Assessing groundwater quality of the shallow alluvial aquifer system in the Midyan Basin, northwestern Saudi Arabia

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A B S T R A C T

The Midyan Basin is characterized by arid climate with rare surface water flow. Groundwater is the main water resources in this region. In order to evaluate their suitability for drinking, domestic and irrigation purposes, chemical characteristics of groundwater in the Midyan Basin (northwestern Saudi Arabia) have been investigated and evaluated. A total of 72 water samples were collected from different wells and analyzed for hydrogen ion concentration, total dissolved solids, electrical conductivity, total hardness, Ca2+, Na+, Mg2+, K+, Cl-, HCO3-, NO3- and SO42-. To understand quality of groundwater and their suitability, chemical indices like sodium percentage, sodium adsorption ratio and salinity values have been calculated using analytical techniques. From traditional Piper diagram for water classification, the water quality is placed at Na+-Ca2+-SO42--Cl- type. According to the results of electrical conductivity and sodium adsorption ratio, 37% of the studied samples are regarded as highly saline, while 63% of them are classified as very highly saline. As per the Arab Gulf and international standards, such waters are not suitable for irrigation under normal condition and further action is required to remediate such problem by salinity control. Sodium content in 24% of the studied samples is regarded as high that can't be used for irrigation purposes for any soils. Thus high level of salinity, sodium adsorption ratio and sodium percentage in most water samples have made them unsuitable

Introduction

Groundwater is the only reliable water resource for domestic, agriculture and industrial uses in the arid country like Saudi Arabia. Rapidly depleting groundwater aquifers as a consequence of high population growth and rapid industrialization are threatening the quality of water resources in Saudi Arabia. To evaluate the suitability of groundwater for different purposes, understanding about the chemical composition of these important resources is necessary. It is possible to investigate changes in groundwater quality due to rock-water interaction (weathering) or due to anthropogenic activities (Babiker et al., 2007; Batayneh et al., 2008; Batayneh et al., 2012). Such improved knowledge can contribute to effective management and utilization of this vital resource. For this purpose, monitoring of the groundwater quality (chemical and physical constituents) is as important as assessing its quantity. The quality of water in any area is very much dependent on the type of uses. Major chemical elements, such as Na+, K+, Ca2+, Mg2+, HCO3-, Cl- and SO42-, play a significant role in classifying and assessing the groundwater quality. In this study hydrochemical assessment of the shallow water aquifer from Midyan Basin has been carried out for the above given elements. The alluvial groundwater aquifer in Midyan Basin, which provides a source of water for different consumptions (mainly for industrial and agricultural purposes), is experiencing serious depletion and quality degradation due to population growth, rapid industrialization and enhanced agricultural activities. Objective of the present study on the Midyan Basin is to assess the suitability of groundwater in the shallow aquifer for different uses.

Materials and Methods

The study area

The Midyan Basin is located in the west of Tabouk province, northwestern Saudi Arabia. The basin is bounded to the north, east and northeast by mountains of the Proterozoic rocks, to the west by sedimentary and Proterozoic rocks, and to the south by the Red Sea (Figure 1). This basin is situated from 28º 00′ to 28º 40′ N latitude and 34º 40′ to 35º 20′ E longitude, which covers an area of about 1500 km2 with a population of about 5000 (Central Department of Statistics & Information, 2012, personal communication). The climate of the region is characterized by hot dry summer and cold dry winter with an annual average precipitation of 60 mm (Saudi Presidency of Meteorology and Environment, 2012, personal communication). The surface elevation ranges between 0 and 300 meters above mean sea level. The dominant industries in the area are machine brick, ceramic, and asphalt manufacturing. Other main activities going on in this area are breeding sheeps, goats and agriculture crop production. The main crops produced in the area are clover, fruits and vegetables farms.

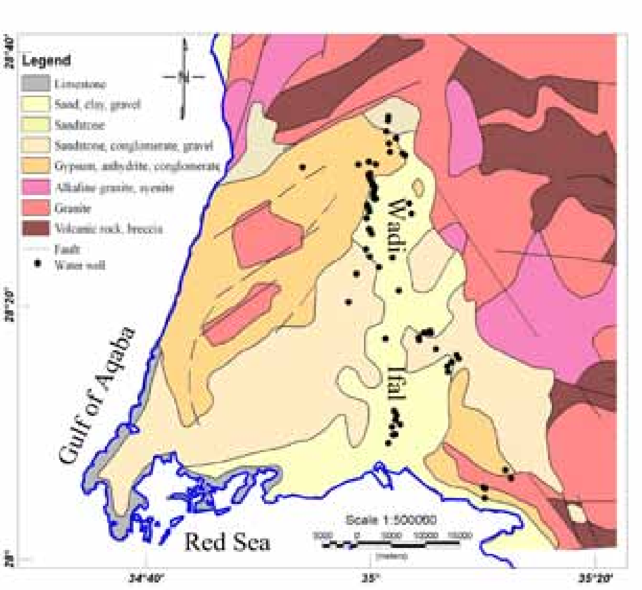

Figure (1) Geological map of Midyan region, northwestern Saudi Arabia (modified after Wyn Hughes et al., 1999). Borehole locations were shown as black circles.

Detailed geological studies on the northwestern Saudi Arabia are relatively rare, but a regional scale geological map (1:250,000 scale) from Midyan Basin has been reported by Clark (1986). Recent work by Wyn Hughes et al. (1999) show that the plain of Wadi Ifal occupies most of the basin (Figure 1). The oldest sedimentary rocks are the Late Cretaceous Adaffa Formation from Suqah Group (fluviatile in origin), which unconformably overlie the Proterozoic basement. The Suqah group is then unconformably overlain by deep marine Early Miocene Burqan Formation from Tayran Group, which in turn is overlain by marine mudstones, carbonates and evaporites of the middle Miocene Maqna Group. The poorly exposed middle Miocene Mansiyah and middle to upper Miocene Ghawwas formations are made of marine evaporites and shallow to marginal marine sediments, respectively. The youngest rocks are the alluvial sands and gravels of the Late Pliocene Lisan Formation. Figure 2 shows a generalized chronostratigraphic succession of the Midyan region (after Wyn Hughes and Johnson, 2005 and Laboun, 2011).

Hydrogeology

The Midyan Basin (Figure 1) is approximately a triangle in shape, which is accessible by one modern highway linking Tabouk city with the Red Sea and the Gulf of Aqaba to the west. The Lisan Formation that was deposited during the opening of the Gulf of Aqaba during the Late Pliocene represents a shallow alluvial aquifer system in the basin (Bokhari, 1981; Clark, 1986; Jado et al., 1990). This formation is made of poorly consolidated fluviatile sandstones and conglomerates. The recharge to this aquifer is taking place either along the elevated areas in the north, east and west, or from local surface water infiltrations. The drainage system in the basin is generally radial in nature to the centre of the basin.

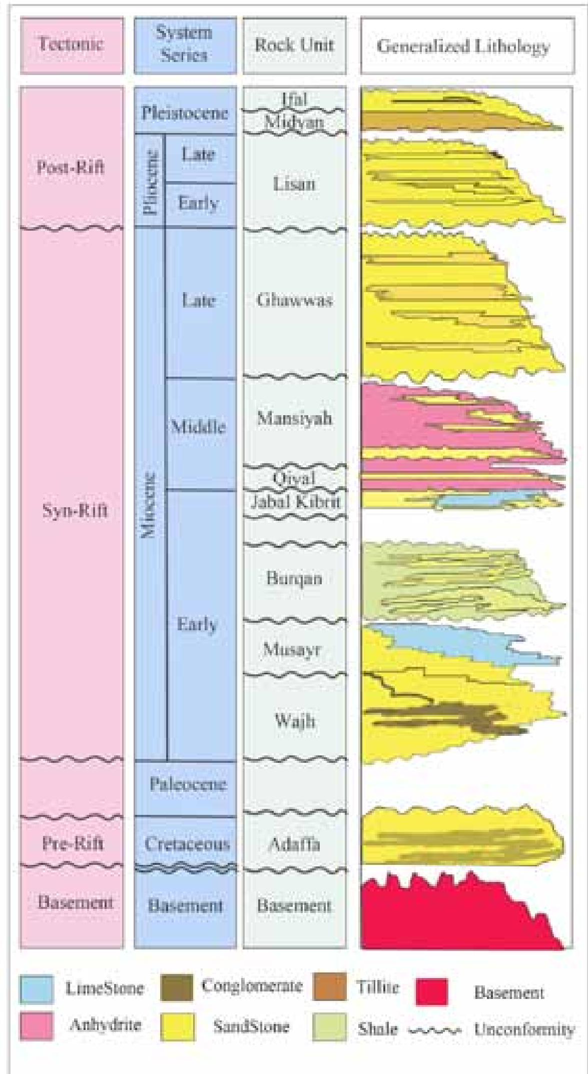

Figure (2) Generalized chronolithostratigraphic succession of the Midyan region (modified after Wyn Hughes and Johnson, 2005 and Laboun, 2011).

Sampling and analysis

Water samples for chemical analyses were collected in January 2012. A total of 72 samples of groundwater were collected from 72 boreholes in the Midyan Basin, northwestern Saudi Arabia (Figure 1). Samples were collected in polyethylene bottles of one-liter capacity. Prior to their filling with sampled water, these bottles were rinsed to minimize the chance of any contamination. The samples preservation and the used analytical techniques were in accordance with the standard methods from American Public Health Association (APHA, 1995). Chemical analyses were made in the laboratory for Ca2+, Mg2+, Na+, K+, SO42-, Cl-, NO3-, and HCO3-. Unstable parameters such as hydrogen ion concentration (pH), total dissolved solids (TDS) and electrical conductivity (EC) were determined at the sampling sites with the help of a pH-meter, a portable EC-meter and a TDS-meter, respectively. Total hardness (TH) was calculated using AquaChem V. 2011.1 software.

Results and Discussion

Chemical types and trends of groundwater

Summary of the physico-chemical parameters for the collected water samples are listed in Table 1. The observed charge balance between the sum of cations and anions did not exceed 5% (Figure 3), confirming the reliability of analytical results.

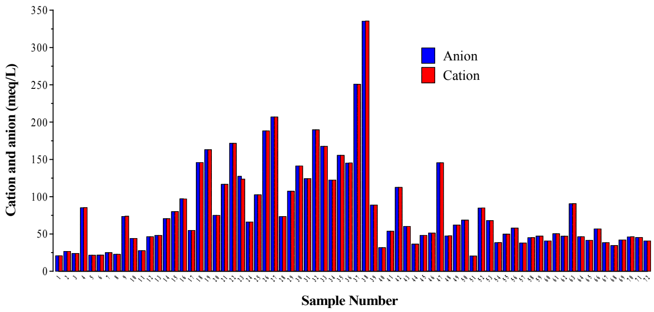

Figure (3) Anion-cation balance from chemical analyses of the studied groundwater samples.

As listed in Table 1, physicochemical parameters for the groundwater from Midyan Basin are compared with standards adopted by Gulf Standardization Organization (GSO, 2009) and World Health Organization (WHO, 2008). The relationships among pH, EC, TDS, SAR, %Na and %MH were determined in terms of correlation coefficient (Table 2). It has been observed that EC is strongly correlated with TDS and SAR with correlation coefficients of 100 and 0.89, respectively.

Table 1. Water chemistry analysis of the groundwater samples from study area (n=72). Units in mg/L except pH, EC in µS/cm, SAR in meq/L. TDS: total dissolved solids, TH: total hardness, SAR: sodium adsorption ratio, %Na: sodium percentage, %MH: magnesium hazard percentage, GSO: Gulf Standardization Organization, WHO: World Health Organization.

As shown in Figure (4), one of the methods to compare chemical analysis of groundwater is a trilinear diagram (Piper, 1944). The cation distribution in this diagram indicates that the studied samples are predominantly characterized by sodium and calcium classifications. In the anion triangle, a tendency toward sulfate-chloride rich water is indicated. Among major cations, Na+ has been found as dominant constituent, representing an average of 51.62%. Calcium and magnesium ions have been observed as secondary important elements, representing average values of 37.63% and 8.49%, respectively. Potassium ion has a minor presence of about 2.26%. Among the major anions, the concentrations of sulfate, chloride and bicarbonate ions lie in the range of 240 to 9500, 248 to 4686, 37 to 366 mg/L (with a mean values of 2478.1, 901.4 and 214.1 mg/L), respectively. The order of their abundance is SO42- > Cl- > HCO3-, contributing an average of 64.15%, 25.69% and 8.44% of the total anions, respectively. The electric conductivity (EC) varies from 1106 to 14290 µS/cm, indicating the probable presence of marginal water (500-1500 µS/cm) and brackish water (> 1500 µS/cm). Total dissolved solids (TDS) ranges from 545 to 7027 mg/L with an average value of 1769.7 mg/L. The pH value of the aquifer indicates an alkaline nature with an average value of 7.80, where the maximum value of 8.29 and a minimum value of 7.38 have been recorded.

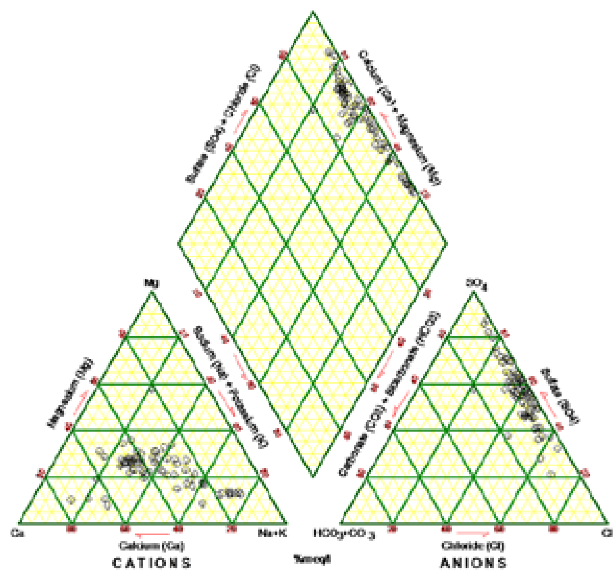

Figure (4) Piper diagram for groundwater quality in the Midyan Basin.

Parameter	Minimum	Maximum	Mean	GSO (2009)	WHO (2008)
pH	7.38	8.29	7.80	6.5-8.5	6.5-8.5
EC	1106	14290	3613.8	1500	1500
TDS	545	7027	1769.7	1000	1000
Ca^{2+}	144.6	1869	519	100	100
K^{+}	8.5	182	28.1	-	12
Mg^{2+}	18.8	899.3	129.2	50	50
Na^{+}	172.5	4637.5	1009.6	200	200
HCO_3^{-}	37	366	214.1	-	125-350
Cl^{-}	248	4686	901.4	150	250
SO_4^{2-}	240	9500	2478.1	150	250
NO_3^{-}	3	63	38	50	50
TH	500.2	8359.6	1827.2	200	500
SAR	3.18	58.36	14.29	-	-
%Na	17.21	82.67	47.77	-	-
%MH	7.1	44.24	28.48	-	-

As evident from the present results, the sodium, calcium, sulfate and chloride ions are clearly dominant, as expected from the chemistry of the lateral groundwater recharge. Due to the effects of recharge on the aquifer system in the study area, the groundwater facies (Na-Ca-SO4-Cl) is strongly influenced by ions input from the surrounding marine sediments (siltstone, halite, gypsum, anhydrite and mudstone); where the dissolution/evaporation process playing a significant role in regulating ion concentrations in the groundwater. The Na+ and Cl- concentrations come mainly from weathering of the marine origin halite sediments; while the high concentration of SO42- and Ca2+ ions come mainly from weathering of gypsum and anhydrite rocks in the recharge areas. Further explanation about the weathering processes has been discussed in the following page.

Water quality assessment

The classical use of water analyses is to produce information concerning its quality, which may yield information about the environments through which the water has circulated (Ta'any et al., 2007; Batayneh et al., 2008; Ghrefat et al., 2011; Batayneh et al., 2012). The main objective following the hydrogeochemical assessment is to determine the groundwater suitability for different uses based on the constituents chemical indices. To assess the suitability of water for drinking and domestic consumptions, hydrochemical parameters of the studied groundwater samples have been compared with prescribed specification available from GSO and WHO (Table 1).

The pH values of the studied groundwater samples vary between 7.38 and 8.29, indicating their slightly alkaline to alkaline nature. According to the GSO and WHO specifications, the range of desirable pH values in water suggested for drinking purposes is 6.5 to 8.5 (Table 1). Almost all the studied water samples have been found within the desirable range. The observed EC and the concentration of TDS are more than the maximum permissible limits of 1500 µS/cm and 1000 mg/L, respectively, in 96% and 71% of the total groundwater samples.

The TH varies from 500.2 to 8359.6 mg/L. Based on the hardness classification from Todd (1980), all the studied groundwater samples are classified as very hard (> 180 mg/L). Hard water is generally not harmful to human's health, but it can pose serious problems to industrial settings, where water hardness is continuously monitored to avoid costly breakdowns of boilers, cooling towers, and other related equipments. In domestic consumptions, hard water is often indicated by a lack of suds formation when soap is dissolved in water. Wherever hard water is consumed, some softening procedures are commonly used to reduce their adverse effects. A recommended limit for sodium concentration in drinking water is 200 mg/L (Table 1). A higher sodium intake may cause hypertension, congenial heart diseases and kidney problems (Singh et al., 2008). In the study area, the concentration of sodium is higher than the prescribed limit of 200 mg/L in 94.5% of the analyzed groundwater samples.

Potential sources and factors contributing to ions content of water

The surface and subsequence geological stratas in the study area consist of marine mudstones, carbonates and evaporites. The youngest rocks are the alluvial sands, gravels and conglomerates. Under natural conditions, elements of geological formations is readily oxidized, transported by surface runoff and/or leached into the surrounding groundwater. To investigate the potential source of ions from the surrounding geologic materials, 7 rock samples were collected from marine sedimentary outcrops and analyzed for major ionic contents. The results are tabulated in Table 3. Relative to others, sandstone, shale and halite samples (1 and 2, Table 3) have high total ion contents dominated by Na^+, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^{2+} and HCO_3^-. The ionic contents in anhydrite and gypsum samples (3 and 4, Table 3) are dominated by Ca^{2+}, SO_4^{2-} and HCO_3^-. Samples from mudstone, siltstone and shale (5, 6 and 7, Table 3) shows high ions content of Ca^{2+}, Mg^+, SO_4^{2-}, Cl^-, and HCO_3^-.

Table 3. Rock samples analysis.

Rock Sample No.	Rock Type	Ca^{2+}	K^+	Mg^{2+}	Na^+	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Dominant Ions
1	Sandstone, shale, halite	16495	8500	32950	23750	11034	33810	71300	8934	Na^+, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^+
2	Sandstone, shale, halite	19000	8470	19750	31500	8641	35262	62500	4378	Na^+, SO_4^{2-}, Cl^-, Ca^{2+}, Mg^+
3	Anhydrite, gypsum	98000	1760	5625	1200	9603	7557	64900	1164	Ca^{2+}, SO_4^{2-}, HCO_3^-
4	Anhydrite, gypsum	97500	600	19000	1450	14250	12276	54010	1769	Ca^{2+}, SO_4^{2-}, HCO_3^-
5	Mudstone	46000	2700	16900	8000	13413	24061	48880	1863	Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^-, HCO_3^-
6	Siltstone, clay, shale	37500	7575	15500	3925	6597	15798	60110	1109	Ca^{2+}, SO_4^{2-}, Cl^-, Mg^+
7	Siltstone, clay, shale	74166	775	11050	5620	9350	16618	55250	2096	Ca^{2+}, SO_4^{2-}, Cl^-, Mg^+

These characteristics of the studied samples suggest that weathering of the surface rock stratas is probably a major source of ions. However, it should be noted that the overall contribution of parent materials (rocks and soils) to major ion elements in the groundwater is different; suggesting some other contributing factors as well. Ions concentration in groundwater depends on many factors, including the size and depth of groundwater, and properties of parent material and soil, through which ions-bearing water percolates after rainfall. Ions input in the groundwater are also dependent on the nature of soils and rocks on the surface. The aquifer depth in the study area is less than 60 m with shallow groundwater table. The presence of joints and fractures mainly in the elevated western, northern and eastern parts of the basin makes the aquifer in the central and southern parts of the main wadi "Ifal" more vulnerable to ions concentration as a result of weathering and leaching. This is consistent with the present findings that ions contents in groundwater located in the central and southern parts of the study area are among the highest in terms of concentrations.

Drainage patterns map of the Midyan Basin showed that the surface runoff direction of water is towards south and southeast. TDS and EC distribution maps (Figure 5) generally indicates their higher concentrations in wells located down-slope of the basin, which can most likely be attributed to increase leaching after intense rainfall as a result of down-slope ions transportation following the general flow direction.

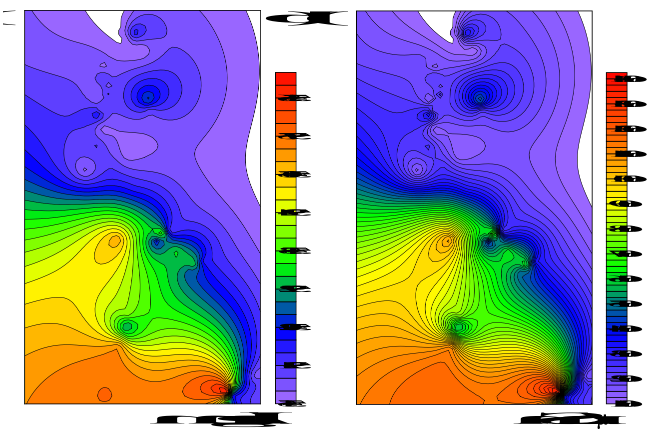

Figure (5) Spatial distribution of physical properties over the study area. (a) Total dissolved solids. (b) Electrical conductivity.

Suitability for irrigation uses

The suitability of groundwater for irrigation purposes is contingent on the effects of mineral constituents on both the plant and the soil (Batayneh et al., 2012). In fact, the presence of salts could be highly harmful, which can limit the growth of plants physically by restricting the water taking through modification in the osmotic processes. The presence of salts may also damage the plant growth chemically by the effects of toxic substances upon metabolic processes (Khodapanah et al., 2009). The amount of salinity, sodicity and toxicity are generally needed to evaluate the quality and suitability of groundwater for irrigation purposes (Todd, 1980). Parameters such as EC, sodium percentage (%Na), sodium adsorption ratio (SAR) and magnesium hazard (MH) have been used to assess the suitability of the studied groundwater for irrigation purposes.

According to our estimations, the EC values range from 1106 to 14290 µS/cm. This large variation in EC values is mainly attributed to lithologic composition and anthropogenic activities prevailing in this region. Generally, the irrigation water with EC value of < 700 µS/cm causes no threat to most crops, while its value of > 3000 µS/cm may limit their growth (Tijani, 1994; Batayneh et al., 2012). Based on the Richard (1954) classification (Figure 6), the studied water samples are classified as high salinity hazard (25 samples) and very high salinity hazard (47 samples), giving a distribution of 34.7% and 65.3%, respectively. Water in the high salinity hazard category (C3) may have detrimental effects on sensitive crops and adverse effects on many other plants. In Such a situation careful management practices have to be adopted. Very high salinity water (C4) is not suitable for irrigation under ordinary conditions but may be used for salt tolerant plants on permeable soils through special management practices.

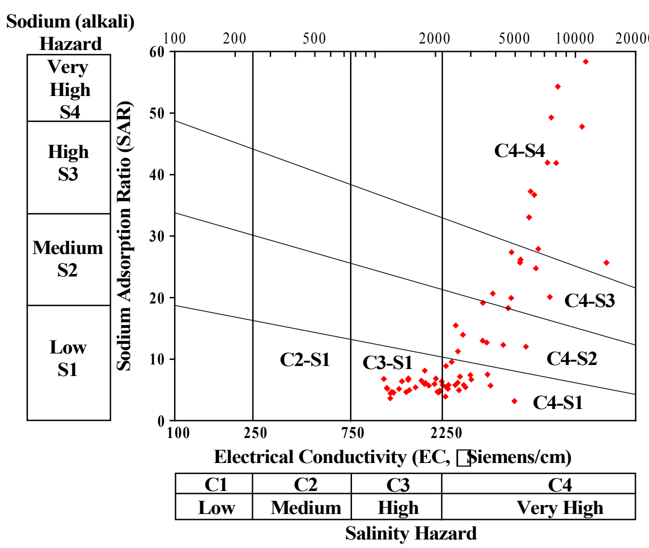

Figure (6) Water classification according to EC and SAR values.

The alkali hazard

While, high salt contents (high EC) in water leads to formation of saline soil, high sodium contents (SAR) leads to development of alkaline soil. Irrigation with Na+ enriched water results in ion exchange reactions, i.e., uptaking of Na+ and release of Ca2+ and Mg2+. This type reaction causes soil aggregates to disperse, reducing its permeability (Tijani, 1994; Batayneh et al., 2008; Batayneh et al., 2012). The presence of sodium or alkali hazard in the irrigation water is determined by absolute and relative concentration of cations, which is expressed by SAR. The following formula is used to calculate SAR, where all ionic concentrations are expressed in milliequivalent per liter:

$$\text{Sodium Adsorption Ratio (SAR)} = \frac{\text{Na}}{\sqrt{\text{Ca} + \text{Mg}/2}} \quad \cdots\cdots\cdots\cdots (1)$$

There is a significant relationship between the SAR values in irrigation water and the extent to which sodium is absorbed in the soils. Continues use of water with a high SAR values leads to a breakdown in the physical structure of the soil as a result of excessive amounts of colloidally absorbed sodium. This breakdown then results in the dispersion of soil clay, causing it to become hard and compact when dry and increasingly impervious to water penetration due to dispersion and swelling when wet. The calculated values of SAR in the studied samples ranges from 3.18 to 58.36 (Table 1). The SAR values plotted on the salinity diagram as alkalinity hazard (Figure 6) classify the sodium hazard in the studied water as low (61.1%), medium (11.1%), high (11.1%) and very high (16.7%). As per the Richard (1954) classification applied to the calculated SAR values, 44 water samples fall into the excellent category, 7 into good category, 9 as doubtful and 12 as unsuitable.

Sodium content

Sodium concentration in the irrigation water is also expressed by percent sodium or soluble-sodium percentage (%Na), which can be determined using the following equation where all ionic concentrations are expressed in milliequivalent per liter:

$$\text{Sodium Percent } (\%\,\text{Na}) = \frac{\text{Na} + \text{K}}{\text{Ca} + \text{Mg} + \text{Na} + \text{K}} \times 100 \cdots\cdots\cdots\cdots (2)$$

The values for the percent sodium in the studied groundwater samples range from 17.21 to 82.67% (Table 1). It is observed that 17 samples have high sodium content (above 60%) and are not suitable for irrigation purposes.

Magnesium hazard

Although, calcium and magnesium ions are essential for plant growth but they may cause aggregation and friability to irrigated soil. Water with calcium and magnesium concentration of higher than 100 mg/L and 50 mg/L, respectively, cannot be used for irrigation purposes. In the studied groundwater, the concentration of calcium and magnesium exceed that limit in 72 and 67 samples, respectively. Another indicator to specify the MH in irrigation water has been proposed by Todd (1980) by following formula, where all ionic concentrations are expressed in milliequivalent per liter:

$$\text{Magnesium Hazard (MH)} = \frac{\text{Mg}}{\text{Mg} + \text{Ca}} \times 100 \cdots\cdots\cdots\cdots (3)$$

If this percentage of magnesium hazard is less than 50, the water is considered safe and suitable for irrigation. From the calculated values, the magnesium hazard range between 7.1 and 44.24% (Table 1), which can be classified as suitable for irrigation.

Water classification

In order to classify the studied groundwater samples for irrigation purposes, a salinity diagram of Richard (1954) is used (Figure 6). In this diagram, EC is taken as salinity hazard and SAR as alkalinity hazard. The measured values for EC in the studied samples ranges between 1106 and 14290 µS/cm and the SAR values varies from 3.18 to 58.36. The plot of data on the salinity diagram classified the water samples into five types; i.e., C3-S1, C4-S1, C4-S2, C4-S3 and C4-S4. Water of class C3-S1 (i.e., high salinity hazard-low sodium hazard) and class C4-S1 (i.e., very high salinity hazard-low sodium hazard) could be used for irrigation on almost all soils, if a moderate amount of leaching occurs. Water of C4-S2 class (i.e., very high salinity hazard-medium sodium hazard) and C4-S3 class (i.e., very high salinity hazard-high sodium hazard) can produce sodium related problems in most soils and, therefore, are not suitable for irrigation under ordinary conditions. Water of C4-S4 class (i.e., very high salinity hazard-very high sodium hazard) is not suitable for irrigating in any type of soil.

Conclusions

The groundwater resources in the Midyan Basin of northwestern Saudi Arabia have been evaluated for their chemical composition and suitability for irrigation purposes. These investigations indicate that among major cations, Na+ is generally a dominant constituent in the studied samples, representing an average value of 51.62%. The order of anions in terms of abundance is $SO_4^{2-} > Cl^- > HCO_3^-$. Based on the TDS analysis, 29% of the water samples are suitable for drinking purposes. A relationship between salinity hazard and sodium hazard reveals that most of the groundwater samples are not suitable for irrigation purposes under normal condition. The salinity hazard for the studied water wells is classified as high to very high. The alkali hazard has also been classified from low to very high. Therefore, salinity has to be considered as principal concern in irrigated agriculture land of the Midyan Basin. High salinity in the area may be caused by dissolution processes within the Miocene rock formations (halite, gypsum and anhydrite). For agricultural development in the study area, proper management of salinity control has to be introduced. In addition, certain types of plants with good salt-tolerance behavior should be considered for the area. According to the quality determining parameters and their comparison with set criteria, groundwater of the study area have been graded unsafe for domestic and irrigation purposes.

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