Evaluation of groundwater quality in central Saudi Arabia using hydrogeochemical characteristics and pollution indices

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Abstract

The groundwater quality and heavy metal contamination were evaluated in thirty palm farms, central Saudi Arabia using pollution indices, irrigation quality parameters, and multivariate statistical analyses. The results showed that the average values of TDS, Ca^{+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, and F^{-} were greater than the permissible limits of the WHO standards for drinking water. The groundwater facies types were Ca–Na–SO_4–Cl (23 samples), Ca–Cl–SO_4, (4 samples), and Ca–SO_4–Cl type (3 samples). The groundwater quality index indicated that 15 groundwater samples were of good quality and 15 were of poor quality, whereas the metal index and heavy metal pollution index indicated that all samples were categorized as slightly affected and with low pollution, respectively. The variation is attributed to the increasing average values of some ions and decreasing HMs. The dissolution/precipitation of silicates, gypsum, and carbonates, and soil leaching were the natural factors affecting groundwater chemistry, whereas higher PO_4^{3-}, NO_3^{-}, F^{-}, Pb, and Zn values in some samples may be attributed to human activities from the extensive use of fertilizers and pesticides on the investigated farms.

Introduction

Groundwater is a critical resource for domestic and agricultural needs, especially in arid countries, where the geochemical processes resulting from aquifer–water interaction often control its quality in such minimal rainfall recharge (Alharbi 2018). The accumulation of heavy metals (HMs) in water resources is potentially harmful to human health, because of their accumulative characteristics, toxicity, and contamination of food sources. Therefore, the pollution of water resources with HMs has become a global problem (Hardaway et al. 2004; Sarkar et al. 2010; Alshahri and El-Taher 2018).

The thick Mesozoic and Cenozoic sedimentary rocks function as a prolific aquifer for groundwater in central Saudi Arabia (Alharbi and Zaidi 2018). Overdependence on groundwater resources, especially in arid countries, often leads to decreased groundwater levels and deteriorates its quality (Alharbi 2018). The rapid population growth in and extension of agricultural activities around Saudi Arabia have increased the need for freshwater resources (Khanfar 2008; Al-Hammad and Abd El-Salam 2016). Saudi Arabia is the second-largest producer of the date palm (Sueleman 2014; Salama et al. 2019). The Al Uyaynah-Al Jubailah region (Fig. 1) is located 40–55 km northwest of Riyadh, inside the narrow, dry riverbed of Wadi Hanifa, which continues southwards through Dir'iyyah and Riyadh.

The Al Uyaynah-Al Jubailah region has many agricultural farms producing several types of dates, leafy green plants (e.g., lettuce, arugula, and radish), vegetables (e.g., pepper, eggplant, tomato, watermelon, onion, and potato), and fruits (e.g., citrus, orange, pomegranate, lemon, and grapes). As groundwater is an important source of HMs for these plants and can reach humans directly or indirectly, this study evaluates the groundwater quality and HM contamination in some palm farms in central Saudi Arabia in the Al Uyaynah-Al Jubailah region and documents the possible sources of contamination, using hydrogeochemical characteristics, pollution indices, and multivariate analyses.

Methods And Materials

A total of 30 groundwater samples were collected from 25 to 100 m-deep wells in Al Uyaynah-Al Jubailah farms, central Saudi Arabia (Fig. 1). Samples were collected in high-density polyethylene sampling bottles that were washed with 5% nitric acid and rinsed with distilled water (Salifu et al. 2015). Geologically, the carbonates of the Upper Jurassic Hanifa, Jubaila, and Arab formations and Quaternary sediments dominate the study area (Al Husseini and Mathews 2005; Hussein et al. 2012). The Hanifa Formation consists of a lower muddy carbonate unit and an upper stromatoporoid and lagoonal carbonate unit, and disconformably overlies the Tuwaiq Mountain Formation. The Jubaila Formation consists of moderately deep marine carbonates overlain by a shallow marine stromatoporoid-associated assemblage and disconformably lies on the Hanifa Formation (Power et al. 1966; Hughes 2009). Twenty samples were collected from wells drilled in Quaternary sediments, nine in Jubaila limestone, and one in the Hanifa Formation (Fig. 2). The hydrogeochemical parameters (pH, electrical conductivity (EC), and TDS), ions (SiO_2, Cl^-, NO_3^-, F^-, PO_4^{3-}, SO_4^{2-}, and HCO_3^-, Mg^{2+}, Ca^{2+}, K^+, and Na^+), and HMs (Hg, Al, Sb, Cu, Cr, B, Pb, Ni, Se, Cd, As, Zn) were analyzed in the laboratories of King Saud University. The hydrogen ion concentration (pH) and EC were measured using pH and EC meters, respectively. Sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) were determined using an atomic absorption spectrophotometer. Bicarbonate (HCO_3^-) and chloride (Cl^-) were analyzed using volumetric methods. Sulfate (SO_4^{2-}) was estimated using colorimetric and turbidimetric methods. Nitrate (NO_3^-) was measured using an ultraviolet–visible spectrophotometer. F^- was determined using a fluoride-selective electrode. HMs were determined using an inductively coupled plasma-mass spectrometer.

The Piper plot was prepared to determine the groundwater facies. The groundwater quality index (GWQI), heavy metal pollution index (HPI), and metal index (MI) were used as pollution indices to document water quality. The status of groundwater for irrigation was measured using the sodium percentage (Na%), Kelly's ratio (KR), salinity hazard (EC), and sodium adsorption ratio (SAR) (Richards, 1954; Doneen, 1964; Kelly, 1963; Raghunath, 1987). Tables 1 and 2 show the procedures and classification of these indices and parameters. Supplementary Table 1 shows the coordinates of groundwater boreholes (samples), hydrogeochemical parameters, major anions, major cations, and HMs. Statistical analyses were conducted using SPSS software. Principal component analysis (PCA), Pearson's correlation coefficients, and hierarchical cluster analysis (HCA; Q and R-modes) were used to identify the possible sources of HMs in the groundwater samples investigated (Alfaifi et al. 2021; Alshehri et al. 2021).

Results And Discussion

Hydrogeochemical characteristics

Table 3 shows the hydrogeochemical dataset. The groundwater pH ranges from 6.5 (sample 25) to 7.8 (sample 21), with an average of 7.3, implying slightly basic to slightly acidic waters, and falls within the standards prescribed for drinking water (WHO 2014). In assessing the groundwater quality for irrigation, TDS is a critical parameter (Salifu et al. 2015), varying from 1,088 mg/l in sample 25 to 3,815 mg/l in sample 14, with an average of 2,334 mg/l, indicating values greater than the acceptable limits (1,000 mg/l) of the World Health Organization (WHO 2011). Regarding irrigation criteria (Ayers and Westcott 1985; UCCC 1974), 8 samples were categorized as slight to moderate (TDS = 450–2,000 mg/l) and 20 samples were severe (TDS > 2,000 mg/l). In drinking water, TDS higher than 500 mg/l could cause gastrointestinal infections in consumers (Dar et al. 2011; Gnanachandrasamy et al. 2018).

Ca^{2+} was the most abundant cation (average 443 mg/l), followed by Na^{+} (average 236 mg/l), K^{+} (average 42 mg/l), and Mg^{2+} (average 28 mg/l). The anions were dominated by SO_4^{2-} (average 1,016 mg/l), followed by Cl^{-} (average 456 mg/l), HCO_3^{-} (average 100 mg/l), NO_3^{-} (average 14 mg/l), F^{-} (average 1.65 µg/l), and PO_4^{3-} (average 0.0219 mg/l). The average values of Ca^{+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, and F^{-} were greater than the permissible limits of WHO standards for drinking water (Table 2). The higher values of these cations and anions could be attributed to the ion exchange reactions or silicate weathering (Li et al. 2016a).

The saturation indices of halite, dolomite, anhydrite, gypsum, calcite, and aragonite were negative (Supplementary Table 1, Fig. 3), indicating undersaturated conditions regarding the capacity of groundwater to dissolve more minerals (Yidana et al. 2010). Some gypsum and calcite samples were almost close to the saturation phase because of the prolonged interaction of groundwater with carbonate aquifers and gypsiferous layers (Deutsch and Siegel 1997). All groundwater samples fell within the Ca-dominant type on the cationic triangle, whereas 90% fell within the SO_4-dominant type, 4% within the Cl-dominant type, and 6% within the nondominant type on the anionic triangle (Fig. 4). SO_4^{2-}, Ca^{2+}, Cl^{-}, and Na^{+} were the most dominant ions, and based on their dominance, the groundwater facies were classified into three types (Fig. 4): Ca–Na–SO_4–Cl (23 samples), Ca–Cl–SO_4, (4 samples), and Ca–SO_4–Cl (3 samples), indicating carbonates and gypsum dissolution/precipitation influences (Kumar, 2014).

Irrigation water quality

The palm forms in the Al Uyaynah-Al Jubailah region depend primarily on groundwater for irrigation; therefore, it is important to evaluate the quality and suitability of groundwater for agricultural use. Na%, SAR, PI, KR, and MR were used as parameters for this evaluation (Table 2, Supplementary Table 2). The Na% is considered an indicator of the soluble sodium content that reacts with the soil to decrease permeability (Janardhana Raju et al. 1992). Values of Na% varied from 8.21% to 47.63%, with an average of 28.97%. Six samples were excellent, 21 were good, and three were in the permissible range, implying that the groundwater is suitable for irrigation.

The SAR ranged from 3.29 to 32.49, with an average of 14.95. The groundwater samples were classified as excellent for irrigation (13 samples), good for irrigation (4 samples), doubtful for irrigation (11 samples), and unsuitable (13 and 14). The average value of Na^{+} (235.59 mg/l) was greater than the permissible limit of WHO standards (2011) for drinking water (200 mg/l). Samples 13 and 14 were of the

Ca–Na–SO_4–Cl facies type and had higher Na^+ values. On the Wilcox diagram, most SAR values were within the S1 class and few within the S2 class, and are of low to medium hazard (Fig. 5).

The EC values ranged from 1,554 to 5,450 μS/cm, with an average of 3,334 μS/cm. Four samples were within permissible limits for irrigation, seven were doubtful for irrigation, and 19 were unsuitable for irrigation. On the Wilcox diagram, most EC values fell within the C4 (very high) and few fell within the C3 (high) salinity zones (Fig. 4), which could be attributed to the reverse ion exchange and lack of recent groundwater recharge (Alharbi 2018). The KR values ranged from 0.09 to 0.93, with an average of 0.48 (Supplementary Table 2). All groundwater samples were safe for irrigation (KR □ 1). Moreover, the MR in the study area varied from 2.88% to 9.96%, with an average of 6.27%, indicating that the samples investigated were suitable for irrigation (MR □ 50%).

HM concentrations and pollution indices

The HM levels in groundwater samples were compared with the maximum allowable concentration of the WHO (2011, 2014). B was the abundant HM (average 51.77 μg/l), followed by Zn (average 13.89 μg/l), Se (average 10.76 μg/l), Cr (average 2.48 μg/l), Cu (average 1.47 μg/l), Pb (average 1.37 μg/l), Al (average 1.34 μg/l), As (average 0.92 μg/l), Co (average 0.59 μg/l), Cd (average 0.57 μg/l), Ni (average 0.44 μg/l), Hg (average 0.07 μg/l), and Sb (average 0.007 μg/l). The average values of these HMs were less than the permissible limits of WHO standards for drinking water (Table 3). The GWQI is a mathematical application transferring large water quality data into a single number, indicating the suitability of water for drinking (Patel and Vadodaria 2015; Sahu and Sikdar 2008). It varied from 53.64 in sample 25 to 145.05 in sample 14 (Supplementary Table 2). Fifteen samples (50%) were of good quality (GWQI = 50–100) and the remaining half were categorized as poor-quality samples (GWQI = 100.1–200). The lowest values of TDS, EC, Ca^{2+}, Mg^{2+}, Na^+, Cl^-, SO_4^{2-}, B, Ba, Cd, Ni, Se, Hg, Pb, and Sb characterize the good-quality samples.

The MI helps to evaluate the overall quality of drinking water quickly and considers possible additive effects of HMs on human health (Enaam Abdullah 2013; Rezaei et al. 2017). The MI values ranged from 1.03 in sample 23 to 1.52 in sample 1, with an average of 1.22 (Supplementary Table 2). All groundwater samples in the study area were categorized as slightly affected (MI = 1.0–2.0). The HPI is a powerful tool used to rank the composite influence of individual HMs on the overall water quality (Rizwan et al. 2011; Sirajudeen et al. 2014; Rezaei et al. 2017). In the study area, HPI values ranged from 7.05 in sample 6 to 17.51 in sample 1, with an average of 11.89 (Supplementary Table 2). As for the MI, all samples were classified as low pollution (HPI $<$ 45), which is attributed to the lower average levels of HMs than the permissible WHO standard limits.

Possible sources of ions and HMs

Q-mode HCA classifies the 30 groundwater samples into clusters based on TDS and ion levels (Fig. 6). Cluster 1 includes samples 1–4, 6–9, 11, 16–19, 21, 23, and 25, which had the lowest levels of TDS, Na^+, and SO_4^{2-} (sample 25), Ca^{2+} and Cl^- (sample 7), HCO_3^- (sample 9), SO_2 (sample 11), PO_4^{3-} (sample 17), and NO_3^- (sample 23). Cluster 2 includes samples 5, 10, 12–15, 20, 22, 24, and 26–30, which had the highest values of TDS, Mg^{2+}, SO_4^{2-}, and Na^+ (sample 14), F^- (sample 28), Cl^- (sample 30), PO_4^{3-}, and SO_2 (sample 29). From the field survey, most samples of cluster 2 are from farms cultivated with orange, pomegranate, lemon, and leafy green plants (e.g., lettuce, arugula, and radish), with or without date palms. Extensive and repeated irrigation of such plant types could dissolve cations and anions through rock–water interactions (Kumar 2014), and increase their values in the samples investigated. However, increasing PO_4^{3-} and NO_3^- could be attributed to the extensive use of fertilizers and pesticides (Alshahri and El-Taher 2018). The high vertical permeability of Quaternary loss could facilitate the vertical transport of contaminants into groundwater (Su et al. 2017). For drinking water, 18 groundwater samples had F^- levels greater than the WHO permissible limit (2011) (1.5 mg/l). The possible F^- sources are the leaching of minerals rich in F^-, industrial emissions, and the extensive use of phosphatic fertilizers (Aswathanarayana et al. 1985; Dissanayake and Chandrajith 2009).

R-mode HCA classifies the hydrogeochemical parameters into two clusters (Fig. 7). The first cluster includes EC and the second cluster includes the remaining hydrogeochemical parameters and HMs. EC showed a significant correlation with TDS, Ca^{2+}, Na^+, Cl^-, and SO_4^{2-}, indicating a similar origin (Supplementary Table 3). Ca^{2+} is correlated positively with Na^+, Cl^-, and SO_4^{2-}, indicating that the dissolution of gypsum is a possible source of the ion levels in groundwater (Li et al. 2016a; Zhang et al. 2018b; Wu 2020). Moreover, a strong positive correlation exists between SO_4^{2-} and Ca^{2+}, Mg^{2+}, Na^+, and Cl^-, implying a common source of these ions (Alfaifi et al. 2021). A positive correlation exists between No_3^- and HCO_3^-, indicating anthropogenic factors, especially agricultural activities, which are controlled enhanced weathering (Adimalla and Li 2018).

PCA was performed to document the possible sources of hydrogeochemical parameters and HMs in groundwater (Wen et al. 2019). Nine principal components accounted for 23.08%, 13.39%, 8.60%, 7.97%, 7.15%, 6.76%, 5.77%, 4.66%, and 4.21% of the total variance (Table 4). PC1 showed a strong association with EC, TDS, Ca^{2+}, Mg^{2+}, Na^+, Cl^-, and SO_4^{2-}, reflecting a natural process of the dissolution/precipitation of silicates, gypsum, and carbonates (Rezaei et al. 2017; Wu 2020). PC3 showed a strong association with NO3– and Pb, attributed to an anthropogenic reason because of the excessive use of fertilizers and pesticides (Li et al. 2018, 2019). PC4 had high loadings for Pb and Zn, indicating soil leaching that could originate from fertilizer and pesticide use (Kukrer and Mutlu 2019; Wen et al. 2019). PC5 showed a strong association with B, Cd, and Hg, which could be influenced by mixed anthropogenic and natural sources. PC6 had high loadings for Ni and Sb, and PC8 had high loadings for Se.

Conclusions

This study used hydrogeochemical characteristics, pollution indices, irrigation quality parameters, and multivariate statistical analyses to evaluate the groundwater quality and HM contamination in some palm farms in central Saudi Arabia. The following findings were obtained:

1. The average values of TDS, Ca^+, Na^+, K^+, Cl^-, SO_4^{2-}, and F^- were higher than the permissible limits of WHO standards for drinking water. The principal mineral phase saturation indices were negative, indicating undersaturated conditions regarding the capacity of groundwater to dissolve more minerals.
2. The most dominant ions, in order, were SO_4^{2-}, Ca^{2+}, Cl^-, and Na^+. According to their dominance, groundwater facies types in the study area were Ca–Na–SO_4–Cl (23 samples), Ca–Cl–SO_4, (4 samples), and Ca–SO_4–Cl (3 samples), indicating carbonates and gypsum dissolution/precipitation influences.
3. The irrigation quality parameters (Na%, SAR, KR, and MR) indicated the suitability of most samples for irrigation. However, the unsuitability of most samples for irrigation, based on EC values, could be attributed to the reverse ion exchange and lack of recent groundwater recharge.
4. The average HM values were lower than the permissible limits of WHO standards for drinking water. The GWQI indicated that half of the groundwater samples were of good quality and half of poor quality. The MI and HPI indicated that all samples were classified as slightly affected and with low pollution, respectively, attributed to increasing values of TDS, Ca^+, Na^+, K^+, Cl^-, SO_4^{2-}, and F^-, and decreasing HM values.
5. Extensive and repeated irrigation could increase ion levels in general. Moreover, increasing PO_4^{3-}, NO_3^-, F^-, Pb, and Zn concentrations in some samples could be attributed to the extensive use of fertilizers and pesticides in the farms.

Declarations

Author Contribution All authorship (Talal Alharbi, Abdelbaset S. El-Sorogy, Saleh Qaysi, Fahad Alshehri) contributed in all parts of the manuscript.

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Data availability All data generated or analyzed during this study are included in this published article and its supplementary information file.

Declarations

Ethical approval and consent to participate Not applicable, ethical committee does not require permission to work on collection specimens

Consent for publication Not applicable

Competing interests The authors declare no competing interests.

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Tables

Due to technical limitations the Tables are available as a download in the Supplementary Files.

Figures

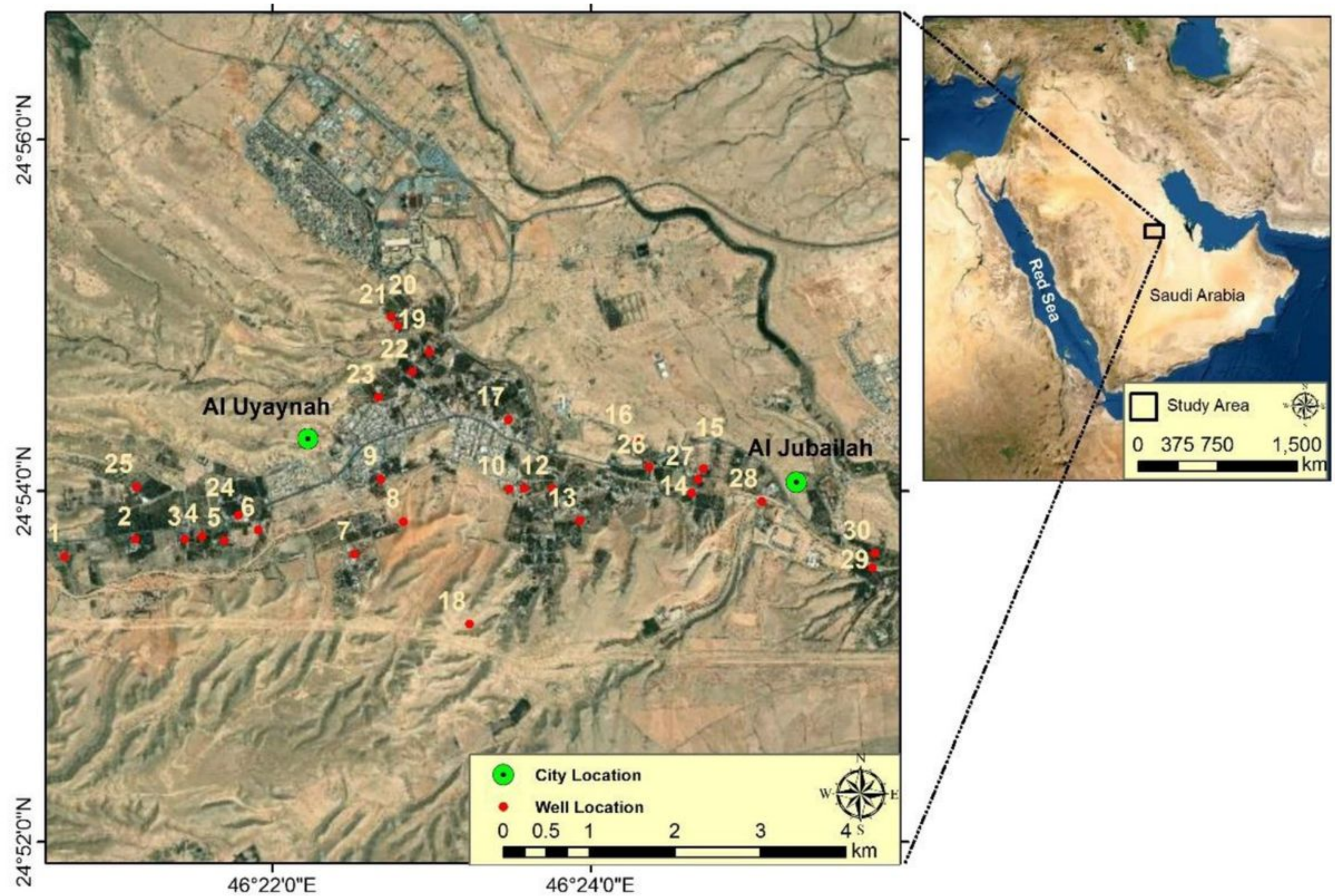

Figure 1

Location map of groundwater samples.

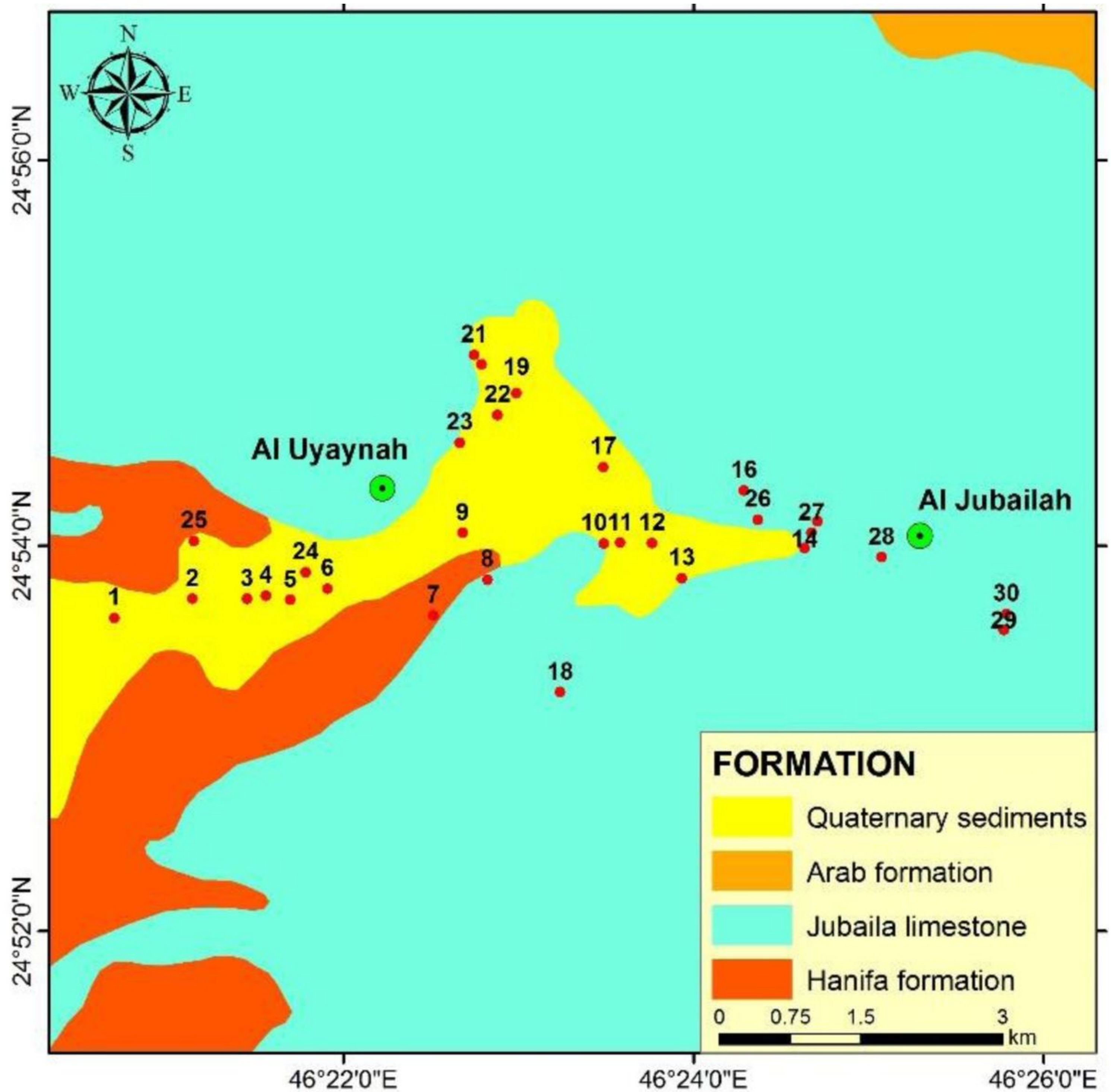

Figure 2

Geological map of the study area.

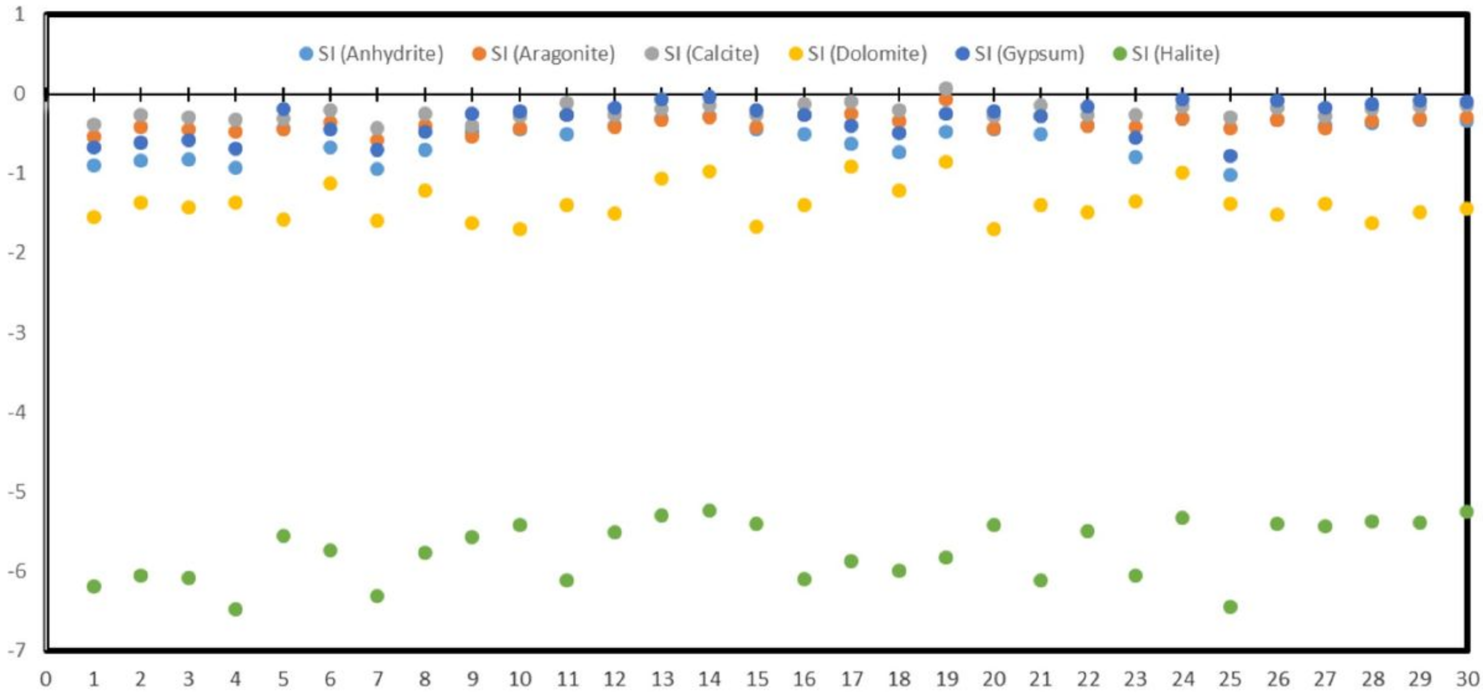

Figure 3

Saturation indices of the principal mineral phases in groundwater.

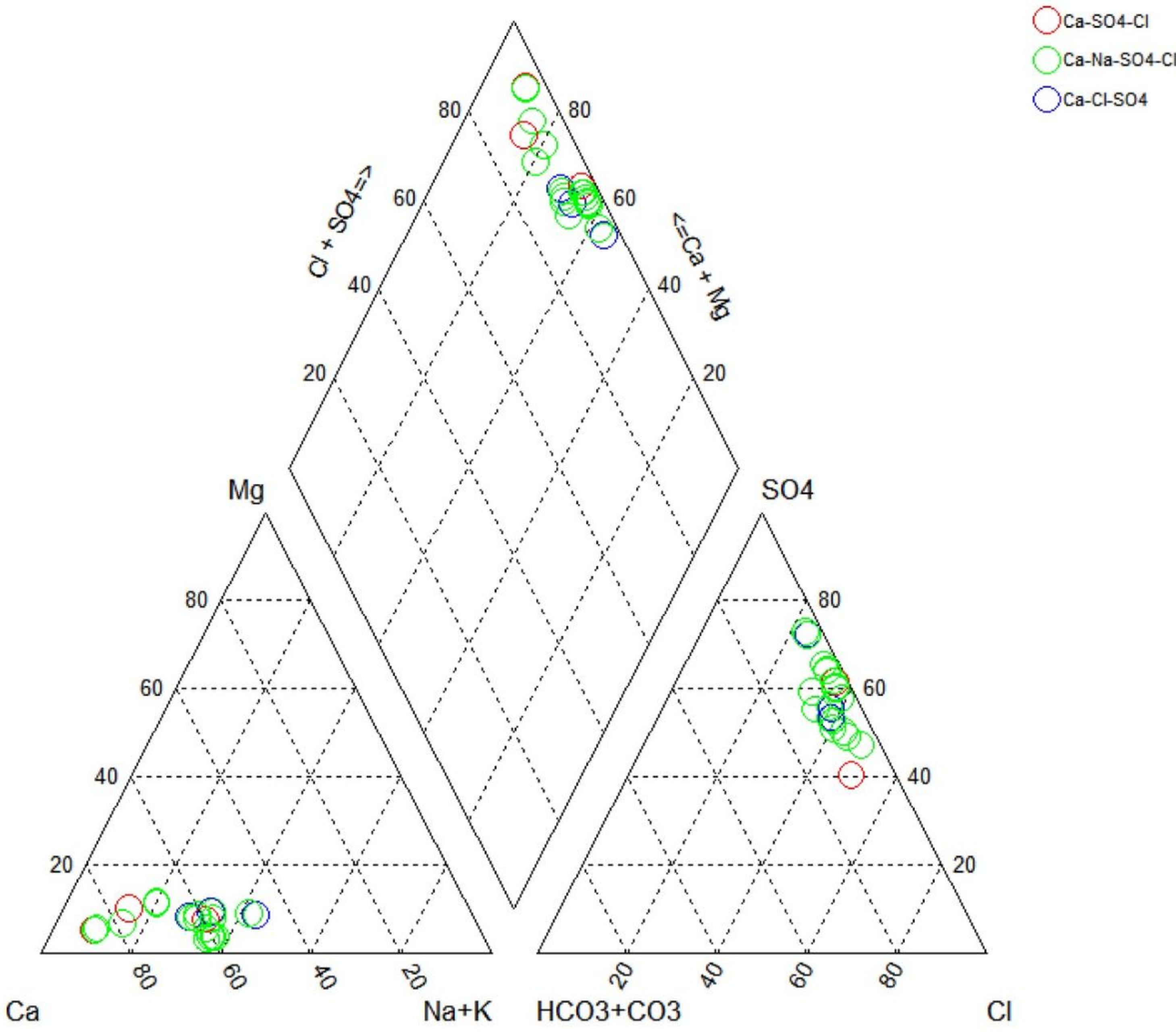

Figure 4

Classification of groundwater facies using the Piper diagram.

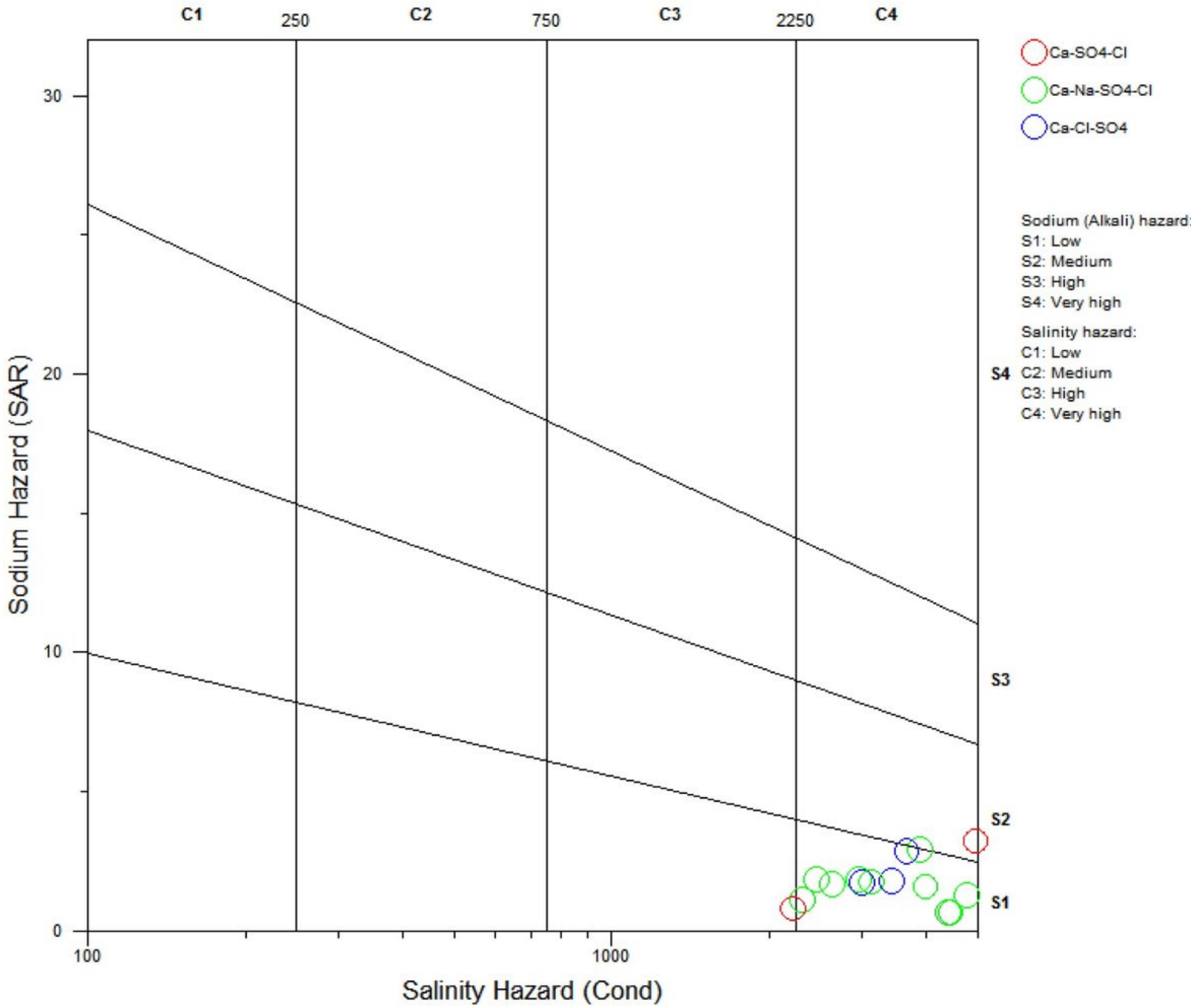

Figure 5

Classification of irrigation water using the Wilcox diagram.

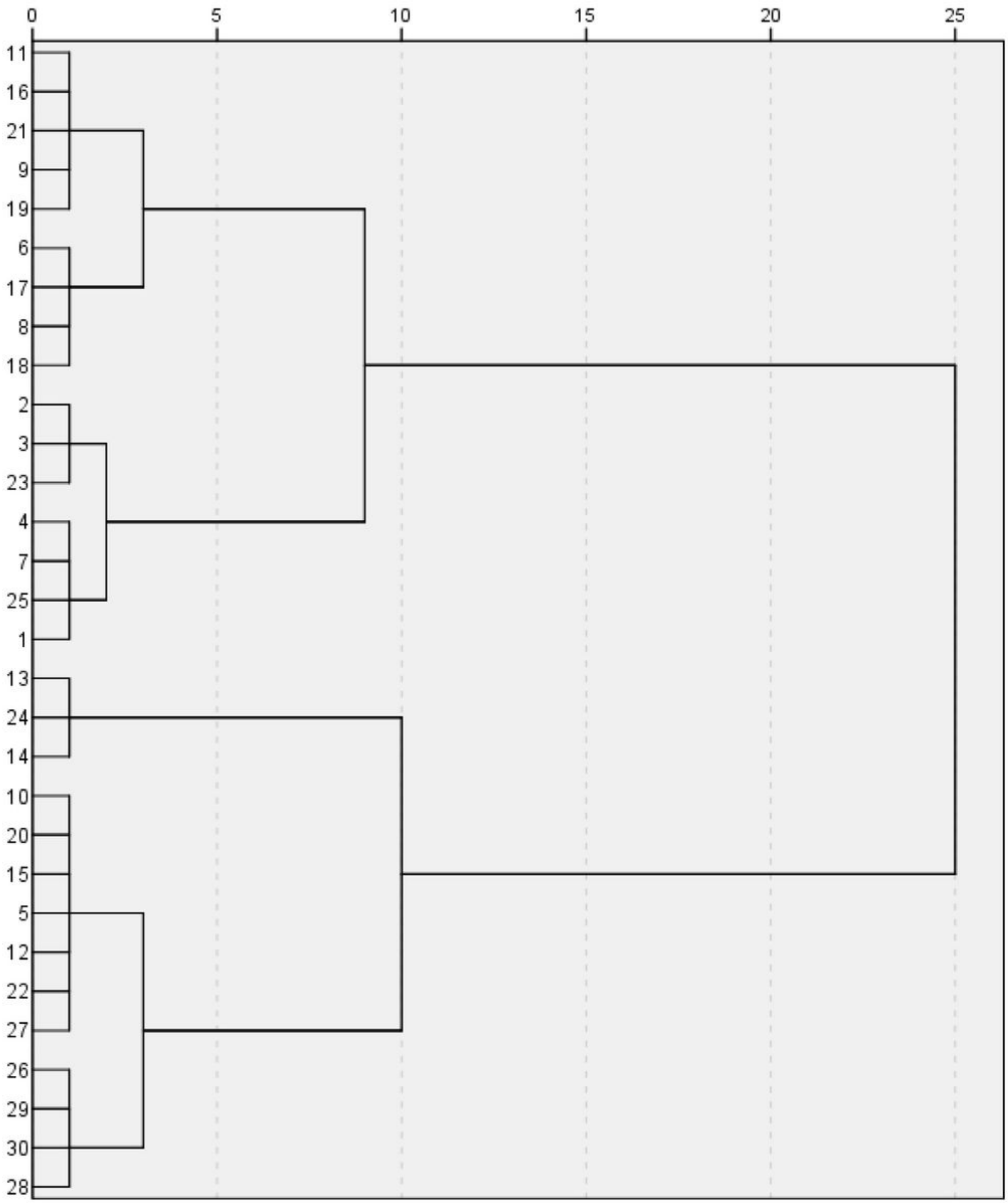

Figure 6

Q-mode HCA for groundwater samples.

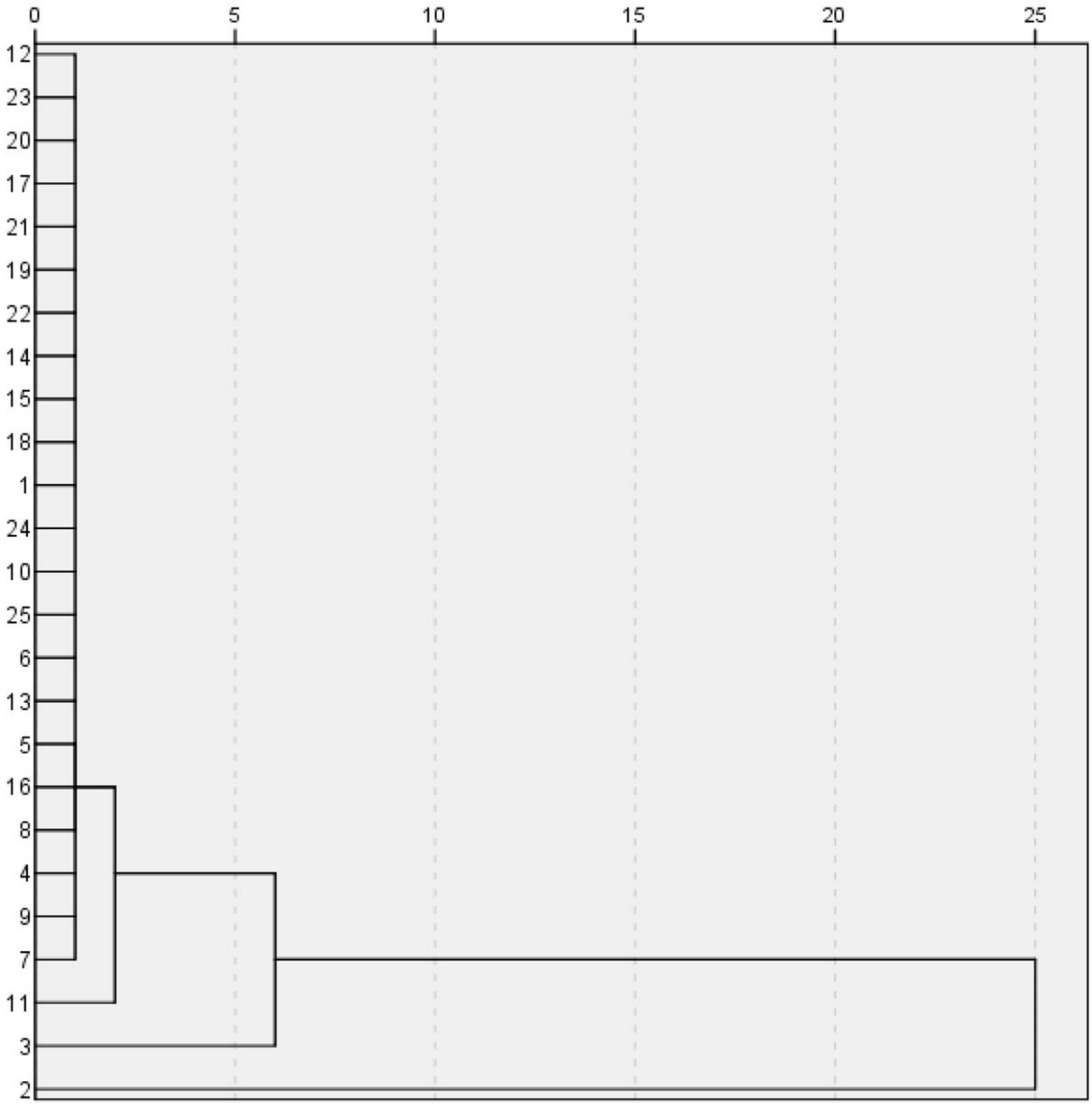

Figure 7

R-mode HCA dendrogram for the hydrogeochemical parameters in groundwater samples.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Tables.pdf
- SupplementaryMaterial.docx