73	3430.00
W22	3.22	31.04	61.07	35.27	-23.49	3320.00
W23	3.70	38.34	50.49	44.46	-14.59	2680.00
W24	1.41	14.69	34.53	17.43	-35.10	2920.00
W25	2.08	18.98	34.90	20.68	-43.47	3810.00
W26	7.23	52.75	40.87	54.30	-20.85	3930.00
W27	6.07	39.05	36.33	40.13	-45.15	5870.00
W28	6.41	39.75	32.08	41.08	-46.85	6380.00
W29	7.52	42.36	41.30	43.26	-52.77	7880.00
W30	8.50	44.92	42.68	45.75	-54.65	9410.00
Min.	1.41	14.69	32.08	17.43	-1.97	1013.00
Max.	8.50	52.75	61.13	68.82	-54.65	9410.00
Average	4.78	40.63	46.86	45.05	-22.95	4070.57

Notes: SAR sodium absorption ratio, %Na percent sodium, MH magnesium hazard, IP permeability index, and RSC residual sodium carbonate.

The SAR is an essential criterion for evaluating the suitability of groundwater for irrigation. The

Sodium Adsorption Rate (SAR) influences soil quality, making irrigation water with elevated salt concentrations particularly problematic. Since it poses a sodium threat to soil health, SAR extracts water from vegetation and reduces soil permeability [60]. When present in adequate quantities in the soil, calcium ions (Ca^{+2}) and magnesium ions (Mg^{+2}) mitigate the effects of sodium ions (Na^{+}) and preserve optimal soil characteristics [61]. SAR is employed to classify groundwater into four categories. Excellent ($\text{SAR} < 10$), Good ($10 < \text{SAR} < 18$), Suspicious ($18 < \text{SAR} < 26$), and Unsuitable ($\text{SAR} > 26$). The water sample's SAR ranged from 8.50 to 1.41, with a mean of 4.78. Consequently, based on a USSL diagram [57], irrigation water quality is classified according to EC relative to SAR. Electrical conductivity (EC) serves as the salinity risk index, while the sodium adsorption ratio (SAR) indicates the sodium hazard for irrigation water.

According to the USSL diagram, approximately 13.33% of the groundwater samples were classified as category S1-C3, while 10% were classified as category S1-C4. Approximately 53.33% of the samples were classified as category S2-C4, and 23.33% as category S3-C4. The groundwater in the study area exhibits high to very high salinity and low to very high salt content (see Table 6). Class A may be suitable for irrigation, provided salinity is monitored continuously. Classes B, C, D, E, and F are not suitable for irrigation without advanced water treatment such as desalination or improved drainage systems.

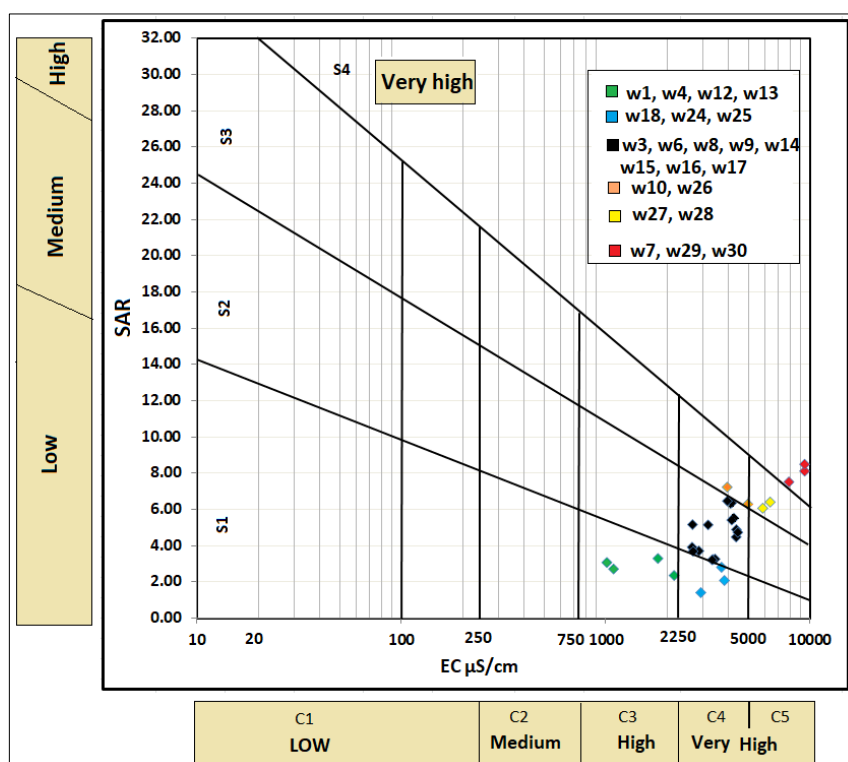


Figure 9. USSL diagram for assessing water irrigation quality

Table 6. Classification of water according to the USSL diagram

Class	Sample	EC μS/cm	SAR	Salinity Hazard Class	Water Type	% Samples	Type of use
A	W1	1092	2.717841	C3-S1	Low sodium and	13.33	Admissible
	W4	2160	2.359431	C3-S1	High salinity water		
	W12	1013	3.075356	C3-S1			
	W13	1802	3.297513	C3-S1			
B	W18	3690	2.815397	C4-S1	Low sodium	10	Poor
	W24	2920	1.41461	C4-S1	and very high salinity		
	W25	3810	2.083678	C4-S1			
C	W2	3170	5.150461	C4-S2		53.33	Poor
	W3	4070	6.336309	C4-S2			
	W5	2650	3.921155	C4-S2			
	W6	4350	4.482535	C4-S2			
	W8	4360	4.896143	C4-S2			
	W9	4130	6.365702	C4-S2			
	W11	2660	5.166794	C4-S2			
	W14	4240	5.523081	C4-S2	Medium Sodium		
	W15	4430	4.739989	C4-S2	and Very high salinity		
	W16	4140	5.418668	C4-S2			
	W17	3940	6.47228	C4-S2			
	W19	2860	3.714414	C4-S2			
	W20	3360	3.243814	C4-S2			
	W21	3430	3.267268	C4-S2			
	W22	3320	3.224271	C4-S2			
	W23	2680	3.696588	C4-S2			
D	W10	4960	6.296296	C4-S3	Medium Sodium	6.67	Very Poor
	W26	3930	7.232737	C4-S3	and very high salinity		
E	W27	5870	6.071011	C5-S3	Medium Sodium	6.67	Very Poor
	W28	6380	6.410334	C5-S3	and very high salinity		
F	W7	9410	8.116208	C5-S4	Very high Sodium	10	Very Poor
	W29	7880	7.521876	C5-S4	and very high salinity		
	W30	9410	8.496147	C5-S4			

5.4.2. Wilcox's Diagram

Wilcox's diagram is used to categorise groundwater for irrigation based on EC vs %Na (see Figure

10). Wilcox's Diagram primarily focuses on grain-size distribution and plasticity, neglecting other significant soil properties such as compressibility and permeability. Consequently, it may not fully reflect the soil's engineering properties. The relationship between water quality and soil properties is closely linked; soil controls water infiltration and pollutant absorption. The more permeable and organically rich the soil, the better it protects water from contamination. Of the 30 samples, only 10% were classified as "good to permissible," 20% as "doubtful to unsuitable," and a troubling 70% as "unsuitable" due to the high salt content in the water.

5.4.3. Water Permeability Index (PI)

The permeability index (PI), an assessment of irrigation water quality concerning alterations in arable soil constituents, serves as a vital indicator, as soil permeability may be influenced by elevated concentrations of Na^+ , Ca^{+2} , HCO_3^- , and Mg^{+2} [62]. The permeability index (PI) values for irrigation water in the study area range from 17.43 to 68.82 per cent. The results indicate that 6.67% of the samples possess a PI of less than 25% (class i), whereas 93.33% exhibit a PI between 25% and 75% (class ii). Groundwater in the study area is deemed good for the Water permeability index (see Table 7).

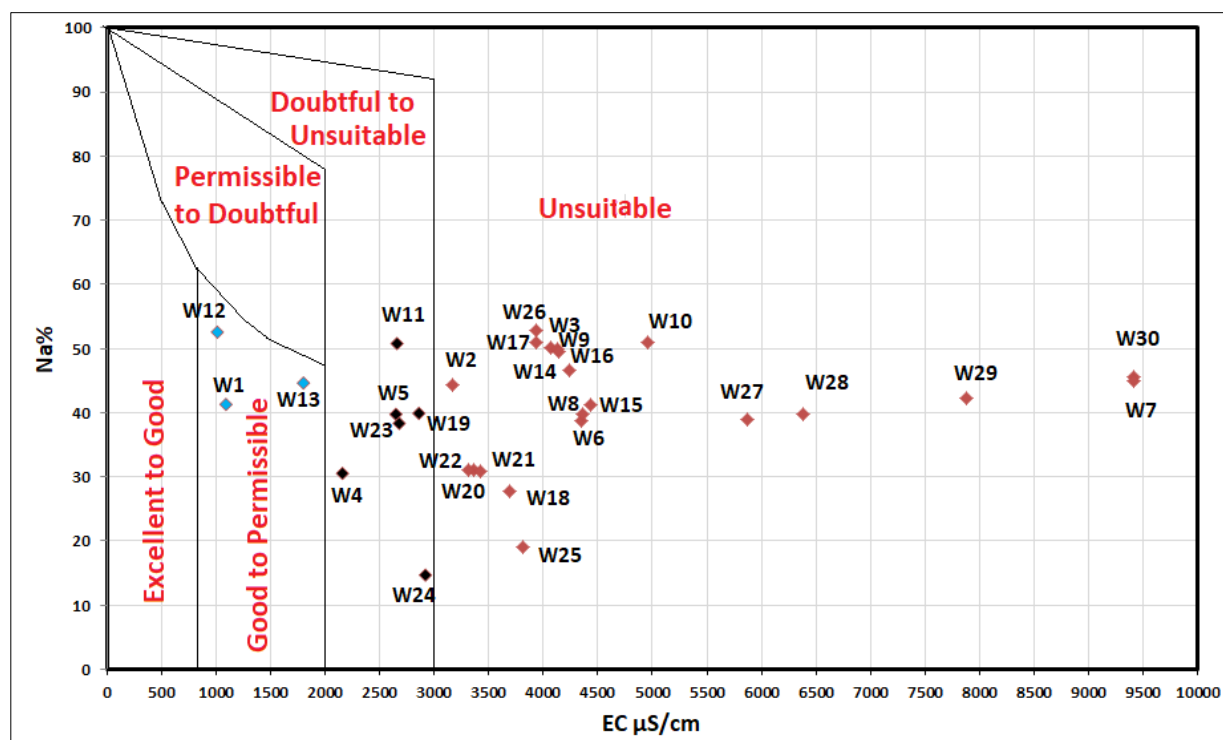


Figure 10. Wilcox's diagram

5.4.4. Magnesium Hazard (MH)

Most waters have a balance of calcium and magnesium. Naseem et al. [64] introduced a ratio, the

magnesium danger index. This indicates that when soil alkalinity increases, a high magnesium hazard value (>50%) adversely affects crop output. The results showed that 63.33% of the water sources had no magnesium concerns, making them suitable for agricultural use. The magnesium hazard index ranged from 32% to 61%.

Table 7. Classified permeability index "PI" for irrigation water in the study's area, Doneen [63]

PI class	Range	Sample no.	% Sample	Water quality
Class- i	<25	W24, and W25	6.67	Very good quality for irrigation
Class - ii	25-75	Other samples	93.33	Good quality for irrigation
Class -iii	>75	-	-	Unsuitable for irrigation

5.4.5. Residual Sodium Carbonate

Residual Sodium Carbonate (RSC) assesses the equilibrium between carbonate/bicarbonate and calcium/magnesium ions in irrigation water. Negative RSC values indicate the absence of alkali hazards and imply favourable water quality. However, reliance solely on RSC is inadequate; a thorough water categorisation requires supplementary metrics such as EC, SAR, and total salinity. These aggregated metrics provide a more precise evaluation of irrigation water appropriateness.

6. Conclusion and Recommendations

This study evaluated the physicochemical characteristics and hydrogeochemical evolution of groundwater from 30 wells in the Damman aquifer in Samawa, southern Iraq. Most samples exceed WHO guideline values for EC and TDS, and the calculated Groundwater Quality Index (GWQI) shows that the majority of wells fall in the "poor" to "very poor" classes for drinking purposes, with only a small number classified as "good" or "excellent". Ca dominates hydrogeochemical facies–Cl and Ca–Mg–Cl types, reflecting the dissolution of carbonate, gypsum, and halite, as well as evaporation and cation-exchange processes. Irrigation indices (SAR, %Na, PI, MH, and RSC), along with USSL and Wilcox diagrams, indicate that most groundwater in the study area has high to very high salinity and is unsuitable for irrigation, or only marginally suitable, without management interventions.

Based on these findings, groundwater from the Damman aquifer in Samawa generally requires desalination or blending before use for drinking. For irrigation, careful selection of salt-tolerant crops, appropriate leaching fractions, and improved drainage are recommended. In addition, regular monitoring of groundwater quality, protection of recharge areas from contamination, and the inclusion of microbial

and trace-element analyses in future studies are essential to support sustainable groundwater use in the region.

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References

- [1] Fanack Water. "Water Quality in Iraq." Fanack Water. <https://water.fanack.com/iraq/water-quality-in-iraq/> (accessed Jan 13, 2025).
- [2] T. Mohanakavitha *et al.*, "Dataset on the assessment of water quality of surface water in Kalingarayan Canal for heavy metal pollution, Tamil Nadu," *Data in Brief*, vol. 22, pp. 878-884, 2019, doi: <https://doi.org/10.1016/j.dib.2019.01.010>.
- [3] K. H. Jodhani *et al.*, "Sustainable groundwater management through water quality index and geochemical insights in Valsad India," *Scientific Reports*, vol. 15, no. 1, p. 8769, 2025, doi: <https://doi.org/10.1038/s41598-025-92053-1>.
- [4] S. A. Abed, S. H. Ewaid, and N. Al-Ansari, "Evaluation of water quality in the Tigris River within Baghdad, Iraq using multivariate statistical techniques," *Journal of Physics: Conference Series*, vol. 1294, no. 7, p. 072025, 2019, doi: <https://doi.org/10.1088/1742-6596/1294/7/072025>.
- [5] N. A. H. Alharbawee and A. J. Mohammed, "Water quality assessment of Tigris River using multivariate statistical techniques," *Iraqi Journal of Science*, vol. 65, no. 3, pp. 1266-1275, 2024, doi: <https://doi.org/10.24996/ij.s.2024.65.3.8>.
- [6] M. A. Al-Dabbas, I. A. Al-Ali, and M. M. Husain, "Water quality assessment of the Euphrates River from Haditha to Al-Nasiriyah, Iraq," *Iraqi Geological Journal*, vol. 57, no. 2B, pp. 272-285, 2024, doi: <https://doi.org/10.46717/igj.57.2B.18ms-2024-8-28>.
- [7] K. Manoj and P. K. Padhy, "Discourse and review of environmental quality of river bodies in India: An appraisal of physico-chemical and biological parameters as indicators of water quality," *Current World Environment*, vol. 10, no. 2, pp. 537-571, 2015, doi: <https://doi.org/10.12944/CWE.10.2.20>.
- [8] H. A. Alfalahi and A. S. Aldhamin, "Effect of pollutants on phytoplankton biodiversity in the Tigris and Diyala Rivers in Baghdad Province," *Journal of Ecological Engineering*, vol. 26, no. 3, 2025, doi: <https://doi.org/10.12911/22998993/197497>.
- [9] M. M. Sharqi, A.-N. A. Al-Tamimi, and O. M. Hassan, "Evaluation of Euphrates River Water Quality on Phytoplankton Biodiversity in Ramadi, Iraq," *Borneo Journal of Resource Science and Technology*, vol. 14, no. 2, pp. 19-30, 2024, doi: <https://doi.org/10.33736/bjrst.6858.2024>.
- [10] I. A. A. Al-Bahathy, Z. Z. Al-Janabi, R. A. Taha, and M. M. Adel, "Biodiversity of Cladocera and water quality for Euphrates River in the eastern of Al-Qadisiyah Governorate, Iraq," *Egyptian Journal of Aquatic Biology and Fisheries*, vol. 28, no. 1, pp. 1-7, 2024, doi: <https://doi.org/10.21608/ejabf.2024.334488>.
- [11] S. M. Abed, K. H. Y. Alaraji, and R. H. Essa, "Assessment of the biological and physiochemical properties of groundwater in Al-Muthanna Province, Iraq," *EurAsian Journal of BioSciences*, vol. 14, no. 2, 2020.

- [12] K. K. Fatah, M. Hamed, M. H. Saeed, and R. Dara, "Evaluation groundwater quality by using GIS and water quality index techniques for wells in Bardarash area, Northern Iraq," *Iraqi Geological Journal*, pp. 87-104, 2020, doi: <https://doi.org/10.46717/igj.53.2c.7Rs-2020-09.07>.
- [13] A. A. F. Beg, S. M. Awadh, M. B. Thamer, and A. H. Al-Sulttani, "Assessment of groundwater quality for drinking purposes using water quality index, and identifying the affecting mechanism in Rashdiya, Central Iraq," *Iraqi Geological Journal*, pp. 20-32, 2021, doi: <https://doi.org/10.46717/igj.54.1F.3ms-2021-06-23>.
- [14] A. A. Rashid, M. A. Al-Dabbas, and W. H. Kadhim, "Assessment of groundwater quality for drinking in Tuz Khurmatu area, Salahadden Governorate, Iraq," *Iraqi Geological Journal*, pp. 91-103, 2016, doi: <https://doi.org/10.46717/igj.39-49.2.7Ms-2016-12-30>.
- [15] A. P. Dimri *et al.*, "Climate change, cryosphere and impacts in the Indian Himalayan Region," *Current Science*, vol. 120, no. 5, pp. 774-790, 2021.
- [16] A. M. Al-Abadi, A. E. Fryar, A. A. Rasheed, and B. Pradhan, "Assessment of groundwater potential in terms of the availability and quality of the resource: A case study from Iraq," *Environmental Earth Sciences*, vol. 80, no. 12, p. 426, 2021, doi: <https://doi.org/10.1007/s12665-021-09725-0>.
- [17] A. Z. A. Al-Ozeer and A. M. Al-Abadi, "Groundwater Quality Index Assessment using the Entropy Method on the Nineveh Plain in Northern Iraq," *Iraqi Geological Journal*, pp. 128-138, 2022, doi: <https://doi.org/10.46717/igj.55.1A.10Ms-2022-01-29>.
- [18] H. A. K. Al-Jaf, "Water Quality Index Application to Evaluate the Ground Water Quality in Kalar City-Kurdistan Region-Iraq," 2022. <https://doi.org/10.1088/1755-1315/1120/1/012002>
- [19] W. H. Kadhim, "The use of water quality index technique to assess ground water for irrigation in Ashtan area, Muthanna Governorate, Southern Iraq," *Advances in Natural and Applied Sciences*, vol. 12, no. 2, pp. 1-5, 2018.
- [20] C. Tokatlı, A. Uğurluoğlu, and S. Muhammad, "Spatiotemporal variation of organic contaminants and their ecotoxicological risk in the Uluabat Lake basin, Türkiye: A Ramsar living wetland," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 138, p. 103851, 2025, doi: <https://doi.org/10.1016/j.pce.2025.103851>.
- [21] S. Muhammad *et al.*, "Spatial distribution of hazard index via heavy metals consumption in water from the Himalayan lacustrine ecosystems," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 138, p. 103858, 2025, doi: <https://doi.org/10.1016/j.pce.2025.103858>.
- [22] A. Agrawal and D. Dohare, "Assessment of groundwater suitability for drinking and irrigation purpose using statistical and geospatial techniques: A review," *The Holistic Approach to Environment*, vol. 14, no. 1, pp. 27-39, 2024, doi: <https://doi.org/10.33765/thate.14.1.4>.
- [23] O. N. Al-Sheikh and A. M. Al-Shamma'a, "Hydrochemical of groundwater for Al Dammam unconfined aquifer within Al-Salman Basin, Al-Muthana Governorate, South West Iraq," *Iraqi Journal of Science*, vol. 60, no. 6, pp. 1336-1349, 2019, doi: <https://doi.org/10.24996/ij.s.2019.60.6.17>.
- [24] Iraqi Meteorological Organization, "Meteorological data/report for Iraq," Iraqi Meteorological Organization, 2017.
- [25] H. A. Alikhan, A. K. Hussein, and A. S. Alshukri, "Groundwater quality assessment using water quality index: A case study of Al Najaf City, Iraq," *Periodicals of Engineering and Natural Sciences*, vol. 8, no. 3, pp. 1482-1490, 2020, doi: <https://doi.org/10.21533/pen.v8.i3.1188>.
- [26] R. Al-Khafaji, S. Muhi, and A. Jassam, "Hydrochemical evaluation of groundwater from selected wells in Al Muthana Governorate, Southern Iraq," *Iraqi Journal of Science*, vol. 62, no. 6, pp. 1930-1942, 2021, doi: <https://doi.org/10.24996/ij.s.2021.62.6.18>.
- [27] M. A. Al-Dabbas, Y. K. Al-Ameri, and W. H. Kadhim, "Groundwater Quality Investigation of the Dammam Unconfined Aquifer, Umaid Area, Muthanna Governorate, Iraq," *Advances in Natural and Applied Sciences*, vol. 12, no. 5, pp. 24-35, 2018, doi: <https://doi.org/10.22587/anas.2018.12.5.5>.

- [28] T. S. Khayyun, A. H. Mseer, and M. M. Ismaeel, "Ground Water Quality Evaluation using WQI and GIS Technique in the Al-Samawa City-Iraq," *Asian Journal of Engineering and Technology*, vol. 5, no. 4, 2017.
- [29] F. R. S. Al-Jabri, "The effect of some elements of climate on archaeological sites in Al-Muthanna Governorate: The effects of Warka as a model," *World Bulletin of Social Sciences*, vol. 11, pp. 29-43, 2022. [Online]. Available: <https://scholarexpress.net/index.php/wbss/article/view/1068>.
- [30] N. C. Brady and R. R. Weil, *The Nature and Properties of Soils*. Upper Saddle River, NJ: Prentice Hall, 1999.
- [31] FAO, IIASA, ISRIC, ISS-CAS, and JRC. *Harmonized World Soil Database (version 1.2)*, FAO and IIASA. [Online]. Available: <https://iiasa.ac.at/models-tools-data/hwsd>
- [32] C. A. J. Appelo and D. Postma, *Geochemistry, Groundwater and Pollution*. Amsterdam, The Netherlands: CRC Press/Balkema, 2005, doi: <https://doi.org/10.1201/9781439833544>.
- [33] N. S. Kawo and S. Karuppannan, "Groundwater quality assessment using water quality index and GIS technique in Modjo River Basin, central Ethiopia," *Journal of African Earth Sciences*, vol. 147, pp. 300-311, 2018, doi: <https://doi.org/10.1016/j.jafrearsci.2018.06.034>.
- [34] N. Adimalla, P. Li, and S. Venkatayogi, "Hydrogeochemical evaluation of groundwater quality for drinking and irrigation purposes and integrated interpretation with water quality index studies," *Environmental Processes*, vol. 5, pp. 363-383, 2018, doi: <https://doi.org/10.1007/s40710-018-0297-4>.
- [35] R. M. Kalin and A. Long, "Application of hydrogeochemical modelling for validation of hydrologic flow modelling in the Tucson Basin Aquifer, Arizona, USA," in "Mathematical Models and Their Applications to Isotope Studies in Groundwater Hydrology," International Atomic Energy Agency, Vienna, Austria, 1994.
- [36] N. Adimalla and A. K. Taloor, "Hydrogeochemical investigation of groundwater quality in the hard rock terrain of South India using Geographic Information System (GIS) and groundwater quality index (GWQI) techniques," *Groundwater for Sustainable Development*, vol. 10, p. 100288, 2020, doi: <https://doi.org/10.1016/j.gsd.2019.100288>.
- [37] S. P. Vaiphei, R. M. Kurakalva, and D. K. Sahadevan, "Water quality index and GIS-based technique for assessment of groundwater quality in Wanaparthy watershed, Telangana, India," *Environmental Science and Pollution Research*, vol. 27, pp. 45041-45062, 2020, doi: <https://doi.org/10.1007/s11356-020-10345-7>.
- [38] W. H. Organization, *Guidelines for Drinking-water Quality: Incorporating the First and Second Addenda*. Geneva, Switzerland: World Health Organization, 2022. [Online]. Available: <https://www.who.int/publications/i/item/9789240045064>
- [39] A. Shuaibu, R. M. Kalin, V. Phoenix, L. C. Banda, and I. M. Lawal, "Hydrogeochemistry and water quality index for groundwater sustainability in the Komadugu-Yobe Basin, Sahel Region," *Water*, vol. 16, no. 4, p. 601, 2024, doi: <https://doi.org/10.3390/w16040601>.
- [40] C. R. Ramakrishnaiah, C. Sadashivaiah, and G. Ranganna, "Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka State, India," *Journal of Chemistry*, vol. 6, no. 2, pp. 523-530, 2009, doi: <https://doi.org/10.1155/2009/757424>.
- [41] I. Mukherjee, U. K. Singh, and S. Chakma, "Evaluation of groundwater quality for irrigation water supply using multi-criteria decision-making techniques and GIS in an agro-economic tract of Lower Ganga basin, India," *Journal of Environmental Management*, vol. 309, p. 114691, 2022, doi: <https://doi.org/10.1016/j.jenvman.2022.114691>.
- [42] M. Batarseh *et al.*, "Assessment of groundwater quality for irrigation in the arid regions using irrigation water quality index (IWQI) and GIS-Zoning maps: Case study from Abu Dhabi Emirate, UAE," *Groundwater for Sustainable Development*, vol. 14, p. 100611, 2021, doi: <https://doi.org/10.1016/j.gsd.2021.100611>.
- [43] M. Alsubih *et al.*, "Assessing surface water quality for irrigation purposes in some dams of Asir Region, Saudi Arabia using multi-statistical modeling approaches," *Water*, vol. 14, no. 9, p. 1439, 2022, doi: <https://doi.org/10.3390/w14091439>.
- [44] M. S. Samtio *et al.*, "Impact of rock-water interaction on hydrogeochemical characteristics of groundwater: Using

- multivariate statistical, water quality index and irrigation indices of Chachro sub-district, Thar Desert, Sindh, Pakistan," *Groundwater for Sustainable Development*, vol. 20, p. 100878, 2023, doi: <https://doi.org/10.1016/j.gsd.2022.100878>.
- [45] H. M. Raghunath, *Ground Water: Hydrogeology, Ground Water Survey and Pumping Tests, Rural Water Supply and Irrigation Systems*. New Delhi, India: New Age International, 1987.
- [46] O. O. Elemile, E. M. Ibitogbe, B. T. Okikiola, and P. O. Ejigboye, "Groundwater quality using indices for domestic and irrigation purposes in Akure, Nigeria," *Results in Engineering*, vol. 13, p. 100347, 2022, doi: <https://doi.org/10.1016/j.rineng.2022.100347>.
- [47] S. M. Awadh, F. M. Abdulhussein, and J. A. Al-Kilabi, "Hydrogeochemical processes and water-rock interaction of groundwater in Al-Dammam aquifer at Bahr Al-Najaf, Central Iraq," *Iraqi Bulletin of Geology and Mining*, vol. 12, no. 1, pp. 1-15, 2016.
- [48] S. Wen et al., "Spatial distribution and mechanisms of groundwater hardness in the plain area of Tangshan City, China," *Water*, vol. 16, no. 24, p. 3627, 2024, doi: <https://doi.org/10.3390/w16243627>.
- [49] T. Listyani and I. A. Prabowo, "Groundwater in Bener area, its quality and contribution for agriculture," 2022. <https://doi.org/10.1088/1755-1315/985/1/012028>
- [50] J. G. Wang, W. Zhou, and S. B. Gao, "Influence on increasing of shallow groundwater hardness with water-soil interaction," *China Mining Magazine*, vol. 21, pp. 107-110, 2012.
- [51] X. B. Wang, M. X. Gu, and X. Y. Wang, "Mechanism of Increasing Ground Water Hardness in Urban District of Shijiazhuang," *Journal of Anhui Agricultural Sciences*, vol. 35, pp. 13709-13711, 2013.
- [52] D. Dimri, A. Davey, A. Kumar, and A. Sharma, "Monitoring water quality of River Ganga using multivariate techniques and WQI (Water Quality Index) in Western Himalayan region of Uttarakhand, India," *Environmental Nanotechnology, Monitoring & Management*, vol. 15, p. 100375, 2021, doi: <https://doi.org/10.1016/j.enmm.2020.100375>.
- [53] D. Ratri, D. P. E. Putra, and W. Wilopo, "Groundwater geochemistry and hydrogeochemical processes assessment in Bantul, Yogyakarta, Indonesia," 2021. <https://doi.org/10.1088/1755-1315/958/1/012013>
- [54] A. M. Piper, "A graphic procedure in the geochemical interpretation of water-analyses," *Transactions, American Geophysical Union*, vol. 25, no. 6, pp. 914-928, 1944, doi: <https://doi.org/10.1029/TR025i006p00914>.
- [55] A. A. O. Al-Azawi and A. M. Al-Shamma'a, "Evaluating the suitability of groundwater for irrigation uses at Al-Salhubia Area, Al-Muthana Governorate, Southern Iraq," *Iraqi Journal of Science*, vol. 57, no. 4C, pp. 2898-2908, 2016. [Online]. Available: <https://ijs.uobaghdad.edu.iq/index.php/eijs/article/view/6277>.
- [56] S. Sudhakaran, H. Mahadevan, V. Arun, A. P. Krishnakumar, and K. A. Krishnan, "A multivariate statistical approach in assessing the quality of potable and irrigation water environs of the Netravati River basin (India)," *Groundwater for Sustainable Development*, vol. 11, p. 100462, 2020, doi: <https://doi.org/10.1016/j.gsd.2020.100462>.
- [57] L. A. Richards, *Diagnosis and Improvement of Saline and Alkali Soils*. Washington, DC: U.S. Government Printing Office, 1954. [Online]. Available: https://books.google.iq/books?id=KP8_AAAAIAAJ
- [58] A. Kadri et al., "Assessment of groundwater suitability for agricultural purposes: A case study of South Oued Righ region, Algeria," *Sustainability*, vol. 14, no. 14, p. 8858, 2022, doi: <https://doi.org/10.3390/su14148858>.
- [59] R. Pivić et al., "Hydrochemical assessment of water used for agricultural soil irrigation in the water area of the three Morava Rivers in the Republic of Serbia," *Agronomy*, vol. 12, no. 5, p. 1177, 2022, doi: <https://doi.org/10.3390/agronomy12051177>.
- [60] M. El-Rawy, E. Ismail, and O. Abdalla, "Assessment of groundwater quality using GIS, hydrogeochemistry, and factor statistical analysis in Qena Governorate, Egypt," *Desalination and Water Treatment*, vol. 162, pp. 14-29, 2019, doi: <https://doi.org/10.5004/dwt.2019.24423>.
- [61] Y. A. El-Amier, W. K. Kotb, G. Bonanomi, H. Fakhry, N. A. Marraiki, and A. M. Abd-ElGawad, "Hydrochemical assessment of the irrigation water quality of the El-Salam canal, Egypt," *Water*, vol. 13, no. 17, p. 2428, 2021, doi: <https://doi.org/10.3390/w13172428>.

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- [62] A. K. Haritash, S. Gaur, and S. Garg, "Assessment of water quality and suitability analysis of River Ganga in Rishikesh, India," *Applied Water Science*, vol. 6, pp. 383-392, 2016, doi: <https://doi.org/10.1007/s13201-014-0235-1>.
- [63] L. D. Doneen, *Notes on Water Quality in Agriculture*. Davis, CA: Department of Water Science and Engineering, University of California, 1964.
- [64] S. Naseem, S. Hamza, and E. Bashir, "Groundwater geochemistry of Winder agricultural farms, Balochistan, Pakistan and assessment for irrigation water quality," *European Water*, vol. 31, pp. 21-32, 2010.