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# GIS-Based Assessment of Groundwater Quality for Drinking Purposes in the East Tigris Basin, Iraq, Using WAWQI and CCME-WQI

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**ABSTRACT**

This study screened the groundwater suitability for drinking purposes using the Weighted Arithmetic Water Quality Index (WAWQI) and the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI), combined with GIS-based inverse distance weighting (IDW). Fourteen physicochemical parameters, measured once in 20 wells in 2025, were compared with drinking-water limits adopted from WHO and IQS 417/2009. The analytical reliability of each sample was screened with the charge balance error (CBE) and consistency checks between electrical conductivity (EC), total dissolved solids (TDS), total hardness (TH), and the major ions. Because the sampling dates of the individual wells were not released, the CCME-WQI ($F_1 = F_2$) was used only as a cross-sectional screening measure. Provisional WAWQI values ranged from 66.18 to 1537.91 (7 poor, 11 very poor and 2 unsuitable), whereas CCME-WQI values ranged from 47.87 to 78.15 (15 marginal and 5 fair). When TH and TDS are recalculated from the major ions, the WAWQI classes are almost unchanged, whereas four wells fall into the CCME-WQI poor class. TH exceeded 500 mg/L in 19 wells as reported (method not specified in the dataset) and in all 20 wells as calculated in this study, and $SO_4^{2-}$ exceeded 250 mg/L in 19 wells. Reported TDS (derived from EC) remained below 1000 mg/L in all wells, whereas TDS calculated from the major ions exceeded 1000 mg/L in 18 wells. The two indices differ mainly because WAWQI weights are inversely proportional to reference values, so that turbidity, pH, potassium ($K^+$) and temperature together carry 85.5% of the total weight, while the CCME-WQI depends on the number and magnitude of the exceedances. Because the data inconsistencies identified by the CBE and consistency checks remain unresolved, the classifications are provisional screening results, not a definitive assessment of drinking-water suitability.

## 1. INTRODUCTION

The drivers of population growth, urbanization, industrialization, climate change, and pressure on freshwater resources have made water sustainability one of the most pressing environmental and socio-economic challenges globally [1]. Groundwater provides a significant source of freshwater for human consumption, agriculture, and industry, especially in areas with scarce or unreliable surface water supplies, such as dry and semi-dry regions [2]. Groundwater is becoming an important strategic water resource in many developing nations, including Iraq, due to the dwindling amount and quality of surface water systems [3]. Therefore, groundwater resources assessment and sustainable management are crucial for ensuring long-term groundwater security and environmental sustainability [4].

The Tigris and Euphrates River systems are very important to Iraq for providing water [5]. But in recent decades, the country has faced serious water shortages caused by climate change, prolonged dry periods, population growth, and improper utilization of water resources, as well as the construction of dams upstream [6]. Under these conditions, the use of groundwater resources has increased in central and southern Iraq [7]. The amount of groundwater use is significantly high as a result of demand for agricultural irrigation, domestic water supplies, and industrial requirements, particularly south and east of the Tigris Basin where surface water supply is comparatively less [8]. Although groundwater is very important, it may suffer from salinity, agricultural return flows, industrial pollution, geogenic processes, and unregulated human activities in many areas in Iraq [9].

Groundwater Quality assessment is an important aspect of water resources management that is directly related to human health, agricultural productivity, and the stability of the ecosystem [10]. The suitability of groundwater for drinking and irrigation uses is generally determined through the physicochemical characteristics of the water [11], such as pH,

electrical conductivity (EC), total dissolved solids (TDS), total hardness (TH), and major ion constituents, including calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), sodium ($Na^{+}$), potassium ($K^{+}$), chloride ($Cl^{-}$), sulfate ($SO_4^{2-}$), nitrate ($NO_3^{-}$), and bicarbonate ($HCO_3^{-}$) [12]. High levels of these parameters can be indicators of contamination processes, mineral dissolution, salinity intrusion, or anthropogenic effects that affect the sustainability of groundwater resources [13]. Groundwater assessments are typically performed using traditional approaches, which often require a significant amount of data and complex hydro-chemical interpretations, which may not be easily understood by decision makers and environmental managers [10]. As a result, Water Quality Indices (WQIs) have become a popular metric to simplify and explain water quality [11]. WQIs combine several water quality parameters to give a single number reflecting the overall water quality [14]. These indices provide a means of comparing sampling sites and a way of identifying polluted or vulnerable sites that need management [15]. The most commonly used indices for groundwater quality assessment are the Weighted Arithmetic Water Quality Index (WAWQI) [10] and the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) [16]. The WAWQI method is based on the weighted arithmetic method that assigns weights to the different physicochemical parameters based on the relative importance that these parameters have in affecting the water quality [17]. This approach offers a simple assessment of the suitability of groundwater and is very useful in delineating severely contaminated or saline groundwater areas [18]. The CCME-WQI approach, on the other hand, assesses water quality based on three key parameters: the scale, number, and severity of regular water quality standards violations [19]. The CCME-WQI method provides a comprehensive method for determining the overall water quality performance against national and international standards [20]. A combination of multiple indices offers a more accurate interpretation of the groundwater conditions and a more reliable overall assessment [21]. GIS has been vital in recent years for managing, analyzing, and visualizing spatial data in groundwater studies [22]. GIS-based spatial analysis can be used to identify areas of spatial variation in groundwater quality, to locate "hotspot" areas of contamination, and produce thematic maps to aid environmental planning and decision-making [23].

Combining GIS with the WQI is now widely used for groundwater quality screening, as it incorporates a numerical evaluation, as well as spatial visualization techniques [24]. Spatial interpolation methods, such as inverse distance weighting (IDW) and kriging, are commonly used to estimate groundwater quality between sampling locations and to produce continuous maps of hydro-chemical parameters [25, 26]. GIS-based evaluations of groundwater for drinking use have already been carried out in Kirkuk, using the weighted arithmetic index [10] and a GIS-based assessment of drinking-water quality [11]. Different indices, however, aggregate the same measurements in different ways, so that a sample can fall into different classes depending on the index used, and index values are only as reliable as the ionic analyses behind them. The present study therefore extends this work to the area east of the Tigris River between Kirkuk and Tikrit and focuses on three aspects: (i) the application of the WAWQI and the CCME-WQI to the same samples; (ii) a decomposition of both indices to identify the parameters that control the final classes; and (iii) the reporting of the charge balance error (CBE) of each sample alongside its index values.

The aim of this study is to assess the suitability of groundwater east of the Tigris River for drinking purposes using GIS-integrated WAWQI and CCME-WQI. The specific objectives are to (1) compare the measured physicochemical parameters with the adopted drinking-water limits; (2) convert the major ions to milliequivalents per liter and check the analytical reliability of each sample with the CBE; (3) calculate and compare the two indices and explain the differences between their classifications; and (4) map the index classes with GIS to locate wells and zones of poor quality. The study is a screening-level assessment based on a single sampling campaign in 2025; it does not address groundwater quantity, recharge, or long-term trends.

GIS techniques can be combined with hydro-chemical analyses and WQIs to provide a spatially explicit assessment of groundwater quality. Study outcomes can aid understanding of the hydrogeological situation in the central part of Iraq and help decision makers and environmental authorities implement adequate monitoring and protection measures. Groundwater resources must be managed sustainably to secure good water quality, minimize environmental impacts, and provide water security for future generations in Iraq in the face of growing climatic and anthropogenic stresses.

## 2. METHODOLOGY

### 2.1 Study area

The study area lies east of the Tigris River in north-central Iraq, west of Kirkuk city, and extends southward to the vicinity of Tikrit, covering approximately 43°45′–44°10′ E and 34°38′–35°28′ N (Figure 1).

Groundwater is an important source of domestic and agricultural water in the east of the Tigris River between Kirkuk and Tikrit, Iraq. The area contains 20 monitoring wells (W1–W20), for which data were provided by the General Commission for Groundwater – Kirkuk.

The study area covers approximately 3,200 km², measured from the boundary polygon shown in Figure 1. All 20 monitoring wells of the General Commission for Groundwater – Kirkuk that are included in the dataset provided to the authors were used, and no well was excluded; the data refer to a single sampling round carried out in 2025 (Section 2.3).

The important features of this area are classified as semi-arid climatic conditions, agricultural lands, dispersed settlements and growing groundwater dependence on irrigations. The hydrogeological situation is mostly characterized by sedimentary structures with different groundwater depth and quality conditions.

The wells are unevenly distributed: they are clustered in the central-western part of the area, whereas large parts of the eastern half contain few wells (Figure 1); therefore, interpolated values in these sparsely monitored areas should be interpreted with caution. This area is significant because groundwater is a critical water source for the region for drinking, agriculture, and local industry.

The study area, east of the Tigris River, is an important groundwater-dependent area with semi-arid climatic conditions, agricultural activities, and growing water demand. Sustainable supply of surface water resources is scarce; consequently, the area is heavily dependent on groundwater for drinking and irrigation. However, in recent years concerns have been raised about the salinity and contamination of

groundwater resources, making groundwater quality assessment a critical need.

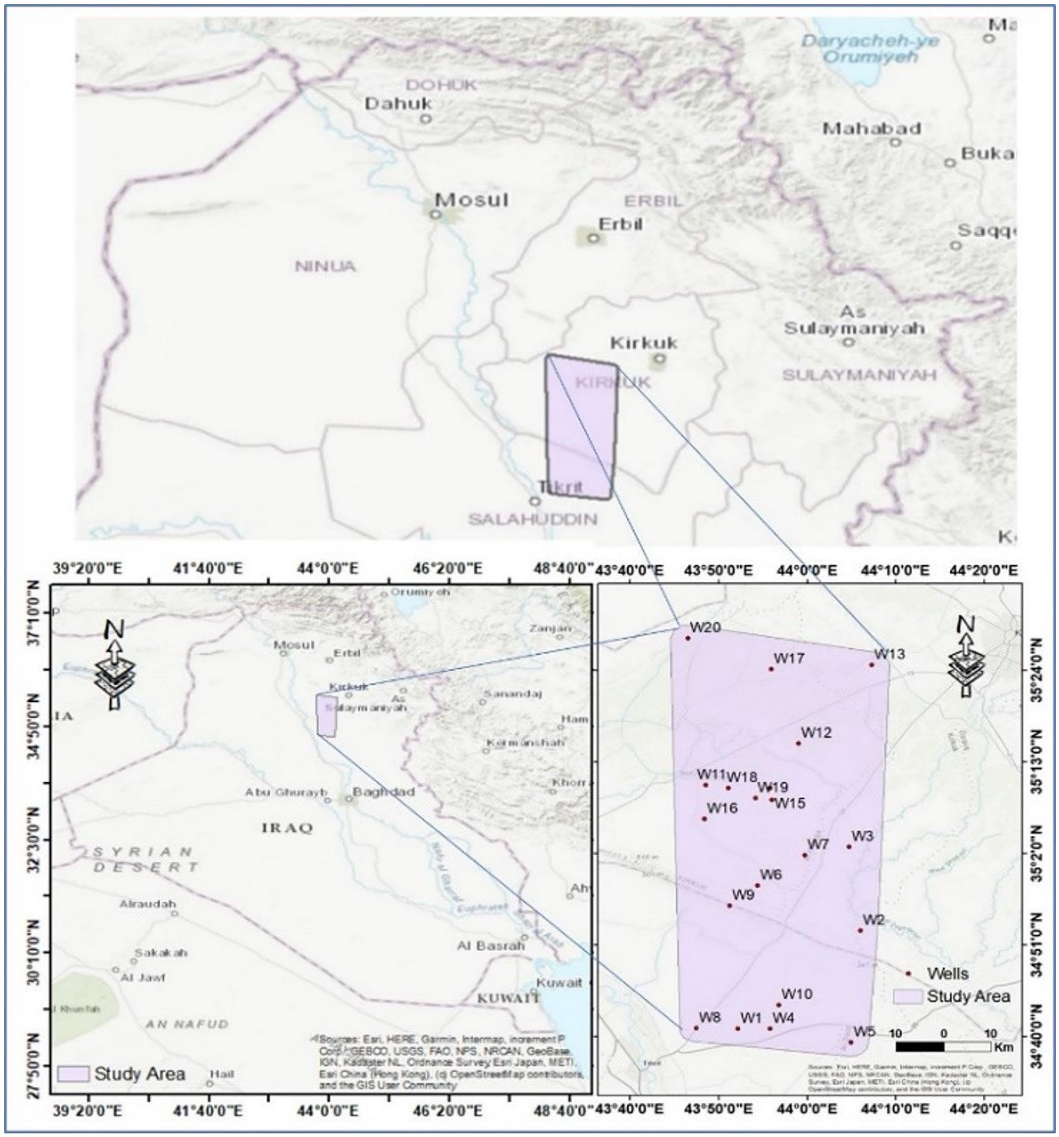



**Figure 1.** Location of the study area east of the Tigris River and of the 20 monitoring wells (W1–W20)
Note: Basemap sources: Esri, HERE, Garmin, Intermap, Increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community.

### 2.2 Flowchart

The method flowchart depicts the order of the methodology adopted for the groundwater quality assessment east of the Tigris Basin with the help of GIS-integrated WQIs (Figure 2).

A study area was selected because of the growing demand for groundwater and questions about water quality issues.

The second phase compiled the data for twenty monitoring wells provided by the General Commission for Groundwater – Kirkuk, which comprise field measurements and laboratory analyses. The parameters analyzed were temperature, pH, turbidity, TH, EC, TDS, $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $Cl^{-}$, $SO_4^{2-}$, $NO_3^{-}$, and $HCO_3^{-}$.

The third step was analyzing and assessing the data used. Groundwater quality parameters were compared with World Health Organization (WHO) [27] and Iraqi drinking water standards (IQS 417/2009) [28] to assess the compliance level as an initial step. The hydro-chemical analysis was then done by converting ionic concentration to milliequivalents per Liter (meq/L) using the method of Hounslow [29]. The analytical reliability of each sample was checked with the CBE %. The corrections made to the calculation workbook during checking are documented in Tables A1 and A2.

The methodology also incorporates two WQIs, the WAWQI and the CCME-WQI. Suitability of groundwater for drinking was classified using these indices. Maps of the index classes were then produced in GIS by IDW to locate groundwater quality hotspots. Finally, the integrated results were interpreted to assess groundwater suitability for drinking and to derive recommendations for groundwater management and monitoring in the study area.

### 2.3 Data source and used data

The dataset was provided by the General Commission for Groundwater – Kirkuk and contains one set of field and laboratory measurements for each of the 20 wells, collected in 2025; the index calculations therefore describe groundwater quality at the time of sampling and not changes over time. The reported values of the 14 parameters are presented in Section 3.1. The data describe a single sampling campaign and selected physicochemical parameters only.

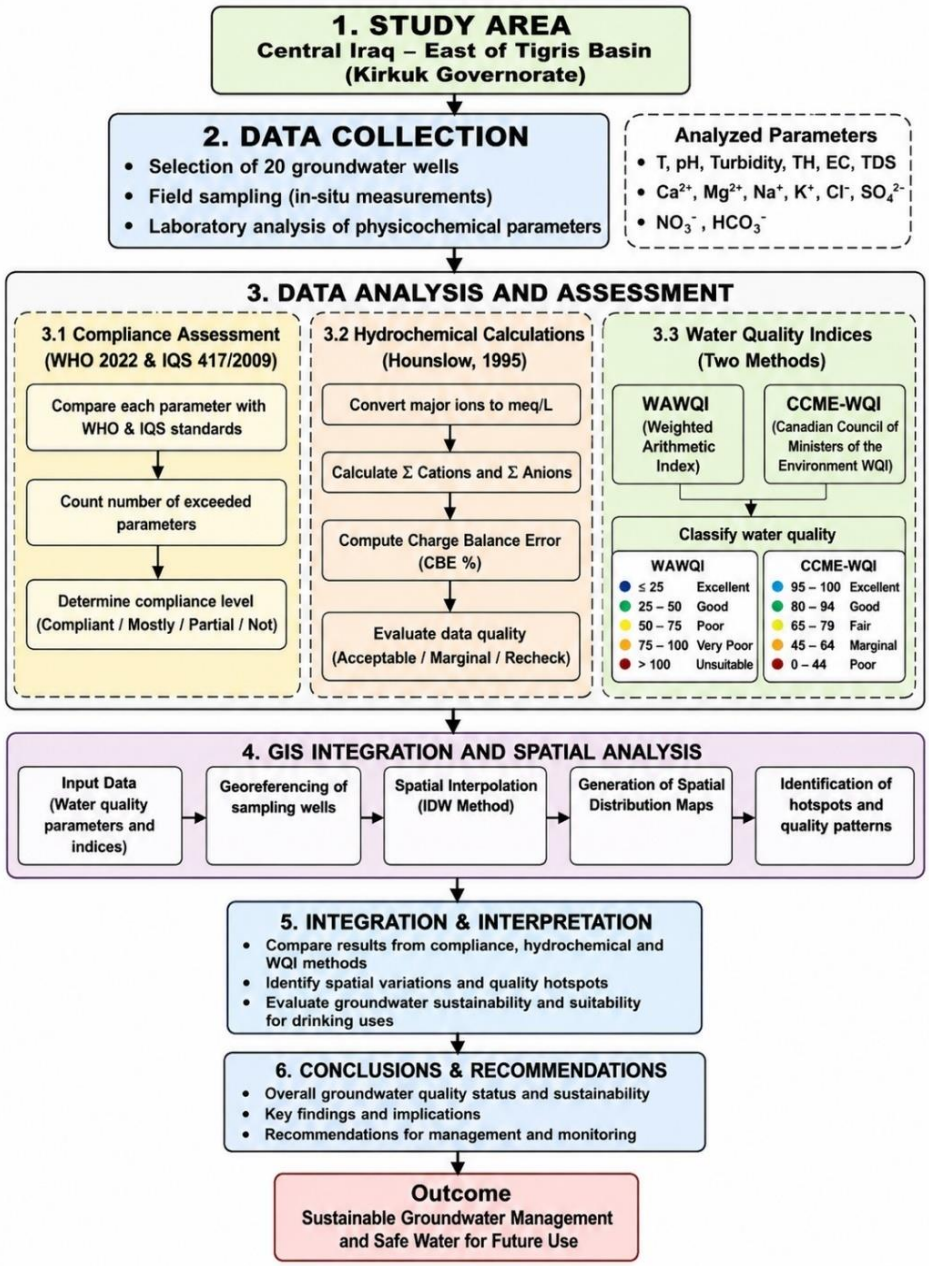



**Figure 2.** Study flowchart

The dataset consists of the results of a single sampling round of the agency's groundwater monitoring program and was provided to the authors as secondary data. The agency's laboratory protocol, instrument specifications, method detection limits, records of replicate analyses, and the sampling dates of the individual wells were not part of the released dataset and could therefore not be reported. Only the sampling year (2025) was released. Because the date, and hence the season, of sampling at each well is unknown, differences in sampling time between wells cannot be accounted for, and the CCME-WQI frequency factor $F_2$ cannot be interpreted as a frequency of exceedance over time (Section 2.5). The analytical reliability of every sample was instead evaluated independently with the data-based checks recommended in Standard Methods [30]: the charge balance, the agreement of the ion sums with EC, and the agreement between calculated and reported TDS and TH (Table A3 and Table A4). The results are interpreted as a cross-sectional snapshot, without seasonal or temporal inference.

Temperature, pH, EC, turbidity, TH, and the concentrations of $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $Cl^{-}$, $SO_4^{2-}$, $NO_3^{-}$, and $HCO_3^{-}$ are values reported in the agency dataset. TDS is not an independent measurement: in every well, it equals 0.64 × EC, i.e., it was estimated from EC with a conversion factor of 0.64.

The milliequivalent concentrations, the ion sums, the CBE, and the TH and TDS calculated from the major ions were computed in this study [29, 30].

The dataset does not state how TH was determined, and the reported values cannot be reproduced from the reported $Ca^{2+}$ and $Mg^{2+}$ (Section 3.2); both the reported and the calculated TH are therefore presented. Throughout the manuscript, "reported TH (method not specified in the dataset)" and "reported TDS (derived from EC)" denote the values of the dataset, whereas "TH calculated in this study" and "TDS calculated in this study" denote the values derived here from the major ions. Unless stated otherwise, the compliance assessment by well and the index values are based on the reported values; the effect of using the calculated values is

assessed in Section 3.5.

The physicochemical parameters analyzed were temperature, pH, turbidity, TH, EC, TDS, $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $Cl^{-}$, $SO_4^{2-}$, $NO_3^{-}$, and $HCO_3^{-}$. The analysis of the obtained results was compared with the WHO guidelines [27] and drinking water standards issued by the Iraqi government (IQS 417/2009) [28, 31] to assess the suitability of groundwater in the study area for drinking.

The analytical reliability of each sample was checked with the charge balance error, CBE = (Σcations − Σanions)/(Σcations + Σanions) × 100 [29, 32], calculated from the milliequivalent concentrations. A CBE within ±10% is considered chemically acceptable, and a CBE between ±10% and ±15% is marginal; samples outside the ±15% range should be retested, because analytical or sampling errors are likely. Standard Methods [30] apply a stricter tolerance of ±2–5% to anion sums of 10–800 meq/L, the range of all samples in this study. Two further consistency checks recommended in Standard Methods [30] were applied to every well: the ion sums in meq/L should be close to one hundredth of EC in µS/cm, and the TDS and TH calculated from the major ions (TDS = Σ major ions − 0.5083 $HCO_3^{-}$; TH = 2.497 $Ca^{2+}$ + 4.118 $Mg^{2+}$) should agree with the reported values.

### 2.4 Descriptive statistical analysis

The groundwater quality data were processed for descriptive statistical analysis to summarize and interpret the data from the study area.

The variation and distribution of physicochemical parameters among groundwater samples were evaluated using statistical parameters such as minimum, maximum, mean, and standard deviation.

The analysis gave a general picture of the groundwater quality conditions and assisted in pinpointing abnormal concentrations and spatial variation of major ions and water-quality parameters.

Descriptive statistics were also used to help interpret the hydro-chemical behavior and levels in the area. The statistical evaluation was an important tool before using the groundwater quality index and spatial interpolation methods using GIS.

### 2.5 Used indices

Two indices were applied to the same 14 parameters: the WAWQI [10, 33, 34] and the CCME-WQI [35].

In the WAWQI, each parameter n receives a quality rating $q_n = 100\cdot(V_n - V_i) / (S_n - V_i)$, where $V_n$ is the measured value, $S_n$ the reference value, and $V_i$ the ideal value (0 for all parameters except pH, for which $V_i = 7$). For pH, acidic and alkaline departures are rated separately against the corresponding bound, $q_{pH} = 100\cdot(V_n - 7) / (8.5 - 7)$ for $V_n \geq 7$ and $q_{pH} = 100\cdot(7 - V_n) / (7 - 6.5)$ for $V_n < 7$, so that both bounds of the 6.5–8.5 range correspond to a rating of 100. The unit weight of each parameter is $W_n = K / S_n$ with $K = 1 / \Sigma(1 / S_n)$, and $WAWQI = \Sigma(W_n q_n) / \Sigma W_n$.

Because $W_n$ is inversely proportional to $S_n$, parameters with low reference values receive high weights (Table 1).

Table 2 gives a worked example for W1. The CCME-WQI combines three factors: $F_1$ (scope), the percentage of variables that fail their objective; $F_2$ (frequency), the percentage of individual tests that fail; and $F_3$ (amplitude), derived from the normalized sum of excursions (nse).

**Table 1.** Reference values ($S_n$) and unit weights ($W_n$) of the 14 parameters used in the WAWQI (K = 1.9381)

| Parameter | Unit | $S_n$ | $W_n$ | Share of Total Weight (%) |
|---|---|---|---|---|
| Temperature | °C | 25 | 0.0775 | 7.75 |
| pH | – | 8.5 (6.5) | 0.2280 | 22.80 |
| Turbidity | NTU | 5 | 0.3876 | 38.76 |
| TH | mg/L | 500 | 0.0039 | 0.39 |
| EC | µS/cm | 1500 | 0.0013 | 0.13 |
| TDS | mg/L | 1000 | 0.0019 | 0.19 |
| $Ca^{2+}$ | mg/L | 75 | 0.0258 | 2.58 |
| $Mg^{2+}$ | mg/L | 50 | 0.0388 | 3.88 |
| $Na^{+}$ | mg/L | 200 | 0.0097 | 0.97 |
| $K^{+}$ | mg/L | 12 | 0.1615 | 16.15 |
| $Cl^{-}$ | mg/L | 250 | 0.0078 | 0.78 |
| $SO_4^{2-}$ | mg/L | 250 | 0.0078 | 0.78 |
| $NO_3^{-}$ | mg/L | 50 | 0.0388 | 3.88 |
| $HCO_3^{-}$ | mg/L | 200 | 0.0097 | 0.97 |
| Total | | | 1.0000 | 100.00 |

Note: For pH, $S_n$ = 8.5 is used for the weight; the lower bound 6.5 is used in the rating of acidic values. Weights are rounded to four decimals.

**Table 2.** Worked example of the index calculations for well W1

| Step | Value |
|---|---|
| CCME-WQI: (14 variables, one test each) | |
| Turbidity: 192 / 5 NTU | 37.400 |
| $Ca^{2+}$: 264.0 / 75 mg/L | 2.520 |
| $Mg^{2+}$: 60.0 / 50 mg/L | 0.200 |
| $Na^{+}$: 239.0 / 200 mg/L | 0.195 |
| $SO_4^{2-}$: 583.0 / 250 mg/L | 1.332 |
| Σexcursion; nse = 41.647/14 | 41.647; 2.975 |
| $F_1 = F_2 = 5/14 \times 100$ | 35.71 |
| $F_3 = 2.975/(0.01 \times 2.975 + 0.01)$ | 74.84 |
| CCME-WQI = $100 - \sqrt{(35.71^2 + 35.71^2 + 74.84^2)}/1.732$ | 47.87 (marginal) |
| WAWQI: contributions $W_n q_n$ | |
| Turbidity: 0.3876 × 3840.0 | 1488.43 (96.8%) |
| pH: 0.2280 × 80.0 | 18.24 (1.2%) |
| $Ca^{2+}$: 0.0258 × 352.0 | 9.10 (0.6%) |
| $K^{+}$: 0.1615 × 41.7 | 6.74 (0.4%) |
| Temperature: 0.0775 × 76.8 | 5.95 (0.4%) |
| $Mg^{2+}$: 0.0388 × 120.0 | 4.65 (0.3%) |
| Remaining eight parameters | 4.82 (0.3%) |
| $WAWQI = \Sigma W_n q_n$ ($\Sigma W_n = 1$) | 1537.91 (unsuitable) |
| WAWQI if turbidity were 5 NTU | 88.24 (very poor) |

The excursion of a failed test is $C_i/S_i - 1$ (or $S_i/C_i - 1$ for a value below a lower bound), nse = Σ excursion/number of tests, and $F_3 = nse/(0.01\cdot nse + 0.01)$.

The index is CCME-WQI = $100 - \sqrt{(F_1^2 + F_2^2 + F_3^2)}/1.732$ [35].

Because each well was sampled once (2025; the sampling dates of the individual wells were not released), the number of tests equals the number of variables and $F_1 = F_2$; the CCME-WQI is therefore used here only as a cross-sectional screening measure rather than as an index of compliance over time, for which the CCME guidance recommends at least four variables sampled at least four times [35].

Consequently, $F_2$ expresses only the percentage of failed tests in the single sample of each well and carries no information on how often the objectives are exceeded over time.

Both indices use the reference values listed in Table 1, which are identical to the values used for the compliance assessment (Section 3.1), where the basis of each value is

given. For EC, $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, and $HCO_3^{-}$, neither WHO [27] nor IQS 417 [31] specifies a value, so the values in Table 1 are reference values for the index calculation rather than regulatory limits; temperature (25 °C) was included as the 14th parameter on the basis of the value proposed for IQS 417 by Abbas [28].

The classification schemes are given in Tables 3 and 4.

**Table 3.** Weighted Arithmetic Water Quality Index (WAWQI) classification [10]

| WAWQI Range | Status |
|---|---|
| 0–25 | WQ is Excellent |
| >25–50 | WQ is Good |
| >50–75 | WQ is Poor |
| >75–100 | WQ is Very Poor |
| >100 | WQ is Unsuitable |

**Table 4.** Water Quality Index (WQI) standards of the Canadian Council of Ministers of the Environment (CCME) [35]

| CCME Range | Status |
|---|---|
| 95–100 | WQ is Excellent |
| 80–94 | WQ is Good |
| 65–79 | WQ is Fair |
| 45–64 | WQ is Marginal |
| 0–44 | WQ is Poor |

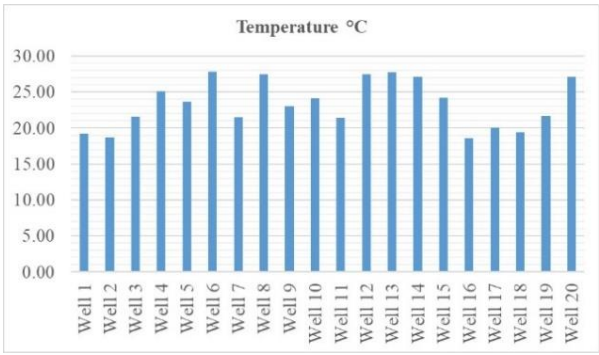
## 3. RESULTS

### 3.1 Physicochemical parameters and compliance with the adopted limits

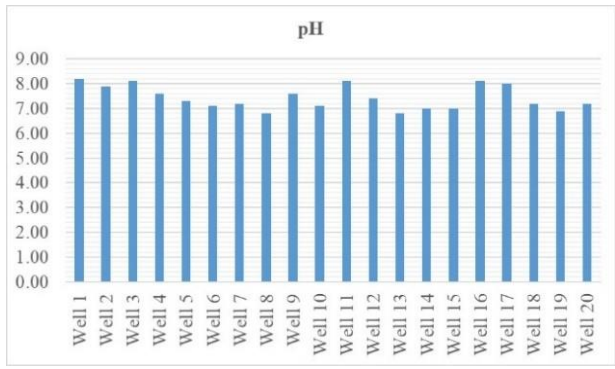
The spatial and statistical distribution of the groundwater quality measured in the twenty groundwater wells that were investigated in the study area on the east side of the Tigris Basin is shown in Figure 3. Variations in physicochemical parameters such as pH, EC, TDS, TH, $SO_4^{2-}$, $Cl^{-}$, $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $NO_3^{-}$, $HCO_3^{-}$, turbidity, and temperature are shown in the bar charts.

The figure shows significant variations in groundwater quality among wells, suggesting spatial variation in groundwater quality conditions.

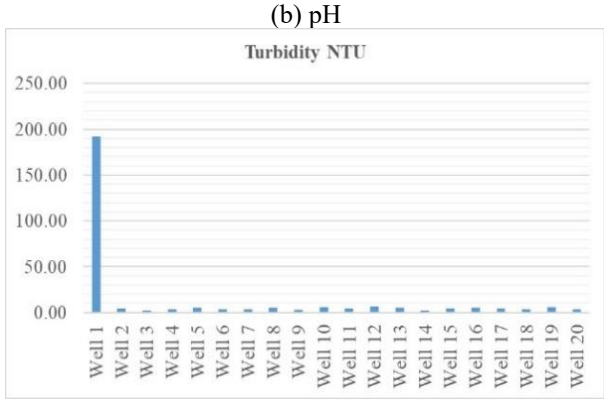
The high TH, $SO_4^{2-}$, $Ca^{2+}$, $Mg^{2+}$, and $Na^{+}$ levels detected in some wells indicate mineral dissolution and salinity effects, whereas EC and the reported TDS (derived from EC) remain below the adopted limits in all wells; the TDS calculated in this study from the major ions, however, exceeds 1000 mg/L in 18 wells. Turbidity is low in most wells but reaches 192 NTU at W1. The graphical representation is used to aid the WQI analysis and to identify areas of groundwater quality degradation.



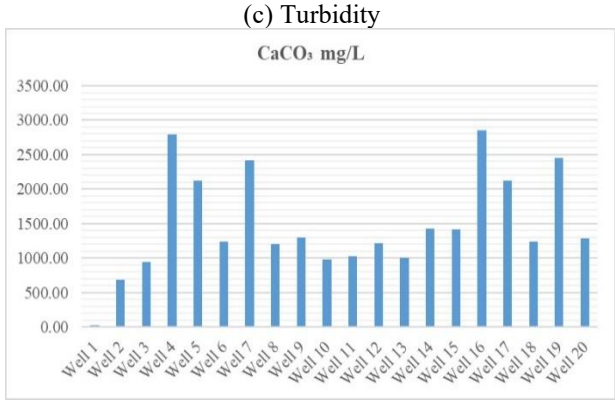

(a) Temperature



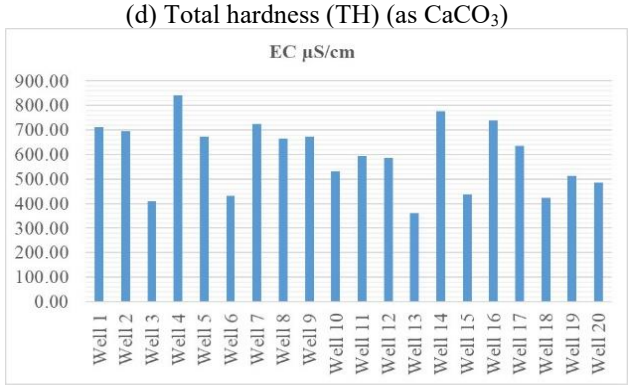

(b) pH



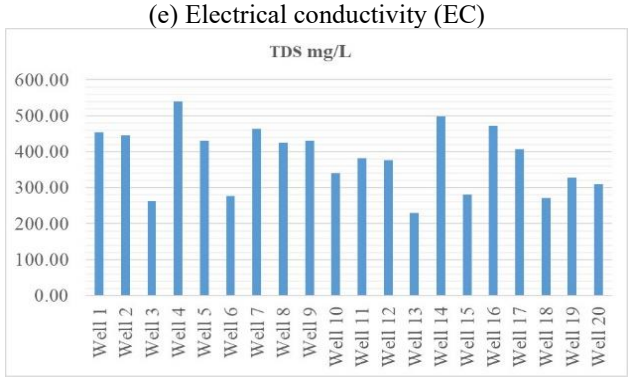

(c) Turbidity



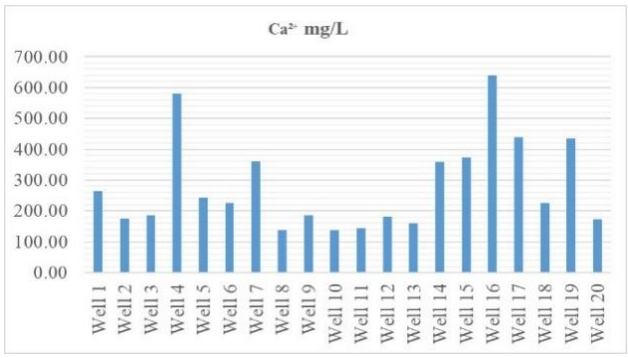

(d) Total hardness (TH) (as $CaCO_3$)



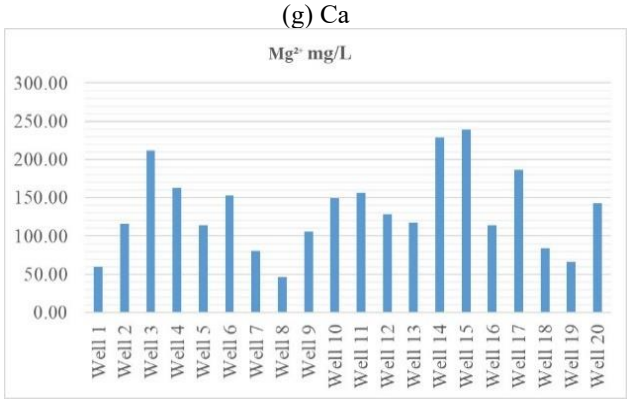

(e) Electrical conductivity (EC)



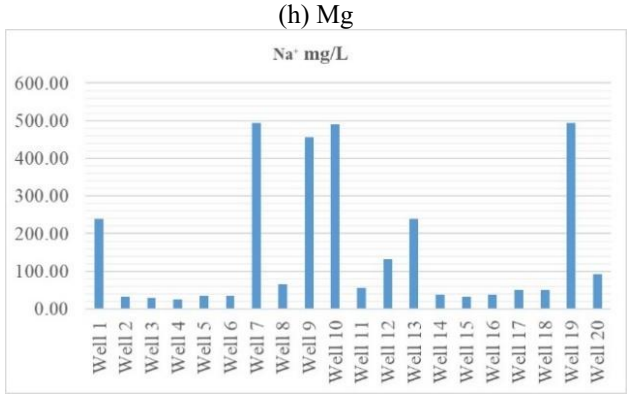

(f) Total dissolved solids (TDS)



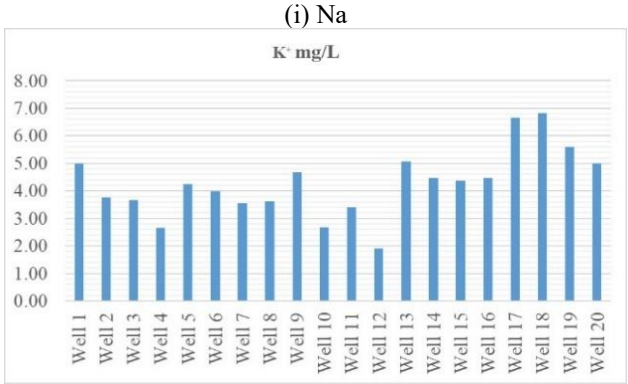

(g) Ca



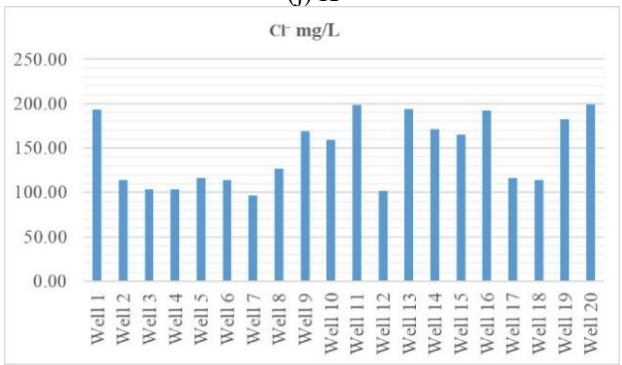

(h) Mg



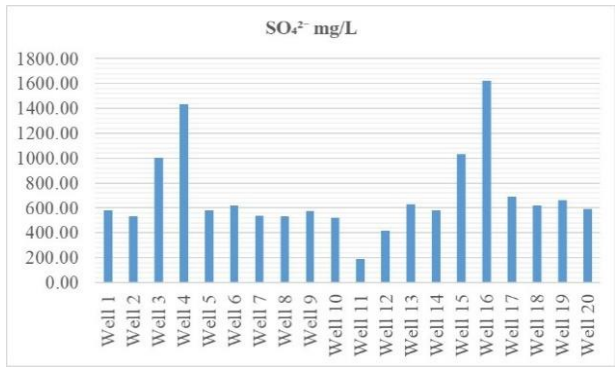

(i) Na



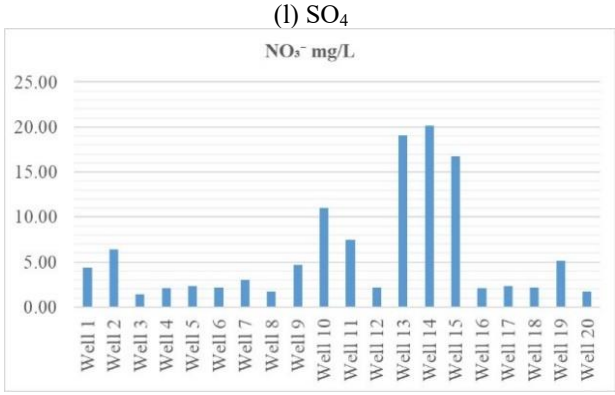

(j) K



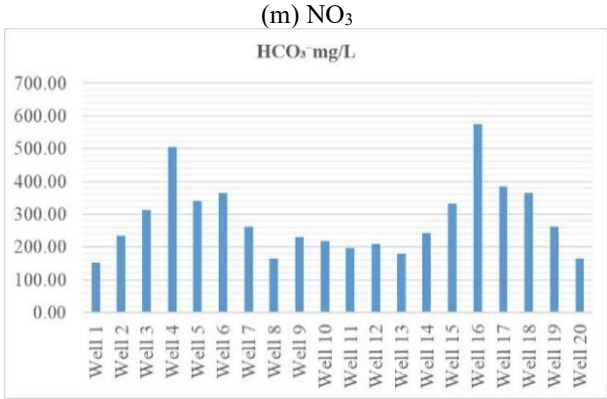

(k) Cl




(l) $SO_4$




(m) $NO_3$




(n) $HCO_3$

**Figure 3.** Physicochemical parameters of the 20 wells as reported in the dataset (TH: method not specified in the dataset; TDS: derived from EC, not measured)
Note: TH: total hardness, TDS: total dissolved solids, EC: electrical conductivity.

Table 5 summarizes the compliance of the wells with the adopted drinking-water limits and index reference values, (a) by parameter and (b) by well, together with the basis of each value.

Table 5 shows that no well exceeded the limits for pH, EC, reported TDS (derived from EC), $K^+$, $Cl^-$, or $NO_3^-$; the TDS calculated in this study exceeded 1000 mg/L in 18 wells (Table 5(a)). The most widespread exceedances were for TH as reported (method not specified in the dataset) and $SO_4^{2-}$ (19 wells each; 20 wells for the TH calculated in this study) and $Na^+$ (6 wells) and, against the index reference values, for $Ca^{2+}$ (20 wells), $Mg^{2+}$ (19 wells) and $HCO_3^-$ (15 wells). EC (360–842 µS/cm) and the reported TDS (derived from EC; 230–539 mg/L) remained below their limits in all wells, whereas the TDS calculated in this study from the major ions (853–2898 mg/L) exceeded 1000 mg/L in 18 wells (all except W8 and W11; see below). Temperature exceeded 25 °C in seven wells, and turbidity exceeded 5 NTU in seven wells, most strongly at W1 (192 NTU). Sixteen wells were partially compliant (4–6

exceedances); W11 was mostly compliant, and W10, W12, and W19 were non-compliant with seven exceedances; if temperature, which has no statutory limit, is excluded, W10 and W19 still have seven exceedances. These counts are based on the reported TH and TDS; with the values calculated in this study, twelve wells would be non-compliant, seven partially compliant, and W11 mostly compliant (Table 5 note).

**Table 5.** Compliance of the 20 wells with the drinking-water limits and index reference values used in this study, including the basis of each value

(a) By parameter (threshold used, basis, and wells exceeding)

| Parameter | Unit | Value Used | Basis of the Value | n | Wells Exceeding |
|---|---|---|---|---|---|
| T | °C | 25 | None; <25 °C proposed for IQS 417 [28][a] | 7 | W4, W6, W8, W12, W13, W14, W20 |
| pH | – | 6.5–8.5 | IQS 417 [31]; WHO: no health-based value [27] | 0 | – |
| Turbidity | NTU | 5 | IQS 417 [31]; WHO: acceptability [27] | 7 | W1, W5[b], W8[b], W10[b], W12[b], W16[b], W19[b] |
| TH (as $CaCO_3$), reported (method not specified in the dataset) | mg/L | 500 | IQS 417 [31]; WHO: no guideline value [27] | 19 | All except W1[c] |
| TH (as $CaCO_3$), calculated in this study | mg/L | 500 | As above; TH = 2.497 $Ca^{2+}$ + 4.118 $Mg^{2+}$ [30] | 20 | All wells |
| EC | µS/cm | 1500 | Not in WHO [27] or IQS 417 [31][d] | 0 | – |
| TDS, reported (derived from EC) | mg/L | 1000 | IQS 417 [31]; WHO: acceptability (taste) [27] | 0 | – |
| TDS, calculated in this study | mg/L | 1000 | As above; Σ major ions − 0.5083 $HCO_3^-$ [30] | 18 | All except W8, W11 |
| $Ca^{2+}$ | mg/L | 75 | Not in WHO [27] or IQS 417 [31][d] | 20 | All wells |
| $Mg^{2+}$ | mg/L | 50 | Not in WHO [27] or IQS 417 [31][d] | 19 | All except W8 |
| $Na^+$ | mg/L | 200 | IQS 417 [31]; WHO: acceptability (taste) [27] | 6 | W1, W7, W9, W10, W13, W19 |
| $K^+$ | mg/L | 12 | Not in WHO [27] or IQS 417 [31][d] | 0 | – |
| $Cl^-$ | mg/L | 250 | IQS 417 [31]; WHO: acceptability (taste) [27] | 0 | – |
| $SO_4^{2-}$ | mg/L | 250 | IQS 417 [31]; WHO: acceptability (taste) [27] | 19 | All except W11 |
| $NO_3^-$ | mg/L | 50 | IQS 417 [31]; WHO: health-based guideline value [27] | 0 | – |
| $HCO_3^-$ | mg/L | 200 | Not in WHO [27] or IQS 417 [31][d] | 15 | All except W1, W8, W11, W13, W20 |

(b) By well (number of exceedances; based on reported TH and reported TDS)

| Well | Parameters Exceeding the Value Used | n | Status | Well | Parameters Exceeding the Value Used | n | Status |
|---|---|---|---|---|---|---|---|
| W1 | Turb., Ca, Mg, Na, $SO_4$ | 5 | Partially compliant | W11 | TH, Ca, Mg | 3 | Mostly compliant |
| W2 | TH, Ca, Mg, $SO_4$, $HCO_3$ | 5 | Partially compliant | W12 | T, Turb., TH, Ca, Mg, $SO_4$, $HCO_3$ | 7 | Non-compliant |
| W3 | TH, Ca, Mg, $SO_4$, $HCO_3$ | 5 | Partially compliant | W13 | T, TH, Ca, Mg, Na, $SO_4$ | 6 | Partially compliant |
| W4 | T, TH, Ca, Mg, $SO_4$, $HCO_3$ | 6 | Partially compliant | W14 | T, TH, Ca, Mg, $SO_4$, $HCO_3$ | 6 | Partially compliant |
| W5 | Turb., TH, Ca, Mg, $SO_4$, $HCO_3$ | 6 | Partially compliant | W15 | TH, Ca, Mg, $SO_4$, $HCO_3$ | 5 | Partially compliant |
| W6 | T, TH, Ca, Mg, $SO_4$, $HCO_3$ | 6 | Partially compliant | W16 | Turb., TH, Ca, Mg, $SO_4$, $HCO_3$ | 6 | Partially compliant |
| W7 | TH, Ca, Mg, Na, $SO_4$, $HCO_3$ | 6 | Partially compliant | W17 | TH, Ca, Mg, $SO_4$, $HCO_3$ | 5 | Partially compliant |
| W8 | T, Turb., TH, Ca, $SO_4$ | 5 | Partially compliant | W18 | TH, Ca, Mg, $SO_4$, $HCO_3$ | 5 | Partially compliant |
| W9 | TH, Ca, Mg, Na, $SO_4$, $HCO_3$ | 6 | Partially compliant | W19 | Turb., TH, Ca, Mg, Na, $SO_4$, $HCO_3$ | 7 | Non-compliant |
| W10 | Turb., TH, Ca, Mg, Na, $SO_4$, $HCO_3$ | 7 | Non-compliant | W20 | T, TH, Ca, Mg, $SO_4$ | 5 | Partially compliant |

Note: [a] No statutory limit exists for temperature; 25 °C is the value proposed for IQS 417 by Abbas [28]. [b] Marginal exceedances (about 5.0–6.7 NTU), implied by the turbidity statistics and the index values (Sections 3.4 and 3.5); to be confirmed against the laboratory records. [c] The TH reported for W1 (24.3 mg/L) is inconsistent with its calcium ($Ca^{2+}$) concentration (264 mg/L, equivalent to 659 mg/L as $CaCO_3$); the TH calculated in this study for W1 is 906 mg/L. [d] Not specified in WHO [27] or in the IQS 417 table reproduced by WHO-EMRO [31]; these are reference values used in the WAWQI and CCME-WQI, not regulatory limits. They are retained because they carry the major-ion information of the indices: removing them would reduce the combined WAWQI weight of the major ions from 30.0% to 8.4% and raise that of turbidity and pH from 61.6% to 80.7%. IQS 417 values are those of the table reproduced by WHO-EMRO [31] (2001 edition); according to Abbas [28], the 2009 update did not change the numerical limits of the major parameters. WHO (2022) sets a health-based guideline value only for nitrate ($NO_3^-$) among these parameters; its other values relate to taste or appearance. Status: mostly compliant ≤ 3, partially compliant 4–6, and non-compliant ≥ 7 exceedances. Part (b) is based on the reported TH (method not specified in the dataset) and the reported TDS (derived from EC). With the TH and TDS calculated in this study, W1 would also exceed the TH value, and all wells except W8 and W11 would exceed the TDS value, giving twelve non-compliant wells (W1, W4, W5, W6, W7, W9, W10, W12, W13, W14, W16 and W19), seven partially compliant wells and one mostly compliant well (W11).

### 3.2 Ion balance and consistency of the reported data

The conversion of the major dissolved ions from milligrams per liter (mg/L) to milliequivalents per liter (meq/L), based on the hydro-chemical method of Hounslow [29], is presented in Table 6; in addition to EC (dS/m), the table contains the concentrations of $Ca^{2+}$, $Mg^{2+}$, $Na^+$, $K^+$, $HCO_3^-$, $Cl^-$, $SO_4^{2-}$ and $NO_3^-$. Table 7 shows the ion sums, the charge balance, and the consistency checks for each well.

The results revealed that $Ca^{2+}$, $Mg^{2+}$, $SO_4^{2-}$, and $Na^+$ are the dominant groundwater constituents in some wells as a result of the dissolution of minerals and salinity influence. The converted values are used to calculate the charge balance and to interpret the characteristics of groundwater hydro-

chemicals. The total concentration of the cations and anions as well as the CBE % (Section 2.3) for each sample of groundwater are summarized in Table 7.

With the ±10% criterion, eight samples (W2, W3, W4, W5, W6, W16, W18 and W20) are acceptable, three (W8, W13 and W15) are marginal and nine (W1, W7, W9, W10, W11, W12, W14, W17 and W19) exceed ±15%; with the ±5% tolerance of Standard Methods [30], only W2, W3, W4, W5 and W18 would be acceptable. The CBE is positive in 16 of the 20 samples and is highest in the sodium-rich wells W7, W9, W10 and W19 ($r = 0.72$ between CBE and $Na^+$), which points to a systematic cation excess, most probably in the sodium determinations.

**Table 6.** Ion concentrations (meq/L) [29]

| Well ID | $Ca^{2+}$ (meq/L) | $Mg^{2+}$ (meq/L) | $Na^+$ (meq/L) | $K^+$ (meq/L) | $HCO_3^-$ (meq/L) | $Cl^-$ (meq/L) | $SO_4^-$ (meq/L) | $NO_3^-$ (meq/L) | EC (dS/m) |
|---|---|---|---|---|---|---|---|---|---|
| Equivalent weight (g/eq) | 20.040 | 12.155 | 22.990 | 39.100 | 61.020 | 35.450 | 48.030 | 62.000 | |
| 1 | 13.174 | 4.936 | 10.396 | 0.128 | 2.491 | 5.444 | 12.138 | 0.071 | 0.711 |
| 2 | 8.782 | 9.543 | 1.413 | 0.096 | 3.835 | 3.216 | 11.118 | 0.103 | 0.696 |
| 3 | 9.232 | 17.441 | 1.233 | 0.094 | 5.129 | 2.906 | 20.883 | 0.023 | 0.411 |
| 4 | 28.942 | 13.419 | 1.082 | 0.068 | 8.284 | 2.923 | 29.837 | 0.034 | 0.842 |
| 5 | 12.128 | 9.399 | 1.491 | 0.108 | 5.555 | 3.278 | 12.056 | 0.038 | 0.673 |
| 6 | 11.254 | 12.575 | 1.470 | 0.102 | 5.986 | 3.215 | 12.892 | 0.035 | 0.431 |
| 7 | 17.971 | 6.654 | 21.482 | 0.091 | 4.278 | 2.724 | 11.212 | 0.049 | 0.724 |
| 8 | 6.828 | 3.762 | 2.800 | 0.092 | 2.690 | 3.580 | 11.076 | 0.028 | 0.664 |
| 9 | 9.281 | 8.684 | 19.859 | 0.120 | 3.760 | 4.756 | 11.975 | 0.075 | 0.672 |
| 10 | 6.831 | 12.293 | 21.329 | 0.068 | 3.559 | 4.485 | 10.906 | 0.177 | 0.532 |
| 11 | 7.211 | 12.859 | 2.414 | 0.087 | 3.212 | 5.585 | 3.977 | 0.121 | 0.595 |
| 12 | 9.072 | 10.543 | 5.737 | 0.049 | 3.409 | 2.877 | 8.745 | 0.035 | 0.587 |
| 13 | 7.984 | 9.705 | 10.396 | 0.130 | 2.955 | 5.475 | 13.087 | 0.307 | 0.360 |
| 14 | 17.936 | 18.844 | 1.613 | 0.114 | 3.967 | 4.834 | 12.088 | 0.325 | 0.777 |
| 15 | 18.624 | 19.623 | 1.408 | 0.111 | 5.449 | 4.669 | 21.521 | 0.270 | 0.438 |
| 16 | 31.883 | 9.399 | 1.680 | 0.114 | 9.400 | 5.421 | 33.833 | 0.034 | 0.739 |
| 17 | 21.906 | 15.302 | 2.192 | 0.170 | 6.304 | 3.278 | 14.384 | 0.038 | 0.636 |
| 18 | 11.254 | 6.911 | 2.192 | 0.175 | 5.986 | 3.215 | 12.892 | 0.035 | 0.423 |
| 19 | 21.756 | 5.413 | 21.482 | 0.143 | 4.278 | 5.149 | 13.802 | 0.082 | 0.513 |
| 20 | 8.633 | 11.765 | 4.021 | 0.128 | 2.690 | 5.614 | 12.284 | 0.028 | 0.485 |

**Table 7.** Ion sums, charge balance and consistency checks for each well

| Well | ΣCations (meq/L) | ΣAnions (meq/L) | CBE (%) | CBE Status | EC (µS/cm) | 100·ΣCations / EC | TDS Reported, Derived from EC (mg/L)[a] | TDS Calculated in This Study (mg/L)[b] | TDS Calc. / Reported | TH Calculated in This Study (mg/L as $CaCO_3$)[c] |
|---|---|---|---|---|---|---|---|---|---|---|
| W1 | 28.634 | 20.144 | 17.40 | Recheck | 711 | 4.0 | 455 | 1423 | 3.1 | 906 |
| W2 | 19.834 | 18.272 | 4.10 | Acceptable | 696 | 2.8 | 445 | 1098 | 2.5 | 917 |
| W3 | 28.000 | 28.941 | −1.65 | Acceptable | 411 | 6.8 | 263 | 1690 | 6.4 | 1335 |
| W4 | 43.511 | 41.078 | 2.88 | Acceptable | 842 | 5.2 | 539 | 2558 | 4.7 | 2120 |
| W5 | 23.126 | 20.927 | 4.99 | Acceptable | 673 | 3.4 | 431 | 1260 | 2.9 | 1077 |
| W6 | 25.401 | 22.128 | 6.89 | Acceptable | 431 | 5.9 | 276 | 1331 | 4.8 | 1193 |
| W7 | 46.198 | 18.263 | 43.34 | Recheck | 724 | 6.4 | 463 | 1705 | 3.7 | 1232 |
| W8 | 13.482 | 17.374 | −12.61 | Marginal | 664 | 2.0 | 425 | 992 | 2.3 | 530 |
| W9 | 37.944 | 20.566 | 29.70 | Recheck | 672 | 5.6 | 430 | 1614 | 3.8 | 899 |
| W10 | 40.521 | 19.127 | 35.87 | Recheck | 532 | 7.6 | 340 | 1580 | 4.6 | 957 |
| W11 | 22.571 | 12.895 | 27.28 | Recheck | 595 | 3.8 | 381 | 853 | 2.2 | 1004 |
| W12 | 25.401 | 15.066 | 25.54 | Recheck | 587 | 4.3 | 376 | 1070 | 2.8 | 982 |
| W13 | 28.215 | 21.824 | 12.77 | Marginal | 360 | 7.8 | 230 | 1452 | 6.3 | 885 |
| W14 | 38.507 | 21.214 | 28.95 | Recheck | 777 | 5.0 | 497 | 1521 | 3.1 | 1841 |
| W15 | 39.766 | 31.909 | 10.96 | Marginal | 438 | 9.1 | 280 | 2028 | 7.2 | 1914 |
| W16 | 43.076 | 48.688 | −6.12 | Acceptable | 739 | 5.8 | 473 | 2898 | 6.1 | 2066 |
| W17 | 39.570 | 24.004 | 24.49 | Recheck | 636 | 6.2 | 407 | 1681 | 4.1 | 1862 |
| W18 | 20.532 | 22.128 | −3.74 | Acceptable | 423 | 4.9 | 271 | 1282 | 4.7 | 909 |
| W19 | 48.794 | 23.311 | 35.34 | Recheck | 513 | 9.5 | 328 | 1980 | 6.0 | 1360 |
| W20 | 24.547 | 20.616 | 8.70 | Acceptable | 485 | 5.1 | 310 | 1285 | 4.1 | 1021 |

Note: [a] Reported TDS, derived from EC (equal to 0.64 × EC in all wells), not measured. [b] Calculated in this study as the sum of the major ions with $HCO_3^-$ converted to $CO_3^{2-}$ (× 0.4917) [30]. [c] Calculated in this study: $TH = 2.497\ Ca^{2+} + 4.118\ Mg^{2+}$ [30]; the reported TH (method not specified in the dataset) of each well is compared with these values in Table A4. Ion sums in meq/L are expected to be close to EC/100 [30]. Charge balance error (CBE) status: acceptable |CBE| ≤ 10%, marginal 10–15%, recheck > 15%.

The two further consistency checks fail in all 20 wells: 100 × Σcations exceeds the reported EC by a factor of 2.0–9.5, and the TDS calculated from the major ions (853–2898 mg/L) is 2.2–7.2 times the reported TDS. $SO_4^{2-}$ alone exceeds the reported TDS in 19 of the 20 wells (all except W11). Because TDS was derived from EC, EC and the major-ion concentrations cannot both be correct. Neither a unit conversion nor an offset between rows explains the

discrepancy, because the ratio varies between wells (2.0–9.5) and EC is only weakly correlated with the ion sums (r = 0.26). The TH calculated from $Ca^{2+}$ and $Mg^{2+}$ (mean 1250 mg/L as $CaCO_3$, Table 8) differs from the reported values (mean 1488 mg/L), agrees within 10% only for W6, W10, and W11 (Figure 3(d)), and is incompatible with the value reported for W1 (24.3 mg/L), since $Ca^{2+}$ alone (264 mg/L) corresponds to 659 mg/L as $CaCO_3$.

Because the original laboratory worksheets were not available, individual values could not be corrected: changing reported concentrations on the basis of these checks alone, without documentary evidence, would amount to altering the data. The index values are therefore reported for all 20 wells as calculated from the dataset, together with the CBE status of each well, and the checks failed by each well are listed in Table A4; the effect of replacing the reported TH and TDS by the values calculated from the major ions is assessed in Section 3.5.

### 3.3 GIS maps

GIS integration allows groundwater quality hot spots and higher contamination risk areas to be visualized. The spatial distribution of groundwater quality classifications derived from the WAWQI and CCME-WQI are shown in Figure 4.

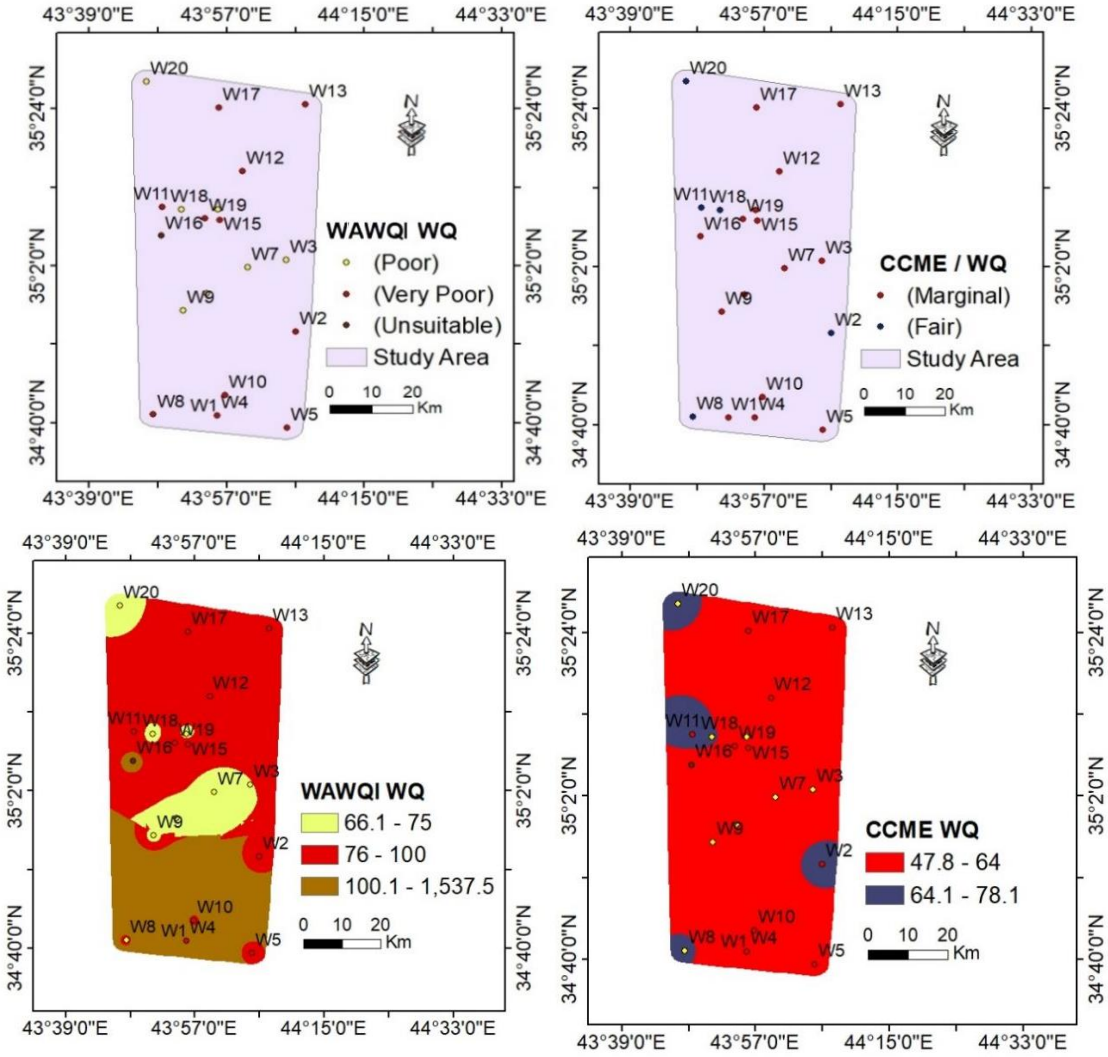



**Figure 4.** GIS-based maps of the provisional Weighted Arithmetic Water Quality Index (WAWQI) and Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) classes

Most groundwater samples have poor, very poor, or unsuitable groundwater quality as shown by the WAWQI map, and this suggests the groundwater quality is very poor in several areas.

The CCME-WQI maps, however, indicate moderate water quality, with some wells exceeding water quality standards, with most rated as marginal to fair.

The variations in space reflected in the two maps highlight the need for GIS to detect hot spots for groundwater quality and to gain insight into how groundwater quality and suitability for drinking water may differ across the region.

The ‘unsuitable’ zone in the south of the WAWQI map is controlled by a single well (W1), whose index is dominated by turbidity (Section 3.5), and should not be read as an area-wide condition.

The interpolated WAWQI surface was computed before the correction of the pH rating, which changes only the class of W8 (from poor to very poor; Section 3.5); in the point maps, W8 is shown with its corrected class (very poor).

### 3.4 Descriptive statistical results

Table 8 provides descriptive statistical analysis of parameters to aid in summarizing the overall groundwater

dataset and to understand the variability among the twenty groundwater wells sampled. Table 9 shows the descriptive statistical indicators (skewness and kurtosis).

| Parameter | T | pH | Turbidity | TH | EC | TDS | $Ca^{2+}$ | $Mg^{2+}$ | $Na^{+}$ | $K^{+}$ | $Cl^{-}$ | $SO_4^{2-}$ | $NO_3^{-}$ | $HCO_3^{-}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Temperature** | 1.000 | -0.683 | -0.294 | -0.080 | -0.212 | -0.212 | -0.300 | 0.207 | -0.070 | -0.371 | -0.001 | -0.186 | 0.295 | -0.301 |
| **pH** | -0.683 | 1.000 | 0.373 | -0.091 | 0.336 | 0.337 | 0.185 | 0.096 | -0.256 | -0.017 | -0.003 | 0.222 | -0.396 | 0.260 |
| **Turbidity** | -0.294 | 0.373 | 1.000 | -0.465 | 0.195 | 0.195 | -0.029 | -0.328 | 0.114 | 0.131 | 0.284 | -0.085 | -0.062 | -0.277 |
| **TH** | -0.080 | -0.091 | -0.465 | 1.000 | 0.363 | 0.363 | 0.796 | 0.014 | 0.043 | 0.046 | -0.182 | 0.564 | -0.238 | 0.710 |
| **EC** | -0.212 | 0.336 | 0.195 | 0.363 | 1.000 | 1.000 | 0.465 | -0.147 | -0.015 | -0.265 | -0.112 | 0.197 | -0.168 | 0.218 |
| **TDS** | -0.212 | 0.337 | 0.195 | 0.363 | 1.000 | 1.000 | 0.465 | -0.147 | -0.017 | -0.266 | -0.113 | 0.197 | -0.170 | 0.219 |
| **$Ca^{2+}$** | -0.300 | 0.185 | -0.029 | 0.796 | 0.465 | 0.465 | 1.000 | 0.143 | -0.097 | 0.164 | 0.005 | 0.775 | -0.079 | 0.785 |
| **$Mg^{2+}$** | 0.207 | 0.096 | -0.328 | 0.014 | -0.147 | -0.147 | 0.143 | 1.000 | -0.432 | -0.130 | -0.035 | 0.241 | 0.436 | 0.250 |
| **$Na^{+}$** | -0.070 | -0.256 | 0.114 | 0.043 | -0.015 | -0.017 | -0.097 | -0.432 | 1.000 | -0.026 | 0.205 | -0.275 | 0.083 | -0.366 |
| **$K^{+}$** | -0.371 | -0.017 | 0.131 | 0.046 | -0.265 | -0.266 | 0.164 | -0.130 | -0.026 | 1.000 | 0.262 | -0.001 | 0.026 | 0.100 |
| **$Cl^{-}$** | -0.001 | -0.003 | 0.284 | -0.182 | -0.112 | -0.113 | 0.005 | -0.035 | 0.205 | 0.262 | 1.000 | -0.031 | 0.454 | -0.286 |
| **$SO_4^{2-}$** | -0.186 | 0.222 | -0.085 | 0.564 | 0.197 | 0.197 | 0.775 | 0.241 | -0.275 | -0.001 | -0.031 | 1.000 | -0.114 | 0.819 |
| **$NO_3^{-}$** | 0.295 | -0.396 | -0.062 | -0.238 | -0.168 | -0.170 | -0.079 | 0.436 | 0.083 | 0.026 | 0.454 | -0.114 | 1.000 | -0.272 |
| **$HCO_3^{-}$** | -0.301 | 0.260 | -0.277 | 0.710 | 0.218 | 0.219 | 0.785 | 0.250 | -0.366 | 0.100 | -0.286 | 0.819 | -0.272 | 1.000 |

**Figure 5.** Pearson correlation matrix of the parameters used

**Table 8.** Descriptive statistical analysis of groundwater quality parameters

| Name | Unit | N | Min. | Max. | Range | Sum | Mean | Median | Std. E | Std. Dev | Variance | CV (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | °C | 20 | 18.6 | 27.8 | 9.2 | 466.9 | 23.3 | 23.4 | 0.7 | 3.3 | 10.9 | 14.1 |
| pH | — | 20 | 6.8 | 8.2 | 1.4 | 148.6 | 7.4 | 7.3 | 0.1 | 0.5 | 0.2 | 6.5 |
| Turbidity | NTU | 20 | 2.3 | 192.0 | 189.7 | 272.6 | 13.6 | 4.3 | 9.4 | 42.0 | 1763.9 | 308.1 |
| TH, reported (method not specified in the dataset) | mg/L | 20 | 24.3 | 2858.3 | 2834.0 | 29760.4 | 1488.0 | 1262.9 | 165.1 | 738.2 | 545004.2 | 49.6 |
| EC | µS/cm | 20 | 360.0 | 842.0 | 482.0 | 11909.0 | 595.5 | 615.5 | 31.1 | 138.9 | 19299.2 | 23.3 |
| TDS, reported (derived from EC) | mg/L | 20 | 230.0 | 539.0 | 309.0 | 7620.0 | 381.0 | 394.0 | 19.9 | 88.9 | 7910.5 | 23.3 |
| $Ca^{2+}$ | mg/L | 20 | 136.8 | 638.9 | 502.1 | 5624.9 | 281.2 | 225.5 | 33.3 | 148.8 | 22152.9 | 52.9 |
| $Mg^{2+}$ | mg/L | 20 | 45.7 | 238.5 | 192.8 | 2662.8 | 133.1 | 123.1 | 12.2 | 54.4 | 2957.8 | 40.8 |
| $Na^{+}$ | mg/L | 20 | 24.9 | 493.9 | 469.0 | 3119.5 | 156.0 | 53.0 | 40.1 | 179.4 | 32175.9 | 115.0 |
| $K^{+}$ | mg/L | 20 | 1.9 | 6.8 | 4.9 | 85.6 | 4.3 | 4.3 | 0.3 | 1.2 | 1.5 | 29.0 |
| $Cl^{-}$ | mg/L | 20 | 96.6 | 199.0 | 102.4 | 2929.7 | 146.5 | 142.9 | 8.7 | 38.7 | 1497.0 | 26.4 |
| $SO_4^{2-}$ | mg/L | 20 | 191.0 | 1625.0 | 1434.0 | 13962.6 | 698.1 | 586.5 | 75.0 | 335.3 | 112439.1 | 48.0 |
| $NO_3^{-}$ | mg/L | 20 | 1.4 | 20.2 | 18.8 | 118.3 | 5.9 | 2.7 | 1.3 | 6.0 | 36.1 | 101.5 |
| $HCO_3^{-}$ | mg/L | 20 | 152.0 | 573.6 | 421.6 | 5688.1 | 284.4 | 251.6 | 25.4 | 113.7 | 12927.8 | 40.0 |
| TH (calculated in this study) | mg/L | 20 | 530.0 | 2119.9 | 1590.0 | 25010.7 | 1250.5 | 1049.1 | 103.0 | 460.6 | 212112.1 | 36.8 |
| TDS (calculated in this study) | mg/L | 20 | 852.6 | 2897.6 | 2045.0 | 31300.2 | 1565.0 | 1486.8 | 112.9 | 504.7 | 254733.9 | 32.2 |

Note: TH (calculated in this study) = 2.497 $Ca^{2+}$ + 4.118 $Mg^{2+}$; TDS (calculated in this study) = sum of the major ions with $HCO_3^{-}$ converted to $CO_3^{2-}$ (× 0.4917) [30]. The reported TDS equals 0.64 × EC, i.e., it was derived from EC and not measured; the method used for the reported TH is not stated in the dataset.

**Table 9.** The descriptive statistical indicators (skewness and kurtosis) and comparison of the means with the reference values used in the indices

| Parameter | Unit | Skewness | Kurtosis | Reference Value | Mean vs. Reference Value |
|---|---|---|---|---|---|
| Temperature | °C | 0.0 | −1.5 | 25 | Below limit |
| pH | — | 0.4 | −1.4 | 6.5–8.5 | Within range |
| Turbidity | NTU | 4.5 | 20.0 | 5 | Exceeds limit |
| TH, reported (method not specified in the dataset) | mg/L | 0.4 | −0.2 | 500 | Exceeds limit |
| EC | µS/cm | −0.1 | −1.1 | 1500 | Below limit |
| TDS, reported (derived from EC) | mg/L | −0.1 | −1.1 | 1000 | Below limit |
| $Ca^{2+}$ | mg/L | 1.2 | 0.5 | 75 | Exceeds limit |
| $Mg^{2+}$ | mg/L | 0.4 | −0.4 | 50 | Exceeds limit |
| $Na^{+}$ | mg/L | 1.3 | −0.1 | 200 | Below limit |
| $K^{+}$ | mg/L | 0.3 | 0.3 | 12 | Below limit |
| $Cl^{-}$ | mg/L | 0.1 | −1.8 | 250 | Below limit |
| $SO_4^{2-}$ | mg/L | 1.7 | 2.9 | 250 | Exceeds limit |
| $NO_3^{-}$ | mg/L | 1.6 | 1.3 | 50 | Below limit |
| $HCO_3^{-}$ | mg/L | 1.1 | 1.0 | 200 | Exceeds limit |
| TH, calculated in this study | mg/L | 0.8 | −0.6 | 500 | Exceeds limit |
| TDS, calculated in this study | mg/L | 1.2 | 1.7 | 1000 | Exceeds limit |

Note: Reference values are those used in the WAWQI and CCME-WQI (Table 1). WHO (2022) does not set health-based guideline values for temperature, TH, EC, $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, or $HCO_3^{-}$. TH and TDS were calculated in this study as shown in Table 8.

Figure 5 shows the Pearson correlation matrix. Descriptive statistics were used because they give vital information about the central tendency (mean, median), dispersion (range, standard deviation, variance), and relative variability (coefficient of variation), which help to identify anomalies in water quality data. There is high variability in some parameters, which suggests spatial heterogeneity and potential localized contamination sources. In the meantime, there is little variation in pH and temperature, indicating relative stability. This statistical method allows for a simplified large dataset and is appropriate for reliable interpretation prior to more in-depth hydro-chemical and GIS analyses. TH and TDS calculated from the major ions are included for comparison with the reported values.

Table 9 (skewness and kurtosis) was used to assess the pattern of distribution of the groundwater quality parameters and their normality and compare the means with the reference values used in the indices (Table 1).

Because several parameters are strongly skewed, the comparison of means is indicative only; for example, the mean turbidity (13.6 NTU) is driven by W1, whereas the median is 4.3 NTU.

Skewness and kurtosis were used to check whether the data are symmetrically distributed and affected by extreme values. The strong positive skewness of turbidity, $SO_4^{2-}$, $NO_3^-$, $Na^+$ and $Ca^{2+}$ indicates outliers or localized hotspots, and the very high kurtosis of turbidity (20.0) reflects the single extreme value at W1. Comparing the means with the reference values identifies turbidity, TH, $Ca^{2+}$, $Mg^{2+}$, $SO_4^{2-}$ and $HCO_3^-$ as the parameters of most concern for drinking use; the mean TDS calculated in this study (1565 mg/L) also exceeds 1000 mg/L, whereas the mean reported TDS (derived from EC; 381 mg/L) does not.

The Pearson correlation matrix shows the statistical relationships between the parameters of groundwater quality that were examined in the study area.

Positive coefficients indicate that two parameters tend to increase together, whereas negative coefficients indicate that one tends to increase as the other decreases. With $n = 20$, coefficients with $|r| \geq 0.444$ are significant at $p < 0.05$ (two-tailed).

The correlation between EC and reported TDS (1.000) is a consequence of the reported TDS having been derived from EC and carries no hydrochemical information. Strong positive correlations between reported TH and $Ca^{2+}$ (0.796), $SO_4^{2-}$ and $HCO_3^-$ (0.819), $Ca^{2+}$ and $HCO_3^-$ (0.785), and $Ca^{2+}$ and $SO_4^{2-}$ (0.775) indicate that the dissolution of carbonate and $SO_4^{2-}$ minerals controls much of the variation in hardness, whereas EC is only weakly correlated with the major ions ($|r| \leq 0.465$).

The moderate correlation between $SO_4^{2-}$ and reported hardness (0.564) supports this interpretation. The negative correlations between pH and $NO_3^-$ (−0.396) and between $Na^+$ and $Mg^{2+}$ (−0.432) are not significant at $p < 0.05$ and are not interpreted further. Correlations involving turbidity are strongly influenced by the single extreme value at W1.

In general, the matrix indicates the major ionic processes affecting groundwater quality variations.

### 3.5 Water quality classifications

Table 10 lists the provisional WAWQI and CCME-WQI values of the 20 wells, calculated with the reported TH and TDS. After the correction of the pH rating, which changed the WAWQI of the three wells with pH below 7 (W8, W13 and W19) and the class of W8 only, the WAWQI ranges from 66.18 to 1537.91: seven wells are poor, eleven very poor and two (W1 and W16) unsuitable. The CCME-WQI ranges from 47.87 to 78.15, with fifteen wells in the marginal class and five (W2, W8, W11, W18 and W20) in the fair class; no well reaches the good class under either index.

The two indices diverge because they aggregate the same exceedances differently. In the WAWQI, the unit weights are inversely proportional to the reference values (Table 1), so turbidity (38.8%), pH (22.8%), $K^+$ (16.2%) and temperature (7.8%) together carry 85.5% of the total weight, whereas the nine salinity- and hardness-related parameters (TH, EC, TDS, $Ca^{2+}$, $Mg^{2+}$, $Na^+$, $Cl^-$, $SO_4^{2-}$ and $HCO_3^-$) carry only 10.7%. A large exceedance of a parameter with a low reference value therefore dominates the result. At W1, turbidity (192 NTU) contributes 96.8% of the WAWQI of 1537.91 (Table 2); with turbidity at the 5 NTU limit, the index would be 88.2 (very poor), so the unsuitable class of W1 reflects turbidity rather than salinity or hardness. At W16, the second unsuitable well, turbidity, $Ca^{2+}$, and pH contribute about 36%, 20%, and 15% of the index. The CCME-WQI, by contrast, gives the same weight to every failed variable and limits the effect of a single extreme excursion through the asymptotic $F_3$ term.

With one sample per well, its value is governed by the number of failed variables (3–7 of 14 in this dataset) and the magnitude of the excursions, which places most wells in the marginal class. Because each well is evaluated independently, excluding the samples with $|CBE| > 15\%$ does not change the index values of the remaining wells, but it reduces the number of points available for interpolation from 20 to 11. Restricting the assessment to the eight wells with $|CBE| \leq 10\%$ gives four poor, three very poor and one unsuitable well (WAWQI) and five marginal and three fair wells (CCME-WQI), i.e., the same overall picture as the full dataset.

Because the reported TH and TDS are inconsistent with the major ions (Section 3.2), the indices were also recalculated with TH and TDS computed from the major ions (Table 7) and with EC omitted, as it cannot be reconciled with the ionic data (Table A5). The WAWQI changed by less than 1 unit in every well except W1 (+2.8), and only W3 changed class (from 75.00 to 75.66, poor to very poor), because TH, TDS and EC together carry less than 1% of the WAWQI weight. The CCME-WQI, in contrast, decreased by 1.1–10.3 units: W1, W4, W16 and W19 fell into the poor class and W2, W18 and W20 from fair to marginal, giving four poor, fourteen marginal and two fair wells. The hardness exceedance does not depend on which TH is used, but the number of wells does: the reported TH (method not specified in the dataset) exceeds 500 mg/L in 19 wells (all except W1, whose reported 24.3 mg/L is inconsistent with its $Ca^{2+}$ concentration), whereas the TH calculated in this study from $Ca^{2+}$ and $Mg^{2+}$ exceeds 500 mg/L in all 20 wells (W1: 906 mg/L). The $SO_4^{2-}$ exceedances (19 wells) are independent of EC, TDS, and TH. The TDS result, in contrast, depends on the data used: the reported TDS (derived from EC) remains below 1000 mg/L in all wells, whereas the TDS calculated in this study from the major ions exceeds 1000 mg/L in 18 wells (all except W8 and W11). With the calculated TH and TDS, the compliance assessment in Table 5(b) would give twelve non-compliant, seven partially compliant, and one mostly compliant well (W11). Both sets of results are therefore reported; all index classes are regarded as provisional screening results, and the CCME-WQI classes should be read together with the consistency checks in Table 7.

**Table 10.** Provisional (screening-level) Water Quality Index (WAWQI) and Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) values, classes and charge-balance status of the 20 wells

| W | WAWQI | Class | CCME-WQI | Class | CBE (%) | CBE Status |
|---|---|---|---|---|---|---|
| 1 | 1537.91 | Unsuitable | 47.87 | Marginal | 17.40 | Recheck |
| 2 | 78.95 | Very poor | 67.79 | Fair | 4.10 | Accepted |
| 3 | 75.00 | Poor | 62.96 | Marginal | −1.65 | Accepted |
| 4 | 91.64 | Very poor | 51.30 | Marginal | 2.88 | Accepted |
| 5 | 79.63 | Very poor | 58.53 | Marginal | 4.99 | Accepted |
| 6 | 68.32 | Poor | 59.23 | Marginal | 6.89 | Accepted |
| 7 | 66.36 | Poor | 56.62 | Marginal | 43.34 | Recheck |
| 8 | 75.63* | Very poor | 68.63 | Fair | −12.61 | Marginal |
| 9 | 68.57 | Poor | 60.13 | Marginal | 29.70 | Recheck |
| 10 | 79.13 | Very poor | 55.25 | Marginal | 35.87 | Recheck |
| 11 | 82.69 | Very poor | 78.15 | Fair | 27.28 | Recheck |
| 12 | 89.80 | Very poor | 55.99 | Marginal | 25.54 | Recheck |
| 13 | 83.32* | Very poor | 61.57 | Marginal | 12.77 | Marginal |
| 14 | 69.42 | Poor | 56.88 | Marginal | 28.95 | Recheck |
| 15 | 83.70 | Very poor | 59.42 | Marginal | 10.96 | Marginal |
| 16 | 109.36 | Unsuitable | 50.81 | Marginal | −6.12 | Accepted |
| 17 | 98.85 | Very poor | 59.33 | Marginal | 24.49 | Recheck |
| 18 | 67.95 | Poor | 65.60 | Fair | −3.74 | Accepted |
| 19 | 92.21* | Very poor | 50.85 | Marginal | 35.34 | Recheck |
| 20 | 66.18 | Poor | 65.90 | Fair | 8.70 | Accepted |

Note: Recalculated with the corrected pH rating (pH < 7); the previous values were 69.55 (W8), 77.24 (W13), and 89.17 (W19). Classes follow Tables 3 and 4. Charge balance error (CBE) status: acceptable |CBE| ≤ 10%, marginal 10–15%, recheck > 15% (Table 7). Index values are provisional screening results calculated with the reported TH (method not specified in the dataset) and TDS (derived from EC); values recalculated with the TH and TDS calculated in this study are given in Table A5.

## 4. DISCUSSION

Groundwater quality east of the Tigris River during the 2025 sampling period reflects the combined influence of the semi-arid climate, agriculture and the reliance on groundwater for domestic and agricultural supply. High levels of TH, $SO_4^{2-}$, $Ca^{2+}$, $Mg^{2+}$ and $Na^{+}$ are consistent with mineral weathering, soil salinity, evaporation and agricultural return flows, although the present data do not allow these sources to be separated.

Figures 3 and 4 show clear spatial variation in the hydro-chemical parameters and index classes; attributing this variation to particular geological formations or activities would require geological and land-use data that were not part of this study. The predominance of poor, very poor, and marginal classes indicates that, at the time of sampling, most of the groundwater did not meet the adopted drinking-water criteria without treatment; whether quality is deteriorating cannot be determined from a single sampling campaign. Similar hydro-chemical problems have been reported for groundwater in Kirkuk [11] and for lake and river water in central Iraq [36, 37].

The groundwater quality data retrieved show that the groundwater quality in many of the wells is poor because of high hardness, $SO_4^{2-}$ and $Ca^{2+}$, and in several wells, elevated turbidity. Spatial variability was observed, with many wells considered to be poor to unsuitable for drinking in the WAWQI assessment and marginal to fair in the CCME-WQI assessment. Similar results were obtained in Hawija and Najaf (Iraq), where groundwater quality was poor to very poor due to high concentrations of EC, TDS, and $SO_4^{2-}$ [38, 39]. Poor to marginal CCME-WQI classes have also been reported for the Tigris River within Baghdad and associated with anthropogenic pollution and salinity [40].

GIS and remote sensing techniques have been used in Kirkuk for air-quality modelling [41-43] and for converting older records to digital form [44].

GIS-based interpolation was useful for visualizing the spatial pattern of the index classes and for identifying wells that require follow-up, such as W1 (turbidity) and W16 ($Ca^{2+}$ and $SO_4^{2-}$). Similar combinations of WQIs and GIS have been applied to groundwater in Upper Egypt [45], integrated index approaches have been applied to river basins [46, 47], and Satellite gravimetry has also been combined with well data to assess groundwater storage in Iraq [22, 48].

With 20 unevenly distributed wells, however, the interpolated surfaces should be read as indicative patterns rather than as predictions at unsampled locations; their uncertainty could be evaluated by cross-validation in future work. Several limitations should be considered when these results are used. Each well was sampled once (in 2025; individual sampling dates were not released), so the CCME-WQI frequency factor cannot describe exceedances over time and no statement about trends is possible. Only physicochemical parameters were measured; microbiological quality and trace elements, which are essential for judging drinking-water safety, were not available. Nine samples have |CBE| > 15%, the EC and reported TDS values are not consistent with the major-ion concentrations, and the hardness reported for W1 is inconsistent with its $Ca^{2+}$ content; these data require verification against the laboratory records. Recalculating TH and TDS from the major ions changes the CCME-WQI class of seven wells (Section 3.5). Finally, the WAWQI is sensitive to the choice of reference values: the low reference values for turbidity, $K^{+}$ and temperature give these parameters a combined weight of 62.7%, although $K^{+}$ and temperature have no health-based guideline values. For these reasons, the index classes are presented as provisional screening results.

## 5. CONCLUSIONS

This study screened the drinking-water suitability of

groundwater from 20 monitoring wells east of the Tigris River, sampled once in 2025, using GIS, the WAWQI, and the CCME-WQI. Groundwater quality varied considerably between wells. Because the sampling dates of the individual wells were not released, the CCME-WQI ($F_1 = F_2$) was used only as a cross-sectional screening measure, and the results describe the 2025 sampling round rather than seasonal or temporal conditions.

TH exceeded 500 mg/L in 19 wells as reported (method not specified in the dataset) and in all 20 wells as calculated in this study, $SO_4^{2-}$ exceeded the adopted limits in 19 wells and $Na^+$ in 6, and $Ca^{2+}$, $Mg^{2+}$ and $HCO_3^-$ exceeded the index reference values in 20, 19 and 15 wells, whereas EC, reported TDS (derived from EC), $Cl^-$, $NO_3^-$ and $K^+$ were within the limits in all wells; the TDS calculated in this study from the major ions, however, exceeded 1000 mg/L in 18 wells. Turbidity exceeded 5 NTU in seven wells and reached 192 NTU at W1. The charge balance was acceptable in eight samples, marginal in three, and outside ±15% in nine, and the reported EC, TDS, and TH are not consistent with the major-ion concentrations. Recalculating TH and TDS from the major ions leaves the WAWQI classes almost unchanged but moves four wells into the CCME-WQI poor class; these data need to be verified against the laboratory records before the results are used for management decisions.

As provisional screening results, the WAWQI classified seven wells as poor, eleven as very poor and two as unsuitable, whereas the CCME-WQI classified fifteen wells as marginal and five as fair. The difference arises mainly from the WAWQI weighting, in which turbidity, pH, $K^+$ and temperature carry 85.5% of the total weight; the unsuitable class of W1, for example, is caused almost entirely by its turbidity.

Using both indices, together with a decomposition of the WAWQI, therefore gives a more informative screening picture than either index alone, and the GIS maps help to locate the wells that require follow-up. These classifications are provisional: they rest on a single sampling round, exclude microbiological and trace-element data, and are based on data whose inconsistencies (charge balance, EC and reported TDS versus the major ions, reported TH) could not be resolved without the laboratory records; they should not be read as a definitive assessment of drinking-water suitability.

For the study area, the results suggest four practical measures: (1) re-sampling of the wells with high turbidity (particularly W1) and of the nine samples with poor ionic balance, including microbiological analyses; (2) regular monitoring of hardness, $SO_4^{2-}$, $Ca^{2+}$ and $Mg^{2+}$, which exceed the limits in most wells; (3) treatment or blending before drinking use where these parameters remain high; and (4) repeated sampling over several seasons, which would allow the CCME-WQI to be applied as intended and changes in groundwater quality to be assessed.

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## REFERENCES

[1] Mishra, R.K. (2023). Fresh water availability and its global challenge. British Journal of Multidisciplinary and Advanced Studies, 4(3): 1-78. https://doi.org/10.37745/bjmas.2022.0207

[2] Nayak, N.P. (2025). Water-related traditional and indigenous practices. In Water Scarcity Management: Enabling Technologies, pp. 207-224. https://doi.org/10.1002/9781394176748.ch13

[3] Jumaah, H.J., Ameen, M.H., Kalantar, B. (2023). Surface water changes and water depletion of Lake Hamrin, Eastern Iraq, using Sentinel-2 images and geographic information systems. Advances in Environmental and Engineering Research, 4(1): 1-11. http://dx.doi.org/10.21926/aeer.2301006

[4] Alao, J.O., Bello, A.Y., Lawal, H.A., Abdullahi, D. (2024). Assessment of groundwater challenge and the sustainable management strategies. Results in Earth Sciences, 2: 100049. https://doi.org/10.1016/j.rines.2024.100049

[5] Olson, K.R., Speidel, D.R. (2024). Tigris, Euphrates, and Shatt Al-Arab River system: Historic and modern attempts to manage and restore Iraq's lifeline. Open Journal of Soil Science, 14(1): 28-63. https://doi.org/10.4236/ojss.2024.141003

[6] Al-Ansari, N., Adamo, N., Hachem, A.H., Sissakian, V., Laue, J., Abed, S.A. (2023). Causes of water resources scarcity in Iraq and possible solutions. Engineering, 15(9): 467-496. https://doi.org/10.4236/eng.2023.159036

[7] Al-Khafaji, M.S., Alwan, I.A., Khalaf, A.G., Bhat, S.A., Kuriqi, A. (2022). Potential use of groundwater for irrigation purposes in the Middle Euphrates region, Iraq. Sustainable Water Resources Management, 8(5): 157. https://doi.org/10.1007/s40899-022-00749-3

[8] Luan, W., Li, X., Kuang, W., et al. (2025). Quantitative assessment of the water stress in the Tigris–Euphrates River Basin driven by anthropogenic impacts. Remote Sensing, 17(4): 662. https://doi.org/10.3390/rs17040662

[9] Hussein, M.A., Sadiq, S., Abudi, Z.N. (2025). Assessment of sulfate and chloride concentrations in groundwater and their impact on public health and the environment in Iraq: A review. Al-Rafidain Journal of Engineering Sciences, 3(2): 69-79. https://doi.org/10.61268/88xcps56

[10] Habbeb, M.G., Sulyman, M.H., Jumaah, H.J. (2022). Modeling water quality index using geographic information systems and weighted arithmetic index in Kirkuk, Iraq. Pollution Research, 41(1): 323-327. http://doi.org/10.53550/PR.2022.v41i01.047

[11] Jumaah, H.J., Mohammed, A., Ameen, M.H., Jumaah, S.J. (2023). GIS-based evaluation of groundwater quality as drinking water in Kirkuk, Iraq. Indian Journal of Environmental Protection, 43(7): 622-628.

[12] Dutta, R., Saikia, J. (2025). A mini review on water quality assessment methods for cations and anions in natural water sources. ISAR Journal of Science and Technology, 3(6): 45-50. https://doi.org/10.5281/zenodo.15761027

[13] Wali, S.U., Usman, A.A., Usman, A.B., Abdullahi, U., Mohammed, I.U., Hayatu, J.M. (2024). Impact of geology on hydrogeological and hydrochemical characteristics of groundwater in tropical environments: A narrative review. International Journal of Hydrology, 8(6): 202-221. https://doi.org/10.15406/ijh.2024.08.00392

[14] Gad, M., Saleh, A.H., Hussein, H., Farouk, M., Elsayed, S. (2022). Appraisal of surface water quality of Nile river using water quality indices, spectral signature and multivariate modeling. Water, 14(7): 1131. https://doi.org/10.3390/w14071131
[15] Patel, P.S., Pandya, D.M., Shah, M. (2023). A systematic and comparative study of water quality index (WQI) for groundwater quality analysis and assessment. Environmental Science and Pollution Research, 30(19): 54303-54323. https://doi.org/10.1007/s11356-023-25936-3
[16] Swain, L.G. (2024). The evolution of the Canadian (CCME) water quality index. Water Quality Research Journal, 59(4): 342-346. https://doi.org/10.2166/wqrj.2024.052
[17] Al-Madany, H. (2025). Evaluation of water quality index in the Euphrates River, Iraq: By using the weighted arithmetic method. Association of Arab Universities Journal of Engineering Sciences, 32(3): 12-18. https://doi.org/10.33261/jaaru.2025.32.3.002
[18] Mshelia, Y.M., Lawan, D.M., Arhyel, M., Inuwa, J. (2023). Physicochemical analysis and water quality assessment of selected location in Maiduguri metropolis using weighted arithmetic water quality index. FUDMA Journal of Sciences, 7(4): 147-151. https://doi.org/10.33003/fjs-2023-0704-1899
[19] Das, A. (2026). Data analytics and integration of CCME-water quality index, water pollution index (WPI): And contamination index (CI) with GIS approach for a better understanding of drinking water quality. In Data Analytics and Remote Sensing-Based Analysis for Sustainable Development, Springer Nature Switzerland, Cham, pp. 39-63. https://doi.org/10.1007/978-3-031-98095-4_4
[20] Panagopoulos, Y., Alexakis, D.E., Skoulikidis, N.T., Laschou, S., Papadopoulos, A., Dimitriou, E. (2022). Implementing the CCME water quality index for the evaluation of the physicochemical quality of Greek rivers. Water, 14(17): 2738. https://doi.org/10.3390/w14172738
[21] Papazotos, P., Vlachomitrou, M., Psarraki, D., Vasileiou, E., Perraki, M. (2025). Coupling advanced geo-environmental indices for the evaluation of groundwater quality: A case study in NE Peloponnese, Greece. Environments, 12(1): 14. https://doi.org/10.3390/environments12010014
[22] Mohammed, H.K., Al-Khafaji, M.S., Alwan, I.A. (2025). Analysis of groundwater storage at the local scale in the Missan Region, Iraq, based on GRACE satellite and well data. Geosciences, 15(3): 91. https://doi.org/10.3390/geosciences15030091
[23] Bushero, D.M., Angello, Z.A., Behailu, B.M. (2022). Evaluation of hydrochemistry and identification of pollution hotspots of little Akaki River using integrated water quality index and GIS. Environmental Challenges, 8: 100587. https://doi.org/10.1016/j.envc.2022.100587
[24] Mohammed, H.K., Alwan, I.A., Al-Khafaji, M.S. (2025). Integrating satellite imagery with in-situ data to monitor groundwater storage: A case study of the Dibdibba aquifer in Iraq. In International Symposium in Environmental Science and Industrial Ecology, Springer Nature Singapore, Singapore, pp. 287-295. https://doi.org/10.1007/978-981-96-1578-0_22
[25] Rawat, K.S., Jacintha, T.G.A., Singh, S.K. (2018). Hydro-chemical survey and quantifying spatial variations in groundwater quality in coastal region of Chennai, Tamilnadu, India–A case study. The Indonesian Journal of Geography, 50(1): 57-69. https://doi.org/10.22146/ijg.27443
[26] Singh, P., Verma, P. (2019). A comparative study of spatial interpolation technique (IDW and Kriging) for determining groundwater quality. In GIS and Geostatistical Techniques for Groundwater Science, pp. 43-56. https://doi.org/10.1016/B978-0-12-815413-7.00005-5
[27] World Health Organization. (2022). Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda. World Health Organization, Geneva.
[28] Abbas, H.A. (2025). Iraqi drinking water quality standards (IQS 417/2009)–revisited. Tikrit Journal of Engineering Sciences, 32(1): 1-7. https://doi.org/10.25130/tjes.32.1.23
[29] Hounslow, A.W. (1995). Water Quality Data: Analysis and Interpretation. Lewis Publishers, Boca Raton, FL.
[30] APHA American Public Health Association. (1998). Standard Methods for the Examination of Water and Wastewater, 20th ed. (Sections 1030 E and 2340 B). APHA, Washington, DC.
[31] World Health Organization Regional Office for the Eastern Mediterranean. (2006). A compendium of drinking-water quality standards in the Eastern Mediterranean Region (WHO-EM/CEH/143/E). WHO Regional Centre for Environmental Health Activities (CEHA).
[32] Freeze, R.A., Cherry, J.A. (1979). Groundwater. Prentice-Hall, Englewood Cliffs, NJ.
[33] Brown, R.M., McClelland, N.I., Deininger, R.A., O'Connor, M.F. (1972). A water quality index—Crashing the psychological barrier. In Indicators of Environmental Quality, Springer US, Boston, MA, pp. 173-182. https://doi.org/10.1007/978-1-4684-2856-8_15
[34] Tiwari, T.N., Mishra, M.A. (1985). A preliminary assignment of water quality index of major Indian rivers. Indian Journal of Environmental Protection, 5(4): 276-279.
[35] Canadian Council of Ministers of the Environment (CCME). (2001). Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0. User's Manual.
[36] Al-Kubaisi, M.H. (2020). Hydrochemical facies description to assess the water quality of Habbaniya Lake, Iraq. The Iraqi Geological Journal, 53(2F): 94-107. https://doi.org/10.46717/igj.53.2F.7Ms-2020-12-30
[37] Abbas, A.A.A., Hassan, F.M. (2018). Water quality assessment of Euphrates River in Qadisiyah province (Diwaniyah River), Iraq. The Iraqi Journal of Agricultural Science, 49(2): 251-261.
[38] Al-Kilabi, J.A. (2013). Hydrogeochemistry of groundwater and the probable effect of Kirkuk irrigation project on its quality in Al-Hawija area, Iraq. College of Sciences, University of Baghdad.
[39] Alikhan, H.A., Hussein, A.K., Alshukri, A.S. (2020). Groundwater quality assessment using water quality index: A case study of Al Najaf City, Iraq. Periodicals of Engineering and Natural Sciences, 8(3): 1482-1490. https://doi.org/10.21533/pen.v8.i3.1188
[40] Majeed, O.S. (2024). Evaluation of Tigris River water quality within Baghdad City using the CCME index for

various purposes. International Journal of Aquatic Biology, 12(4): 360-373. https://doi.org/10.22034/ijab.v12i4.2274
[41] Jumaah, H.J., Kamran, K.V., Hasan, W.A., Ibraheem, Z.H. (2026). A comprehensive research of air quality modeling methods: A case study Kirkuk, Iraq. NTU Journal of Engineering and Technology, 5(1). https://doi.org/10.56286/3djjdv04
[42] Salih, A.S., Hassan, N.D. (2023). The impact of urban trees on air pollution in Kirkuk City: A Gaussian dispersion model approach. NTU Journal of Engineering and Technology, 2(4). https://doi.org/10.56286/ntujet.v2i4.602
[43] Salih, A.S., Hassan, N.D., Abdulmajeed, N.S. (2025). Air pollution dispersion modeling from point sources using Gaussian plume model: A case study of Kirkuk, Iraq. Tikrit Journal of Engineering Sciences, 32(1): 1-15. https://doi.org/10.25130/tjes.32.1.10
[44] Abdalhadee, H.M., Hassan, N.D. (2024). Re-browsing the old calendar with a modern digital one using GIS-RS programs and updating it to its digital form. NTU Journal of Engineering and Technology, 3(3). https://doi.org/10.56286/ntujet.v3i3.990
[45] Rabeiy, R.E. (2018). Assessment and modeling of groundwater quality using WQI and GIS in Upper Egypt area. Environmental Science and Pollution Research, 25(31): 30808-30817. https://doi.org/10.1007/s11356-017-8617-1
[46] Qian, Y., Zhou, J., Chen, J., Chen, J., Liu, Z., Jin, H. (2026). Improved entropy-AHP-TOPSIS method in comparison to traditional methods for assessing reclaimed water's impact on river water quality and ecological health. Scientific Reports, 16: 20628. https://doi.org/10.1038/s41598-026-50296-6
[47] Das, A. (2026). An integrated water quality assessment and its prediction utilizing the CWQI, CRITIC based-improved CWQI, sensitivity analysis, multivariate techniques, machine learning algorithms and GIS approaches to determine pollution intensities in the river basin (Odisha). Environmental Science and Pollution Research, 33(10): 4325-4362. https://doi.org/10.1007/s11356-026-37531-3
[48] Mohammed, H.K., Alwan, I.A., Al-Khafaji, M.S. (2025). Comparative analysis of spatiotemporal variability of groundwater storage in Iraq using GRACE satellite data. Hydrology, 12(4): 69. https://doi.org/10.3390/hydrology12040069

## NOMENCLATURE

| | |
|---|---|
| CBE | Charge Balance Error, % |
| CCME-WQI | Canadian Council of Ministers of the Environment Water Quality Index |
| CV | Coefficient of Variation, % |
| EC | Electrical Conductivity, µS/cm |
| $F_1$ | Scope factor, % |
| $F_2$ | Frequency factor, % |
| $F_3$ | Amplitude factor |
| GIS | Geographic Information System |
| IDW | Inverse Distance Weighting |
| IQS | Iraqi Quality Standard |
| K | WAWQI proportionality constant |
| meq/L | Milliequivalents per liter |
| nse | Normalized sum of excursions |
| $C_i$, $S_i$ | Value and objective of a failed test (CCME-WQI) |
| NTU | Nephelometric Turbidity Unit |
| $q_n$ | Quality rating |
| $S_n$ | Reference value |
| Std. Dev. | Standard Deviation |
| T | Temperature, ℃ |
| TDS | Total Dissolved Solids, mg/L |
| TH | Total Hardness, mg/L |
| $V_n$ | Measured parameter value |
| W | Monitoring well |
| $W_n$ | Unit weight of parameter n |
| WAWQI | Weighted Arithmetic Water Quality Index |
| WQI | Water Quality Index |
| WHO | World Health Organization |

### Chemical symbols

| | |
|---|---|
| $Ca^{2+}$ | Calcium ion, mg/L |
| $Cl^-$ | Chloride ion, mg/ L |
| $HCO_3^-$ | Bicarbonate ion, mg/L |
| $K^+$ | Potassium ion, mg/L |
| $Mg^{2+}$ | Magnesium ion, mg/L |
| $Na^+$ | Sodium ion, mg/L |
| $NO_3^-$ | Nitrate ion, mg/L |
| pH | Potential of Hydrogen |
| $SO_4^{2-}$ | Sulfate ion, mg/L |

### Greek symbol

| | |
|---|---|
| Σ | Summation |
| ΣAnions | Sum of anion concentrations, meq/L |
| ΣCations | Sum of cation concentrations, meq/L |

### Subscript

| | |
|---|---|
| i | Ideal value ($V_i$); individual test ($C_i$, $S_i$) |
| n | Parameter number |

## APPENDIX

**Table A1.** Corrections applied to the calculation workbook during checking

| # | Sheet | What was Wrong | Corrected Formula | Reference |
|---|---|---|---|---|
| 1 | WAWQI | pH q-value used the linear formula $(V_n - 7)/(8.5 - 7)\cdot 100$, which yields a negative $q_n$ for pH < 7. | $qpH = \|V_n - 7\|/(8.5 - 7)\cdot 100$, later replaced by the piecewise rating (see note) | [33] |
| 2 | Ion_Conversion_meqL | CBE formula multiplied by 100·2 (×200), doubling the CBE scale. | CBE % = (Σcations − Σanions)/(Σcations + Σanions)·100 | [29, 32] |

Note: The absolute-deviation pH rating of correction 1 gives qpH = 33.3 at pH 6.5; it was replaced in the manuscript by a piecewise rating (Section 2.5), which affects only W8, W13 and W19 (pH < 7; Table 10).

**Table A2.** Index formulas verified in the calculation workbook

| Index | Formula in Workbook (Verified) | Reference |
|---|---|---|
| WAWQI | $WAWQI = \Sigma(W_n \cdot qn)/\Sigma W_n$; $Wn = K/S_n$; $K = 1/\Sigma(1/S_n)$ | [33, 34] |
| CCME-WQI | $WQI = 100 - \sqrt{(F_1^2 + F_2^2 + F_3^2)}/1.732$; $F_3 = nse/(0.01 \cdot nse + 0.01)$; pH dual bound 6.5/8.5 | [35] |

**Table A3.** Status of each parameter in the dataset (reported, derived or calculated)

| Parameter | Unit | Status in the Dataset | Remarks |
|---|---|---|---|
| T, pH, turbidity, EC | °C, –, NTU, µS/cm | Reported in the agency dataset | Single sampling round in 2025; sampling dates of the individual wells not released. |
| $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$ | mg/L | Reported in the agency dataset (laboratory analysis) | Checked by the charge balance (Table 7). |
| $Cl^{-}$, $SO_4^{2-}$, $NO_3^{-}$, $HCO_3^{-}$ | mg/L | Reported in the agency dataset (laboratory analysis) | Checked by the charge balance (Table 7). |
| TH, reported | mg/L as $CaCO_3$ | Reported in the agency dataset; method not specified in the dataset | Not reproducible from $Ca^{2+}$ and $Mg^{2+}$; TH calculated in this study is given in Tables 5, 7, 8 and 9. |
| TDS, reported | mg/L | Reported in the agency dataset; derived from EC (not measured) | Equal to 0.64 × EC in all wells; TDS calculated in this study is given in Tables 5, 7, 8 and 9. |
| meq/L values, ion sums, CBE | meq/L, % | Calculated in this study | Hounslow [29]; CBE as defined in Section 2.3. |
| TH and TDS, calculated in this study | mg/L | Calculated in this study | Standard Methods 2340 B and 1030 E [30]. |

Note: The dataset was provided by the General Commission for Groundwater – Kirkuk as secondary data; laboratory protocols, instrument specifications, detection limits, and replicate records were not part of it. Analytical reliability was therefore assessed with the data-based checks of Table 7 and Table A4. TH: Total hardness; TDS: Total dissolved solids.

**Table A4.** Well-by-well consistency check of the reported data (Standard Methods 1030 E and 2340 B [30]); samples of the single 2025 sampling round

| Well | $Ca^{2+}$ | $Mg^{2+}$ | TH calc. (this Study) | Σions (mg/L) | TDS calc. (this Study) | TDS rep. (from EC) | TDS calc./rep. | EC (µS/cm) | 100·Σcat | 100·Σcat / EC | CBE (%) | Checks Failed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| W1 | 264.0 | 60.0 | 906 | 1500 | 1423 | 455 | 3.1 | 711 | 2863 | 4.0 | 17.40 | CBE, EC, TDS, TH, $SO_4$ > TDS |
| W2 | 176.0 | 116.0 | 917 | 1217 | 1098 | 445 | 2.5 | 696 | 1983 | 2.8 | 4.10 | EC, TDS, TH, $SO_4$ > TDS |
| W3 | 185.0 | 212.0 | 1335 | 1849 | 1690 | 263 | 6.4 | 411 | 2800 | 6.8 | −1.65 | EC, TDS, TH, $SO_4$ > TDS |
| W4 | 580.0 | 163.1 | 2120 | 2815 | 2558 | 539 | 4.7 | 842 | 4351 | 5.2 | 2.88 | EC, TDS, TH, $SO_4$ > TDS |
| W5 | 243.0 | 114.2 | 1077 | 1432 | 1260 | 431 | 2.9 | 673 | 2313 | 3.4 | 4.99 | EC, TDS, TH, $SO_4$ > TDS |
| W6 | 225.5 | 152.8 | 1193 | 1517 | 1331 | 276 | 4.8 | 431 | 2540 | 5.9 | 6.89 | EC, TDS, $SO_4$ > TDS |
| W7 | 360.1 | 80.9 | 1232 | 1838 | 1705 | 463 | 3.7 | 724 | 4620 | 6.4 | 43.34 | CBE, EC, TDS, TH, $SO_4$ > TDS |
| W8 | 136.8 | 45.7 | 530 | 1075 | 992 | 425 | 2.3 | 664 | 1348 | 2.0 | −12.61 | CBE, EC, TDS, TH, $SO_4$ > TDS |
| W9 | 186.0 | 105.6 | 899 | 1731 | 1614 | 430 | 3.8 | 672 | 3794 | 5.6 | 29.70 | CBE, EC, TDS, TH, $SO_4$ > TDS |
| W10 | 136.9 | 149.4 | 957 | 1690 | 1580 | 340 | 4.6 | 532 | 4052 | 7.6 | 35.87 | CBE, EC, TDS, $SO_4$ > TDS |
| W11 | 144.5 | 156.3 | 1004 | 952 | 853 | 381 | 2.2 | 595 | 2257 | 3.8 | 27.28 | CBE, EC, TDS |
| W12 | 181.8 | 128.2 | 982 | 1176 | 1070 | 376 | 2.8 | 587 | 2540 | 4.3 | 25.54 | CBE, EC, TDS, TH, $SO_4$ > TDS |
| W13 | 160.0 | 118.0 | 885 | 1544 | 1452 | 230 | 6.3 | 360 | 2822 | 7.8 | 12.77 | CBE, EC, TDS, TH, $SO_4$ > TDS |
| W14 | 359.4 | 229.0 | 1841 | 1644 | 1521 | 497 | 3.1 | 777 | 3851 | 5.0 | 28.95 | CBE, EC, TDS, TH, $SO_4$ > TDS |
| W15 | 373.2 | 238.5 | 1914 | 2197 | 2028 | 280 | 7.2 | 438 | 3977 | 9.1 | 10.96 | CBE, EC, TDS, TH, SO4>TDS |
| W16 | 638.9 | 114.2 | 2066 | 3189 | 2898 | 473 | 6.1 | 739 | 4308 | 5.8 | −6.12 | EC, TDS, TH, $SO_4$ > TDS |
| W17 | 439.0 | 186.0 | 1862 | 1876 | 1681 | 407 | 4.1 | 636 | 3957 | 6.2 | 24.49 | CBE, EC, TDS, TH, $SO_4$ > TDS |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| W18 | 225.5 | 84.0 | 909 | 1467 | 1282 | 271 | 4.7 | 423 | 2053 | 4.9 | −3.74 | EC, TDS, TH, $SO_4$ > TDS |
| W19 | 436.0 | 65.8 | 1360 | 2113 | 1980 | 328 | 6.0 | 513 | 4879 | 9.5 | 35.34 | CBE, EC, TDS, TH, $SO_4$ > TDS |
| W20 | 173.0 | 143.0 | 1021 | 1368 | 1285 | 310 | 4.1 | 485 | 2455 | 5.1 | 8.70 | EC, TDS, TH, $SO_4$ > TDS |

Note: TH calc. and TDS calc. are calculated in this study: TH = 2.497 $Ca^{2+}$ + 4.118 $Mg^{2+}$; TDS = Σions − 0.5083 $HCO_3^-$. TDS rep. is the reported TDS, derived from EC (0.64 × EC); the reported TH (method not specified in the dataset) is shown in Figure 3(d). Ion sums in meq/L are expected to approximate EC/100 [30]. Checks failed: CBE |CBE| > 10%; EC 100·Σcat/EC outside about 0.9–1.1; TDS calculated exceeds reported TDS by more than 20%; TH reported (method not specified in the dataset; Figure 3(d)) differs from the calculated TH by more than 10%; $SO_4$ > TDS sulfate alone exceeds reported TDS. Concentrations in mg/L; TH in mg/L as $CaCO_3$.

**Table A5.** Sensitivity of the provisional index values to the inconsistent parameters: reported TH and TDS replaced by the TH and TDS calculated in this study, EC omitted (13 parameters, reference values of Table 1)

| Well | WAWQI (Table 10) | Class | WAWQI (Scenario) | Class | CCME-WQI (Table 10) | Class | CCME-WQI (Scenario) | Class |
|---|---|---|---|---|---|---|---|---|
| W1 | 1537.91 | U | 1540.72 | U | 47.87 | M | 37.58 | P |
| W2 | 78.95 | VP | 79.29 | VP | 67.79 | F | 59.13 | M |
| W3 | 75.00 | P | 75.66 | VP | 62.96 | M | 54.22 | M |
| W4 | 91.64 | VP | 91.55 | VP | 51.30 | M | 43.78 | P |
| W5 | 79.63 | VP | 78.99 | VP | 58.53 | M | 51.65 | M |
| W6 | 68.32 | P | 68.53 | P | 59.23 | M | 50.69 | M |
| W7 | 66.36 | P | 65.68 | P | 56.62 | M | 49.71 | M |
| W8 | 75.63 | VP | 75.28 | VP | 68.63 | F | 67.54 | F |
| W9 | 68.57 | P | 68.51 | P | 60.13 | M | 51.82 | M |
| W10 | 79.13 | VP | 79.44 | VP | 55.25 | M | 45.81 | M |
| W11 | 82.69 | VP | 82.81 | VP | 78.15 | F | 76.68 | F |
| W12 | 89.80 | VP | 89.84 | VP | 55.99 | M | 47.13 | M |
| W13 | 83.32 | VP | 83.55 | VP | 61.57 | M | 52.78 | M |
| W14 | 69.42 | P | 69.97 | P | 56.88 | M | 47.91 | M |
| W15 | 83.70 | VP | 84.47 | VP | 59.42 | M | 51.01 | M |
| W16 | 109.36 | U | 109.27 | U | 50.81 | M | 43.31 | P |
| W17 | 98.85 | VP | 98.99 | VP | 59.33 | M | 52.09 | M |
| W18 | 67.95 | P | 67.97 | P | 65.60 | F | 58.05 | M |
| W19 | 92.21 | VP | 91.74 | VP | 50.85 | M | 42.97 | P |
| W20 | 66.18 | P | 66.22 | P | 65.90 | F | 58.19 | M |

Note: Classes: E-excellent, G-good, P-poor, VP-very poor, U-unsuitable (WAWQI, Table 3), F-fair, M-marginal (CCME-WQI, Table 4). Scenario values were computed with the same procedure as in Table 10; when applied to the original inputs, this procedure reproduces all values in Table 10 within ±0.04.