Evaluation of groundwater quality for drinking and irrigation purposes using physicochemical parameters at Salilah area, Madinah Munawarah District, Saudi Arabia

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ABSTRACT
Evaluation of groundwater quality for drinking and irrigation purposes was carried out at the Salilah village, Madinah Munawarah District, KSA. Groundwater samples were collected from 20 wells in February 2018. The abundance of major cations is Na⁺ and Ca²⁺, and anions is Cl⁻ followed by HCO₃⁻. The total dissolved solids (TDS) values in the study area are more than 1000 mg/L, and 30% of the samples have nitrate concentration of 50 mg/L, indicating unsafe water for drinking. The sodium adsorption ratio of 90% of the samples indicate excellent water for irrigation and the remaining 10% indicate good water. The USSL diagram shows that all samples are of different salinity and sodium content. 80% of the samples have Na% less than 60 indicating good to permissible class. Residual sodium carbonate, permeability index and magnesium hazard values indicate safe water for irrigation. A proper management plan is necessary to preserve valuable groundwater resources.

1. Introduction
Groundwater is the major source of water for domestic, agricultural and industrial purposes in many countries. Water quality issues and their management options need to be given greater attention in developing countries. Intensive agricultural activities have increased the demand for groundwater resources in Saudi Arabia. Many naturally occurring major, minor and trace elements in drinking water can have a significant effect on human health either through deficiency or excessive intake [1].

Geological processes of the groundwater and reactions with dissolved minerals have a profound effect on water quality. Groundwater quality may be affected by natural factors, such as geology and geochemical processes. Geogenic sources are one of the causes of the variation in the chemical composition of groundwater, which changes with space and time [2–8]. It depends on the parent rock, intensity of weathering, residence time and external factors, such as precipitation and evaporation. Hydrogeochemical processes, such as weathering, dissolution, mixing and ion exchange, control the concentration of major and minor ions in groundwater [9–13]. Hence, these various processes that are very essential to understand the geochemical properties of groundwater depend on the chemistry of water in the recharge area as well as on the different geological processes that take place in the subsurface. The groundwater chemically evolved due to the interaction with aquifer minerals or intermixing among different groundwater reservoirs along flow paths in the subsurface [14–22].

Hydrogeochemical studies assist in taking proper measures to protect aquifers from groundwater contamination by natural phenomena or anthropogenic activities. In arid regions, groundwater salinization results from physical and chemical processes of the groundwater and leads to deterioration in water quality and reduction of usable groundwater [23–34].

The groundwater in the study area is the only source for freshwater, which is used for drinking and irrigation purposes. The attention to the quality of groundwater of the western district of Saudi Arabia has been increased [35–40]. Few hydrogeological and hydrogeochemical studies were performed in the study area [41–64]. This study aims to assess the groundwater quality for drinking and irrigation purposes using physicochemical parameters in the Al Sulaiha area, Al Madinah Al Munawarah district of Saudi Arabia.

2. Study area
The study area lies in the western district of Saudi Arabia about 220 km east of the Red Sea between latitudes 25°31’ and 25°44’ N and longitudes 38°19’ and 39°32’ E with an area of about 2939 km² (Figure 1). The area of study is important for agricultural activities and it lies within the desert belt which is characterized by very...
high temperature and semi-arid to extremely arid conditions. The mean daily maximum temperature is 45°C in summer and the minimum is 10°C in winter. The mean annual rainfall ranges between 10 mm/y in the western part of the study area and 170 mm/y in the southeastern part [65]. Topographic elevations in the study area range from 290 to 320 m above sea level.

3. Hydrogeological setting

The study area is characterized by Neoproterozoic rocks separated by Wadi Al Hamd [66]. Wadi Al Hamd is a very important valley in western Saudi Arabia, and it was referred to it as a river [67]. All wadis of Al Madinah Munawarah pour into this wadi at Al Uyon area [62]. This valley carries the surface water to the Red Sea to the west. In the study area, the Wadi Al Hamd valley splits into two main valleys in which the Wadi Al Hamd continues to run NW towards the Red Sea and the other valley, known as Wadi Al Jazl, runs north towards Al Ula city (Figure 2).

Wadi Al Hamd runs from SE to NW, splitting the rock units of the study area into three outcrops (Figure 2). To the southwest of Wadi Al Hamd, there are folded units of Fashghah formation, gneiss and schist and middle and upper Farri group, serpentinite of Haja complex and Mayghebat formation, from older to younger, respectively. To the east of Wadi Al Hamd, there is the gabbro and diorite of Haja complex, and gneiss and schist unit is repeated again, in which these two units are faulted against Siqam formation of Hadiah group. In the northwestern part of the study area, a small outcrop of Al Ays and Farri groups, Fashghah and Mayghabat formations crop out with the serpentinite unit, surrounded by Wadi Al Hamd [68].

Figure 3 shows lithostratigraphy of the study area, which suggests that the oldest group is the Farri group that over lain by Al Ays and Hadiyah groups. Farri group is met-volcanic rock, composed of pillow basalts, rhyolites and andesites [66]. Al Ays group is composed of Fashghah, Mayghabat and Murshid formations, in ascending order (Figure 3). Fashghah formation is up to several metres thick, composed of diamictites near its base, with limestone and sandstone-siltstone clasts in a fine argillaceous–arenaceous matrix [69]. Above the Fashghah formation is Mayghabat formation, which has measured sections ranging from 2 to 3.8 km in thickness, and composed of conglomerate-sandstone grading into diamictite overlies a sequence of ignimbrites, epiclastic volcanic breccia and shallow water sandstone-shale [69]. The Siqam formation is the lower unit of the Hadiyah group and is (~ 2000 m thick) volcanic rock unit, composed of pillow lava, welded tuff, basalt to andesite breccia, basal flow [68]. NW trending anticlines and synclines affect all of the above-mentioned rocks. They were also cut by NW–SE faults probably related to the younger Najd fault system. Quaternary surficial gravel and sand, as well as Wadi alluvium fill the bottom and flanks of Wadi Al Hamd, respectively.

The hydraulic behaviour of aquifers of the study area is continuous and alluvial, ranging from unconfined in the surficial deposits underlain by the above-mentioned weathered Proterozoic bedrock formations. The thickness of the alluvial deposits in the study area varies from a few centimetres to about 19 m. The aquifer has a limited lateral extent. The saturated thickness of the alluvium changes throughout the aquifer due to variation in bedrock topography. Groundwater is stored and transmitted through the fractured and weathered
bedrock and the overlying alluvial deposits. The wadi-fill in the study area is moderately to poorly sorted and is composed mostly of fine to coarse-sized sand. Most of the groundwater wells of the area of study (Figure 1) are located in agricultural areas. Depth to the water table ranges from 40 to 70 m below ground surface.

Rainfall is the main source of recharge of the aquifer. Discharge from the aquifer takes place through uncontrolled pumping and evaporation. The overpumping accompanied by low recharge rates has led to the depletion of the aquifer that is observed by the serious drop in the water level reaching about 70 m depth below ground surface.

4. Sampling and analytical procedures

To determine the hydrochemical characteristics of groundwater in the study area, 20 groundwater samples were collected from private wells (Figure 1).

Collecting the groundwater samples was done in accordance with the US Environmental Protection Agency guidelines [70], and strict consideration was given to individual parameter holding time criteria as outlined by the American Public Health Association [71]. All the samples were analysed for major constituents. Results of chemical analyses of the groundwater samples in the study area are presented in Table 1.

Duplicate water samples were taken at each well. One duplicate sample was collected at its natural pH, in polyethylene bottles after rinsing several times with water from the point of collection and preserved (approximately 4°C) for anion analysis. The second sample was also collected in polyethylene bottles and acidified using HNO₃ to pH < 2 for cation analysis. All the samples for laboratory analyses were filtered through 0.45 µm membrane filters. The cation and anion concentrations in groundwater samples were determined. Hydrogen ion concentration (pH), electrical conductivity (EC) and total dissolved solids (TDS) were measured at the wellhead using portable HI 991,300 Hanna Instruments.

Chemical analysis of major ions (calcium (Ca²⁺), magnesium (Mg²⁺), sodium (Na⁺), potassium (K⁺), bicarbonate (HCO₃⁻), sulphate (SO₄²⁻), chloride (Cl⁻) and nitrate (NO₃⁻)) was performed in the groundwater samples using the standard methods [71]. The values were observed within a standard limit of ±5% [72,73].

Bicarbonate concentration was determined using titration against HCl. Chloride was estimated by titration against the standard solution of AgNO₃. Sulphate and nitrate concentrations were determined using the DR4000 HACH Spectrophotometer. Ca²⁺ and Mg²⁺ concentrations were determined using titration against EDTA. Na⁺ and K⁺ were determined using the PFP7 Flame Photometer. The geochemical computer
program PHREEQC [74] was used to calculate saturation indices in the groundwater.

5. Results and discussion

5.1. Water chemistry

Results of chemical analysis of groundwater samples are represented in Table 1. The quality of groundwater is very important because it is the main factor determining its suitability for drinking, domestic and agricultural purposes. The pH values of groundwater ranged between 7.12 and 7.81; with a mean value of 7.48. This shows that the groundwater of the study area is of alkaline nature reflecting some extent of water–rock interaction within the aquifer materials. The pH values approaching 8.00 propose the dissolution of silicates and carbonates [75]. The EC values ranged between 2092 and 5706 µS/cm; with a mean value of 3223 µS/cm. Such a wide range of EC values indicates that the hydrochemistry of groundwater at the area of study is controlled by various hydrochemical processes such as water–rock interaction, cycling salting and agricultural activities.

The TDS values depend on climate, the bearing rocks and the time of the groundwater resident in the geologic matrix. TDS values tend to be higher in arid areas [76]. The values of TDS of the groundwater samples in the study area ranged between 1339 and 3652 mg/L; with a mean value of 2063 mg/L indicating brackish water. The constructed iso-salinity contour map (Figure 4) shows that the TDS concentration increases from all directions towards the centre of the study area. The increase in salinity in the central part of the study area is due to leaching of ions from the bearing rocks and from the agricultural activities; where agriculture return flow dissolves many salts which are precipitated in the soil zone due to their extreme high evaporation rate. This causes a noticeable increase in salinity of the underlying groundwater. These high salinity values of the groundwater in such agricultural arid areas are mainly due to cycling salting [77]. This means that salts are concentrated and precipitated in the soil zone from irrigation groundwater under high evaporation rates, and then they are leached from the soil zone by either irrigation water or rainwater and percolated till reaching the groundwater.

Sodium is the dominant cation in 10 analysed groundwater samples (50%), where Ca is the dominant cation in the other 10 groundwater samples (50%).

Exchange of Ca$^{2+}$ for Na$^{+}$ results in an increase in dissolved Na$^{+}$ and further dissolution of carbonate minerals. Through the mechanism of cation exchange, high concentrations of Na$^{+}$ are generated in the groundwater. The sodium concentration in the groundwater samples of the study area ranged between 164 and 813 mg/L; with a mean value of 373 mg/L and a standard deviation of 217.44 mg/L.

High calcium concentration in groundwater may be explained by the presence of calcium-rich silicate minerals and gypsum in the alluvium at the study area, where it ranged between 164 and 295 mg/L; with a mean value of 207 mg/L and a standard deviation of 34.79 mg/L in the groundwater samples of the study area.

Lowest potassium concentrations were observed in the groundwater of the study area, where it is originated from agricultural fertilizers and wastewater from the weathering of plagioclase-bearing rocks [78]. The K$^{+}$ concentration in the groundwater samples of the study area ranged from 16 to 41 mg/L; with a mean value of 28 mg/L and a standard deviation of 8.72 mg/L.

Magnesium in groundwater may be originated from dissolution of silicate minerals and dolomite [79]. The Mg$^{2+}$ concentration in the groundwater of the study area ranged between 32 and 92 mg/L; with a mean value of 55 mg/L and a standard deviation of 23.76 mg/L.

Cl$^{-}$ was the dominant anion with 65% of the groundwater samples. The concentration of Cl$^{-}$ ranged from 198 to 1256 mg/L; with a mean value of 527 mg/L and a standard deviation of 353.07 mg/L in groundwater samples. The presence of chloride in the groundwater may
be attributed to septic system pollution [80]. High chloride (and sodium) can also result from dissolution of soil and rock minerals and/or evapotranspiration of the runoff and irrigation water resulting in the concentration of salts [60].

Chlorides is not absorbed or held back by soils, therefore, it moves readily with the soil–water, is taken up by the crops, moves in the transpiration stream and accumulates in the leaves [81,82].

Bicarbonate was the dominant anion with 35% of the groundwater samples. The possible sources of bicarbonate include the presence of organic matter in the groundwater which is oxidized to produce carbon dioxide, which in turn promotes dissolution of minerals. This weathering enriches groundwater in Ca\(^{2+}\), Mg\(^{2+}\) and HCO\(_3^−\). Weathering of silicate minerals may also be accounted as a source for bicarbonate [83], in addition to cations such as Ca\(^{2+}\) and Mg\(^{2+}\). The dominance of HCO\(_3^−\) indicates the presence of recharge areas.

The concentrations of bicarbonate in the groundwater samples of the study area ranged from 213 to 502 mg/L; with a mean value of 377 mg/L and a standard deviation of 108.78 mg/L. Cl\(^−\) replaces HCO\(_3^−\) reflects the geochemical evolution along the flow path of groundwater and the influence of agricultural activities and residential areas. Where the irrigation water leaches the readily soluble salts in the soil zone leading to change of chemical water type from CaHCO\(_3^−\) indicating the meteoric origin of groundwater to NaCl together with an increase in salinity. Therefore, the hydrochemical change in relation to the hydrochemical processes and land-use in the study area is predominantly in cation and anion distribution.

The sources of sulphate in the groundwater samples in the study area may be attributed to the impact of cultivated areas in the vicinity of these water samples. However, sulphate might come from dissolution of sulphate minerals such as gypsum and anhydrite precipitated in the soil [84].

The concentrations of sulphate in the groundwater samples of the study area ranged from 274 to 951 mg/L; with a mean value of 496 mg/L and a standard deviation
Nitrate (NO$_3^-$) contamination in groundwater is a common occurrence in many parts of the world. The U.S. Environmental Protection Agency has set 10 mg N/L as the maximum contaminant level for nitrate in drinking water [85], as consumption of high-nitrate water can cause methemoglobinemia – a potentially fatal condition in infants [86].

The concentration of nitrate exceeding 50 mg/L in drinking water can be toxic for infants and also responsible for an increase in stomach cancer for others [87]. The nitrate concentration in the groundwater is normally low but can reach high levels as a result of agricultural activities and/or contamination from human or animal wastes [88]. Possible sources of nitrate contamination include manure applied to land, agricultural fertilizer [89], industrial effluent, domestic wastewater, septic systems, human waste lagoons, animal feedlots and native soil organic matter, as well as geologic sources [90]. Because nitrate is very mobile in most soils, it can be leached from all these sources into groundwater [91]. The determination of the sources of nitrate in groundwater is an important first step in the process of improving the groundwater quality, and perhaps reducing the amount of nitrate discharging to water bodies.

The variation in the concentration of nitrates in groundwater is due to soil drainage [92]. So, the low concentrations of nitrate in the groundwater have been attributed to slow oxidation of nitrogenous compounds and the difference in the rate of manure and nitrogen compound use. NO$_3^-$ concentrations may be further affected by complex hydrochemical processes such as nitrification and denitrification [93–95].

Fourteen groundwater samples in the study area (70%) have nitrate concentration within the safety limits for drinking purposes. Whereas, the nitrate concentration of six groundwater samples (30%) have exceeded the standards [80,96] (Table 1).

The NO$_3^-$ concentration in the groundwater samples in the study area ranged between 14 and 112 mg/L; with a mean value of 38 mg/L and a standard deviation of 26.92 mg/L.

Table 1 presents that major constituents having wide range of concentrations indicate the involvement of several hydrochemical processes influencing the water quality. The groundwater of the study area can be grouped into five water types: Na–Ca–Cl–SO$_4$ (45%) (9 samples: 8, 9, 10, 11, 12, 13, 14, 15, 16), Ca–Na–HCO$_3$–Cl (30%) (6 samples: 2, 3, 4, 18, 19, 20), Ca–Na–Cl–HCO$_3$ (15%) (3 samples: 5, 6, 17), Ca–Na–HCO$_3$–Cl (1%) (1 sample: 1) and Na–Ca–Cl–HCO$_3$ (1%) (1 sample: 7).

The different water types of the groundwater of the study area indicate recharge water where the salinity is 1339 mg/L. This groundwater is affected by agricultural activities, where irrigation water leaches the readily soluble salts in the soil zone (NaCl salt) that increases its concentration in the underlying groundwater leading to changing of chemical water type from CaHCO$_3$ to NaCl together with an increase in salinity. Plotting
the results of chemical analysis on Schoeller’s diagram (Figure 5) [97] revealed that the groundwater samples of the study area nearly have the same trend of increase and decrease of major ions indicating the same water resource.

5.2. Hydrochemical classification

The classification of groundwater facies was done using Piper’s diagram [98]. The plots of desirable data on the diamond-shaped field classify the groundwater types into two groups (Figure 6).

All the groundwater samples falls in groups I and II which show evolved groundwater type where unique chemical masking is achieved through rock–water interaction, ion exchange, reverse ion exchange, reactions within unsaturated zones, increased resident time and anthropogenic influences.

To study the effect of the ion exchange process in the groundwater of the study area, a plot between \((\text{Na}+\text{K})-\text{Cl}\) and \((\text{Ca}+\text{Mg}) - (\text{HCO}_3 + \text{SO}_4)\) is performed [99]. The \((\text{Na}+\text{K})-\text{Cl}\) represents the quantity where (Na + K) achieved/vanished relative to that supplied by the dissolution of chloride salt, while \((\text{Ca}+\text{Mg}) - (\text{HCO}_3 + \text{SO}_4)\) represents the Ca and Mg quantity achieved or lost related to that supplied by the dissolution of dolomite, gypsum and calcite. When no cation exchange process occurs, all the data are plotted near to the origin [100]. In the study area, the data plot with a slope of \(-0.993\) and an \(R^2\) value of 0.857 indicates that ion exchange practice is also a cause of ions in water (Figure 7).

When the ratio of Na/Cl is more than 1, it indicates that silicate weathering is the source for Na in water [101]. About 85% of the groundwater samples of the study area have the Na/Cl ratio more than 1 indicating silicate weathering, 10% of them have ratio equal to 1, whereas one sample (No.12) has the Na/Cl ratio less than 1 (Table 1). The scattered diagram between Na and Cl (Figure 8) demonstrates that some of the ions fall on aquiline indicates halite dissolution. In contrast, 85% of the samples fall towards Na side suggest that other sources like silicate weathering and ion exchange process are accountable for the occurrence of Na in groundwater [99].

5.3. Geochemical modelling

Using the saturation index approach, it is possible to predict the reactive mineralogy of the subsurface from groundwater data without collecting the samples of the solid phase and analysing the mineralogy [102]. The chemical equilibrium between minerals and water was identified by calculating the saturation indices (SIs) of the most common minerals in the aquifer matrix. If the groundwater is saturated with respect to a mineral, it is prone to precipitate some of the solute load.
On the other hand, if it is undersaturated (SI < 0) it will take more mineral into the solution (dissolution). Hence, the SI of a mineral is calculated based on the following equation [77]:

\[
SI = \log \frac{IAP}{K_{sp}}
\]

where IAP is the ion activity product and \(K_{sp}\) is the solubility product of the mineral.

PHREEQC [74] interfaced with Aquachem 2010.1 was used to calculate the SIs for associated minerals in the groundwater of the study area. The groundwater of the study area is slightly undersaturated to slightly oversaturated with respect to carbonate minerals; where the SI of these minerals were varied from −0.36 to 0.15 for aragonite, from −0.21 to 0.30 for calcite and from −0.51 to 0.13 for dolomite (Table 2).

Oversaturation with respect to these minerals may be attributed to the influence of evaporation of the shallow groundwater, which concentrates dissolved species in the soil zone. Recharge of rainwater concentrated solutions from the soil zone into groundwater as well as dissolves the precipitated minerals, which increases the SI of groundwater. However, as recharge continues, the saturation levels go down due to dilution.

The groundwater of the study area is moderately undersaturated with respect to gypsum and anhydrite and strongly undersaturated with respect to halite.
The presence of high levels of TDS may also be objectionable to consumers, owing to excessive scaling in water pipes, heaters, boilers and household appliances. No health-based guideline value for TDS has been proposed.

However, all the groundwater samples of the study area have a TDS value higher than 1000 mg/L. Concerning nitrate, 70% of the groundwater samples have nitrate concentration within the safety limits for drinking purposes. Whereas, 30% of the samples have nitrate concentration exceeded the WHO and SASO [88,96] of 50 mg/L. Generally, groundwater can't be used safely for drinking purposes, unless treated to eliminate the effect of high concentrations of TDS and nitrate.

5.4. Agricultural purpose

Groundwater is the main irrigation water source in the study area, and the groundwater quality assessment for irrigation could be useful in the future regional water resource management. The suitability of groundwater for irrigation is contingent on the effects of the mineral constituents in the water on both the plants and soil. Salts may harm plant’s growth physically by limiting the uptake of water through modification in the osmotic processes or chemically by metabolic reactions such as those caused by toxic constituents. Effects of salts on soils cause changes in soil structure, permeability and aeration, which indirectly affect plant growth. An important factor allied to the relation of crop growth to water quality is drainage.

If soil is open and well drained, crops may be grown on it with the application of generous amounts of saline water; on the other hand, a poorly drained area combined with application of good quality water may fail

\[ y = 0.9411x + 2.2426 \]

\[ R^2 = 0.9821 \]

Figure 8. Relationship between concentrations of Cl and Na in the groundwater samples of the study area.
to produce a satisfactory crop. Different hydrochemical parameters have been used to assess the suitability of groundwater for irrigation, such as sodium adsorption ratio (SAR), US Salinity Laboratory (USSL) diagram, residual sodium carbonate (RSC), sodium percent (Na%), permeability index (PI) and magnesium hazard (MH).

5.4.3. Sodium adsorption ratio

The SAR is an important parameter because high Na content in irrigation water may increase soil hardness and reduce its permeability. The SAR is a measurement of the ratio of sodium (Na⁺) ions to calcium (Ca²⁺) and magnesium (Mg²⁺) ions, expressed in meq/L. The following formula was used to evaluate SAR values [103]:

\[
\text{SAR} = \frac{\text{Na}^+}{\sqrt{\left(\text{Ca}^{2+} + \text{Mg}^{2+}\right)/2}}
\]

The SAR is an important parameter for determining the suitability of groundwater for irrigation because it is a measure of alkali/sodium hazard to crops. The SAR can indicate the degree to which irrigation water tends to enter into cation exchange reactions in the soil. Sodium replacing adsorbed calcium and magnesium is a hazard as it causes damage to the soil structure owing to dispersion of the clay particles and becomes compact and impervious. Ninety per cent (18 samples) of the groundwater samples of the study area have SAR values ranging between 2.88 and 9.48 meq/L (i.e. < 10), indicating excellent water for irrigation. Whereas, the SAR values in two samples (Nos. 10, 11) were higher than 10, indicating 10% of samples is good water for irrigation (Table 3).

5.4.4. Residual sodium carbonate

Eaton [105] proposed a formula for calculating the RSC using the following equation:

\[
\text{RSC} = (\text{CO}_3^{2-} + \text{HCO}_3^-) - (\text{Ca}^{2+} + \text{Mg}^{2+}),
\]

where all ionic concentrations are expressed in meq/L.

The RSC values of the groundwater samples of the study area are ranged between −18.47 and −3.75 (< 1.25 meq/L) (Table 3), indicating the safety of water for irrigation [105].

5.4.5. Sodium per cent

The percentage of sodium in the soil is vital for determining groundwater suitability for irrigation purposes. Na reacts with soil resulting in the reduction of soil permeability. This phenomenon is harmful to plant growth. The sodium content is usually expressed in terms of percentage sodium calculated by [106]:

\[
\text{Na\%} = \left(\frac{\text{Na}^+ + \text{K}^+}{\text{Na}^+ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+}}\right) \times 100
\]

in which Na, Ca, Na and K are expressed in meq/L.

The estimates of sodium percentage (Na%) range from 38.08 to 62.81 (Table 3). The majority of samples (80%) have Na% values less than 60 which are corresponding with good to permissible class. Whereas, four samples that have Na% values more than 60 indicate doubtful water class for irrigation. The different types of water classes of the groundwater in the study area indicate variation in agricultural activities [107].

5.4.6. Permeability index

Soil permeability is affected by the long-term use of irrigation water with high salt content. Permeability is influenced by sodium, calcium, magnesium, chloride and bicarbonate contents of the soil. Doneen [108] has

| Well # | SAR  | RSC  | Na%   | PI | MH   |
|-------|------|------|-------|----|------|
| 1     | 3.10 | −3.95| 40.38 | 53.37 | 24.90 |
| 2     | 3.27 | −3.75| 41.33 | 54.49 | 23.55 |
| 3     | 3.33 | −3.93| 44.23 | 56.29 | 23.06 |
| 4     | 3.44 | −5.04| 41.77 | 53.27 | 24.80 |
| 5     | 3.57 | −5.76| 42.26 | 53.19 | 25.55 |
| 6     | 3.63 | −6.04| 42.80 | 53.31 | 23.76 |
| 7     | 4.52 | −5.92| 48.02 | 57.58 | 21.64 |
| 8     | 6.24 | −10.46| 53.04 | 59.08 | 45.19 |
| 9     | 8.31 | −10.67| 61.57 | 65.94 | 43.95 |
| 10    | 10.67| −18.47| 62.30 | 64.95 | 32.97 |
| 11    | 10.57| −17.08| 62.81 | 65.64 | 31.44 |
| 12    | 9.48 | −13.46| 61.37 | 65.44 | 37.87 |
| 13    | 8.74 | −14.16| 59.87 | 63.59 | 38.72 |
| 14    | 7.80 | −13.95| 57.73 | 61.45 | 39.07 |
| 15    | 7.87 | −12.14| 59.17 | 63.32 | 35.47 |
| 16    | 6.44 | −7.24 | 57.63 | 64.58 | 24.49 |
| 17    | 3.88 | −6.97 | 42.67 | 52.57 | 22.56 |
| 18    | 3.40 | −5.56 | 40.61 | 51.91 | 23.27 |
| 19    | 3.36 | −4.35 | 43.72 | 54.88 | 24.37 |
| 20    | 2.88 | −5.24 | 38.08 | 50.36 | 25.40 |

Notes: SAR: sodium adsorption ratio; RSC: residual sodium carbonate; Na%: sodium percent; PI: permeability index; MH: magnesium hazard.
classified irrigation waters based on the PI, which indicates the suitability of groundwater for irrigation use.

The groundwater may be classified into classes 1 (Excellent), 2 (Good) and 3 (Unsuitable) based on the permeability indices. Classes 1 and 2 are suitable for irrigation, with 75% or more maximum permeability, and class 3 is unsuitable, with 25% maximum permeability.

PI was calculated for the groundwater. Ragunath [109] defined a formula for the calculation of PI using $\text{Na}^+$, $\text{Ca}^{2+}$, $\text{Mg}^{2+}$ and $\text{HCO}_3^-$. The PI is calculated according to the following equation:

$$\text{PI} = \frac{\text{Na}^+ + \sqrt{\text{HCO}_3^-}}{\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+} \times 100$$

The PI values of groundwater samples range from 50.36 to 65.94 (Table 3). It revealed that 100% of the groundwater samples fall in Class I (Excellent). These waters are not likely to create any permeability problem.

**5.4.7. Magnesium hazard**

Szabolcs and Darab [110] had proposed an MH for assessing the suitability of water quality for irrigation. Normally, a high level of $\text{Mg}^{2+}$ is caused by exchangeable Na in irrigated soils. An increased proportion of $\text{Mg}^{2+}$ relative to $\text{Ca}^{2+}$ increases sodication in soils which causes the dispersion of clay particles thus damages soil structure and decreases the relative hydraulic conductivity of soils as $\text{Mg}^{2+}$ behaves like $\text{Na}^+$. A magnesium ratio of more than 50 is considered to be harmful and unsuitable for irrigation use. This would adversely affect the crop yield, as soils become more alkaline.

The MH value for irrigation water is given by the following formula (where the concentrations are expressed in meq/L):

$$\text{MH} = \frac{\text{Mg}^{2+}}{\text{Ca}^{2+} + \text{Mg}^{2+}} \times 100$$

The MH of the analysed groundwater samples are ranged from 21.64 to 45.19 indicating the suitability of groundwater for irrigation purposes. Generally, the groundwater of the study area can be used safely for irrigation on clay soil; however, specific crops should be selected according to their salt tolerance.

**6. Conclusions**

Saudi Arabia has relied on groundwater resources to support its comprehensive socio-economic, agricultural
and industrial developments, especially during the last few decades. The government has followed rationalizes approach to utilize groundwater resources. The alkaline nature of pH in the groundwater of the study area reflects to some extent of water–rock interaction within the aquifer materials. The wide range of EC values indicate that the hydrochemistry of groundwater at the area of study is controlled by various hydrochemical processes such as water–rock interaction, cycling salting and agricultural activities.

The values of TDS in the Salilah area ranged between 1339 and 3652 mg/L indicate brackish water. The iso-salinity contour map shows that the TDS concentration increases from all directions towards the centre of the study area. This increase is due to leaching of ions from the bearing rocks and from agricultural activities. This causes noticeable increase in salinity of the underlying groundwater in centre of the study area.

Sodium and calcium are the dominant cations in the analysed groundwater. The dominant anion in groundwater samples is Cl. The dominance of HCO₃ indicates the presence of recharge areas. Seventy per cent of groundwater samples in the study area have nitrate concentration within the safety limits for drinking purposes. However, the major constituents have wide range of concentrations indicating the involvement of several hydrochemical processes influencing the water quality.

Five different water types of the groundwater of the study area were found. This groundwater is affected by agricultural activities. Schoeller’s diagram revealed that the groundwater samples of the study area nearly have the same trend of increase and decrease of major ions indicating the same water resource. All the groundwater samples fall in groups I and II in Piper’s diagram which show evolved groundwater type where unique chemical masking is achieved through rock–water interaction, ion exchange, reverse ion exchange, increased resident time and anthropogenic influences.

Groundwater of the study area is slightly undersaturated to slightly oversaturated with respect to carbonate minerals. On the other hand, they are mostly undersaturated with respect to gypsum, anhydrite and halite indicating the dissolution of these minerals in the aquifer matrix, which leads to an increase in Na, Ca, Cl and SO₄ concentrations in groundwater.

Generally, groundwater can’t be used safely for drinking purposes, unless treated to eliminate the effect of high concentrations of TDS and nitrate. Different hydrochemical parameters have been used to assess the suitability of groundwater for irrigation. The SAR values of 90% of the groundwater samples of the study indicate excellent water for irrigation and the remaining 10% indicate good water for irrigation. All samples are falling under C3S1, C4S1, C4S2 and C4S3 categories in the USSL diagram. These indicate that the groundwater shows different salinity and different sodium content.

The RSC values of the groundwater samples of the study area indicate the safety of water for irrigation. The majority of samples (80%) have Na% values less than 60 which are corresponding with good to permissible class. Whereas, four samples have Na% values more than 60, indicating doubtfull water class for irrigation. The different types of water classes of the groundwater in the study area indicate variation in agricultural activities.

The PI values revealed that 100% of the groundwater samples are not likely to create any permeability problem. The MH of the analysed groundwater samples indicates the suitability of groundwater for irrigation purposes.

Generally, the groundwater of the study area can be used safely for irrigation on clay soil; however, specific crops should be selected according to their salt tolerance.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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