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Hydrogeochemical Processes and Isotopic Characteristics of Inland Sabkha, Saudi Arabia*

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Abstract: Al-Awshaziyah inland sabkha is an elongated north-south depression, almost flat, enclosed by Khuff Formation (Permian-Triassic) in Al-Qaseem region, Saudi Arabia. It is situated between latitude 26° N and longitude 44° E. and covers more than 18 km². The area is an important agricultural region in Saudi Arabia due to its huge groundwater reserves. A field study was carried out to determine the hydrogeochemical processes and the isotopic characteristics of the Sabkha for its management and rehabilitation. Sabkha water is highly saline, where the dominant cations concentration order is Na⁺ > Mg⁺⁺ > K⁺ > Ca⁺⁺ and that of anions is Cl⁻ > SO₄⁻⁻⁻ > NO₃⁻ > HCO₃⁻. The total dissolved solids (TDS) of the Sabkha water ranged from 124860-464750 mg L⁻¹ with an average value of 351670 mg L⁻¹. Sabkha water is dominant by sodium-magnesium chloride, magnesium-sodium-chloride and sodium-chloride water types. Halite is the most abundant evaporate mineral which is an economic source of NaCl salt in the region. The dominant cations and anions concentration order of shallow wells is Na⁺ > Ca⁺⁺ > Mg⁺⁺ > K⁺ and Cl⁻ > SO₄⁻⁻⁻ > NO₃⁻ > HCO₃⁻, respectively. Whereas the dominant cations and anions concentration order of deep wells is Na⁺ > Ca⁺⁺ > Mg⁺⁺ > K⁺ and SO₄⁻⁻⁻ > Cl⁻ > NO₃⁻ > HCO₃⁻, respectively. The total dissolved solids (TDS) ranged from 7184-9952 mg L⁻¹ with an average value of 8982 mg L⁻¹ for the shallow wells and from 4340-8580 mg L⁻¹ with an average value of 6265 mg L⁻¹ for the deep wells. The hydro-geochemical processes and the isotopic composition (δ¹⁸O and δ²H) indicated that the source of Sabkha water, shallow wells and deep well water is of meteoric origin. It also showed some mixing and ion-exchange phenomenon between Sabkha water, shallow and deep well waters. Further investigations are needed to explore more about the occurrence of these inland Sabkhas and their environmental impact in the area.

Key words: Inland Sabkha, Saudi Arabia, sabkha water, hydro-geochemistry, isotopes

INTRODUCTION

Sabkhas are prominent physiographical features in the arid and semi arid climate. It's an Arabic term used to describe a flat terrain of clay, silt and sand encrusted with salt generally associated with shallow water table having a depth less than 1 m from the soil surface. Sabkhas, in Saudi Arabia, cover different parts of the country and that are of great concern for industrial and agriculture purposes. Besides, there is a possibility of expansion of Sabkhas into the adjoining productive lands thus contaminating the shallow groundwater aquifers with poor quality water (water salinity more than 2,00 mg L⁻¹). Sabkhas are being studied in Saudi Arabia for residential (Ali and Hossain, 1988; Hossain and Ali, 1988; Oweis and Bowman, 1981), industrial (establishment of different types of industries) and other purposes (James and Little, 1986). Recently, Sabtan and Shehata (2003) and

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Bayumi *et al.* (2004) stated that hydrology of Al-Lith coastal Sabkha, its chemical composition and the conditions of use determine the quality of well water for irrigation. However, little information is available regarding the physio-chemical characteristics of Sabkhas and the relationship between hydrochemistry of Sabkha water and the surrounding well waters.

The Al-Awshaziyah inland Sabkha lies between latitude 26°N and longitude 44°E. It covers more than 18 km² in Al-Qaseem region. The area is an important agricultural region in Saudi Arabia due to its huge groundwater reserves. The major source of sabkha water seems to be the shallow groundwater, rainwater and runoff from over-irrigation in the adjoining agricultural activities. Water in the sabkha basin comes mostly from south-east and south-west of the area. It overlies the Khuff Formation (Permian-Triassic) in the south-east and south-west and by quaternary sediments in the north-east and western side. The main objective of this paper was to determine hydrogeochemical processes and isotopic characteristics of Al-Awshaziyah inland Sabkha and its relationship with the neighboring aquifers.

Geological and Hydrogeological Setting

The rocks of the area are Permian-Triassic (Khuff Formation) and comprise shales and sandstone of continental to shallow marine origin and limestone (Fig. 1). The Khuff Formation consists off four members namely Huqayl, Duhaysan, Midhnab and Khortam. Al-Awshaziyah inland Sabkha is well developed on the foot of the Khortam member, a cuesta of Khuff Formation (Manivit *et al.*, 1986). The Upper part (36.5 m thick) comprises cream oolitic and bioclastic limestone and gray dolomite. Middle part of the member comprises bioclastic dolomite with inter beds of clayey laminated limestone. The lower part of the Khortum member is represented by green oolitic limestone and fine grained microsparitic limestone (Delfour *et al.*, 1982). The Unayzah Formation (Carboniferous-Permian) also occurs as a thick unit of sandstone, shale and claystone. Khuff Formation overlies the Unayzah Formation and is resting on an erosion surface. The contact between the Khuff Formation and Sudair Shale (Triassic) appears to be conformable wherever exposed. The Sudair shale of the area also comprises silty and clayey dolomite and is overlain by the dark-red gypsiferous claystone (Fig. 2). The

| Age | | Formation | Member | Thickness (m) | Lithology | Discriptions |
|-------------------------------|--------------------------------------|-----------|---------|---------------|--------------------------------------|------------------------------------------------------------------------|
| Triassic | Scythian | KHUFF | Sudair | 311 | | Brick-red green gypsiferous claystone with massive gypsum interbedded |
| Permian | Later late permian to early triassic | | Khartam | 49 | | Massive oolitic limestone claystone and sandstone at the base |
| | | | Midhnat | 72 | | Green clayey siltstone, gypsiferous dolomatic claystone with sandstone |
| | | | Duhysan | 28 | | Gray dolomite, dolomitic or calcareous claystone |
| | | | Huqayl | 45 | | Dolomite with anhydrite, with red gypsiferous claystone |
| Early late permian (Kazanian) | | Unayzah | 36 | | Beige cross-bedded sandton claystone | |

Fig. 1: Geological coulmner section of study area

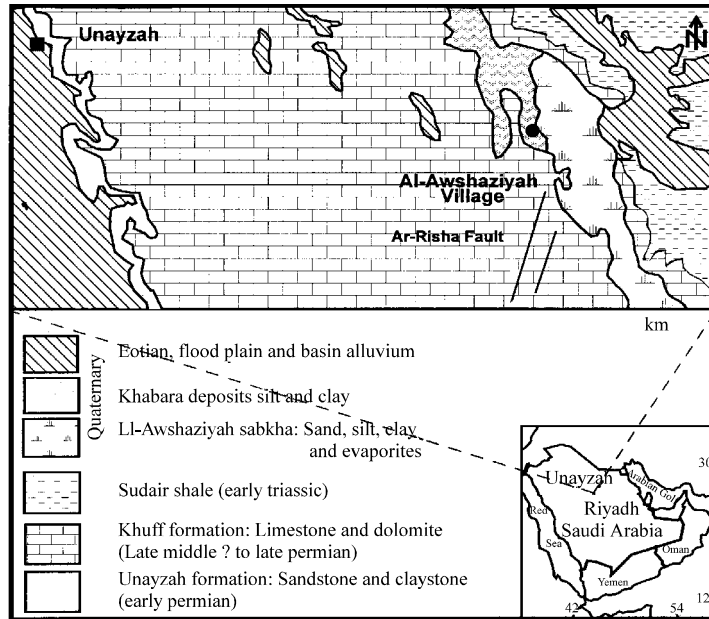


Fig. 2: Geological map of the study area (Manivit *et al.*, 1986)

area contains the most prominent fault known as Ar-Risha fault, which strikes N5°E and throws several meters, occurs in Khuff Formation. This fault is supposed to be one of the main architects in the development of sabkha basin.

The Khuff Formation outcrops in Qaseem region where groundwater has been developed as shallow aquifer. From the outcrop area, the formation dips regularly towards the east, with a slope of 20 m km⁻¹. The thickness of the aquifer is approximately 350 m in the area (BRGM, 1984).

Recently, Al-Harbi *et al.* (2006) classified the sediment of Al-Awshaziyah Sabkha into three facies, i.e., salt, black-mud and silty-sand facies. Silty-sand facies is the thickest among all the facies. Its thickness varies from 10-150 cm and is dominant in the southern side of the Sabkha basin and is considered as the lower most facies of the Sabkha. It consists of silty-sand and gray material, whitish gray silt and traces of blackish and silty clay. Black mud is laminated with an alternation of dark and light layers and with grayish-black spots of decayed organic materials. The total thickness of this facies varies from 1.0-10 cm. This facies, occurring below the salt facies, are intercalated with thin halite layers and in some cases shows remains of preserved organic matter. Salt crust is the top most facies of the Al-Awshaziyah basin. Its thickness varies from 1-45 cm and extends from the periphery to the central part of the basin. Its lower part exhibits a gradual transition with black mud facies. It occupies more than 70% of the sabkha surface and is one of the main features of the Sabkha (Al-Harbi *et al.*, 2006).

Groundwater aquifers in the area are most probably separated by clayey limestone which occurs as the middle member of Khuff Formation. The water bearing layers of the Khuff Formation are mostly carbonate rocks, with hard dolomatic limestone and dolomite, in some places chalky and re-crystallized.

The deep aquifer is considered as a secondary aquifer and the water is highly mineralized (Water Atlas of Saudi Arabia, 1985). Although this aquifer is considered as a useful source of water in the area but was not considered for large-scale development. Al-Alawi and Abdul Razzak (1994) stated the total groundwater resources in the Khuff aquifer as 30×10⁹ m³, including poor quality water with a Total Dissolved Solids (TDS) ranging between 3800-6000 mg L⁻¹.

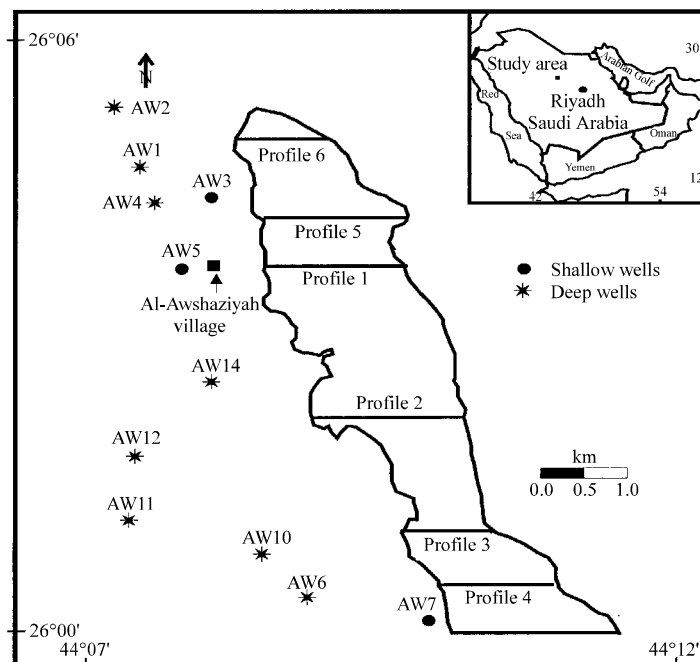


Fig. 3: Location map of Sabkha water and wellwater samples

Climate of the Area

The Arabian Peninsula is characterised by hot climate for the greater part of the year to northerly winds moving from the eastern Mediterranean towards the Arabian Gulf. Variation of rainfall between years is high and long periods of drought are common without rain. The climate of the area is extremely hot and dry as indicated by the climatic data for the years 1996-1999. The average mean, maximum and minimum air-temperature ranged between 19.32 and 45.4, rainfall 0 and 60 mm year⁻¹ and the pan-evaporation between 81.4 and 395.8 mm year⁻¹. The data show a great variation in the climatic parameters between the years. This indicated that evaporation of water will be highly affected by climatic factors during the whole year.

Sampling and Analytical Methods

Thirty-two Sabkha water and, eleven shallow and deep well water samples were collected from the Sabkha basin and the surrounding wells (Fig. 3). The Sabkha water samples were collected from the pit holes of each profile 24 h after digging when the water table became static and reached equilibrium with the land topography of the Sabkha. The well water samples were collected from the operational wells only. All the water samples (Sabkha water and well water) were collected in high-density bottles for chemical and isotopic analysis. The water samples were stored temporarily in an ice chest before transferring to the analytical laboratory.

Physical parameters such as water temperature, pH and EC were measured instantly at the time of sample collection. Major cations (Na⁺, K⁺, Ca⁺⁺ and Mg⁺⁺) were analyzed using flame photometer. The anions (Cl⁻, SO₄²⁻, NO₃⁻ and HCO₃⁻) were determined using ion chromatography (IC). Calculations of cation-anion balance show acceptable data quality. The AQUACHEM 4 (PHREEQC) program was used to calculate all ionic relationships and the saturation indices for Sabkha water and well waters (Parkhurst, 1995).

Thirteen Sabkha water and six well water samples were analyzed for stable isotope ($\delta^{18}\text{O}$ and δD) by the Pakistan Institute of Nuclear Science and Technology, Radiation and Isotope Application Division.

RESULTS AND DISCUSSION

Sabkha Water

The dominant cations order is $\text{Na}^+ > \text{Mg}^{++} > \text{K}^+ > \text{Ca}^{++}$ and that of anions is $\text{Cl}^- > \text{SO}_4^{--} > \text{NO}_3^- > \text{HCO}_3^-$. The total dissolved solids (TDS) ranged from 124860-464750 mg L^{-1} with an average value of 351670 mg L^{-1} (Table 1). The Na^+ ion ranged from 28420-100000 mg L^{-1} with an average value of 76978 mg L^{-1} and Cl^- ranged from 73103-227696 mg L^{-1} with an average value of 129713 mg L^{-1} in Sabkha water. High evaporative climatic conditions are mainly responsible for high concentration of Na^+ and Cl^- in the Sabkha water.

The data was plotted on a piper diagram (Fig. 4). The Sabkha water was classified into three types of water i.e. $\text{Na}^+ \text{-Mg}^{++} \text{-Cl}^-$ water (13 samples); $\text{Na}^+ \text{-Mg}^{++} \text{-Cl}^-$ water (10 samples) and $\text{Na}^+ \text{-Cl}^-$ water (9 samples). The data was also plotted on Durov diagram and fall into the zones of reverse ion exchange (Fig. 5). The ionic ratios of the Sabkha water show that $\text{Mg}^{++}/\text{Ca}^{++}$ ratio ranged from 1.68-345, Na^+/K^+ ratio from 3.5-66.9 and $\text{Cl}^-/\text{SO}_4^{--}$ ratio from 4.03-46.71 (Table 1).

Table 1: Isotopic, chemical composition and ionic ratio of sabkha water

| Profile No. | Sample No. | TDS | Ca | Mg | K | Na | HCO_3^- | Cl | NO_3^- | SO_4^{--} | $\delta^{18}\text{O}$ | δD | Mg/Ca | Na/K | Cl/ SO_4^{--} | |
|-------------|------------|-----------------------|------|--------|-------|--------|------------------|--------|-----------------|--------------------|-----------------------|------------------|--------|-------|------------------------|--|
| | | (mg L ⁻¹) | | | | | | | | | | -----(%)----- | | | | |
| 1 | P1 | 185250 | 2080 | 12393 | 2000 | 28420 | 292.8 | 82383 | 15.4 | 11162 | 4.38 | 12.91 | 5.96 | 14.21 | 7.38 | |
| | P2 | 416000 | 800 | 15066 | 3000 | 100000 | 229.4 | 217524 | 19.8 | 14762 | 10.54 | 46.97 | 18.83 | 33.33 | 14.74 | |
| | P4 | 443950 | 480 | 48114 | 9357 | 50000 | 854.0 | 222043 | 35.2 | 28670 | 16.40 | 69.35 | 100.24 | 5.34 | 7.74 | |
| | P5 | 464750 | 320 | 60070 | 10000 | 35000 | 1161.5 | 215684 | 30.8 | 41375 | 17.35 | NR | 187.72 | 3.50 | 5.21 | |
| | P6 | 449150 | 160 | 55307 | 10000 | 37000 | 1024.8 | 227696 | 35.2 | 42915 | 17.52 | NR | 345.67 | 3.70 | 5.31 | |
| | P7 | 461500 | 320 | 60070 | 10322 | 37000 | 1284.0 | 226557 | 41.8 | 51150 | 16.57 | 65.10 | 187.72 | 3.58 | 4.43 | |
| | P8 | 445250 | 320 | 51808 | 9354 | 50000 | 1088.4 | 215388 | 41.8 | 40256 | 16.49 | 70.53 | 161.90 | 5.35 | 5.35 | |
| | P9 | 421850 | 480 | 38588 | 8387 | 60000 | 732.0 | 219387 | 24.2 | 32796 | 14.72 | 59.59 | 80.39 | 7.15 | 6.69 | |
| 2 | P13 | 417950 | 800 | 14580 | 2500 | 95000 | 170.8 | 209056 | 19.8 | 11864 | 9.87 | 44.50 | 18.23 | 38.00 | 17.62 | |
| | P14 | 415350 | 960 | 12247 | 2500 | 92390 | 170.8 | 211523 | 15.4 | 11861 | 9.02 | 41.67 | 12.76 | 36.96 | 17.83 | |
| | P15 | 416000 | 1280 | 15260 | 2500 | 93560 | 180.6 | 212996 | 19.9 | 14084 | 10.22 | 44.46 | 11.92 | 37.42 | 15.12 | |
| | P16 | 430950 | 480 | 27216 | 4000 | 77340 | 854.0 | 212286 | 26.4 | 21604 | 12.27 | 52.88 | 56.70 | 19.34 | 9.83 | |
| | P17 | 427700 | 960 | 34215 | 5000 | 60000 | 854.0 | 201208 | 28.6 | 27958 | 14.40 | NR | 35.64 | 12.00 | 7.20 | |
| 3 | P18 | 124860 | 2280 | 3839.5 | 799 | 41294 | 104.9 | 73103 | 213.9 | 2774 | - | - | 1.68 | 51.68 | 26.35 | |
| | P19 | 276138 | 560 | 17642 | 2550 | 80000 | 167.1 | 163400 | 180.0 | 11450 | - | - | 31.50 | 31.37 | 14.27 | |
| | P20 | 305634 | 480 | 16719 | 2550 | 92000 | 183.6 | 181000 | 180.0 | 12500 | - | - | 34.83 | 36.08 | 14.48 | |
| | P21 | 323177 | 400 | 16160 | 2439 | 100000 | 278.0 | 189000 | 178.0 | 14550 | - | - | 40.40 | 41.00 | 12.99 | |
| 4 | P23 | 251564 | 2160 | 5734.8 | 1470 | 86800 | 83.0 | 149200 | 800.0 | 5150 | - | - | 2.66 | 59.05 | 28.97 | |
| | P24 | 252140 | 2380 | 5913 | 1452 | 86400 | 87.8 | 151100 | 538.0 | 4012 | - | - | 2.48 | 59.50 | 37.66 | |
| | P25 | 259875 | 1920 | 6830 | 1580 | 87800 | 87.8 | 154000 | 600.0 | 6800 | - | - | 3.56 | 55.57 | 22.65 | |
| | P26 | 282746 | 1900 | 6810 | 1450 | 97000 | 87.8 | 168000 | 740.0 | 6500 | - | - | 3.58 | 66.90 | 25.85 | |
| | P27 | 275235 | 1910 | 6800 | 1565 | 94000 | 97.6 | 165000 | 750.0 | 4850 | - | - | 3.56 | 60.06 | 34.02 | |
| | P28 | 268778 | 2780 | 5803 | 1655 | 93500 | 87.8 | 160000 | 545.0 | 4150 | - | - | 2.09 | 56.50 | 38.55 | |
| | P29 | 268955 | 2800 | 5903 | 1707 | 93000 | 58.6 | 160500 | 550.0 | 4150 | - | - | 2.11 | 54.48 | 38.67 | |
| 5 | P31 | 401353 | 540 | 42823 | 8180 | 80000 | 744.2 | 219000 | 1750.0 | 48500 | - | -- | 79.30 | 9.78 | 4.52 | |
| | P32 | 390092 | 340 | 42164 | 8440 | 76292 | 673.4 | 209000 | 1550.0 | 51800 | - | - | 124.01 | 9.04 | 4.03 | |
| | P33 | 392871 | 430 | 40901 | 8900 | 79500 | 658.8 | 213000 | 1450.0 | 48000 | - | - | 95.12 | 8.93 | 4.44 | |
| | P34 | 389118 | 480 | 38863 | 10400 | 80500 | 585.6 | 216000 | 1240.0 | 41000 | - | -- | 80.96 | 7.74 | 5.27 | |
| | P35 | 379540 | 440 | 36266 | 5322 | 85000 | 536.8 | 215200 | 1150.0 | 35500 | - | - | 82.42 | 15.97 | 6.06 | |
| 6 | P36 | 346760 | 730 | 20716 | 2940 | 100000 | 119.5 | 208300 | 600.0 | 13200 | - | - | 28.38 | 34.01 | 15.78 | |
| | P37 | 346672 | 1650 | 13393 | 2395 | 96000 | 117.1 | 212500 | 219.0 | 5400 | - | - | 8.12 | 40.08 | 39.35 | |
| | P38 | 322296 | 2700 | 15150 | 2240 | 98500 | 104.9 | 198500 | 600.0 | 4250 | - | - | 5.61 | 43.97 | 46.71 | |

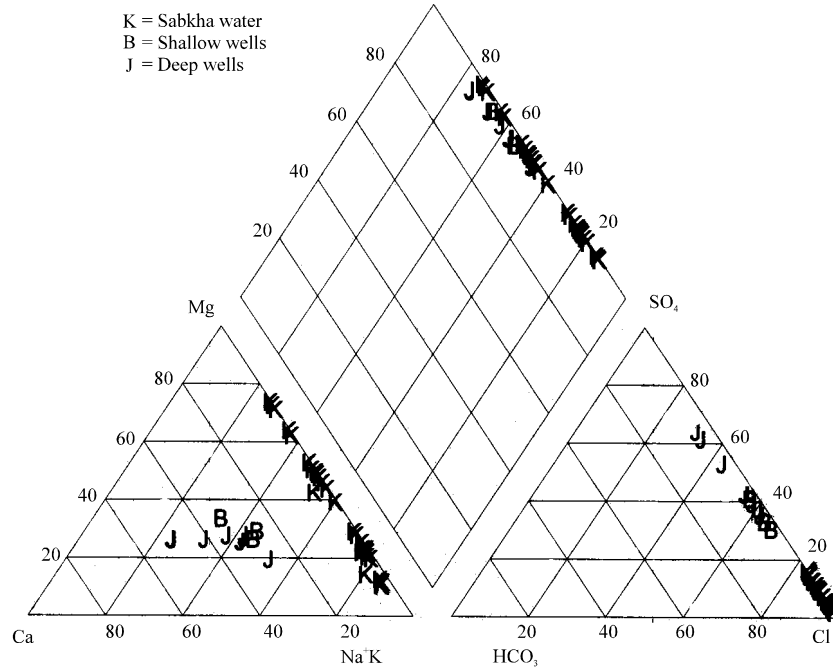


Fig. 4: Piper diagram of sabkha water and wells water samples

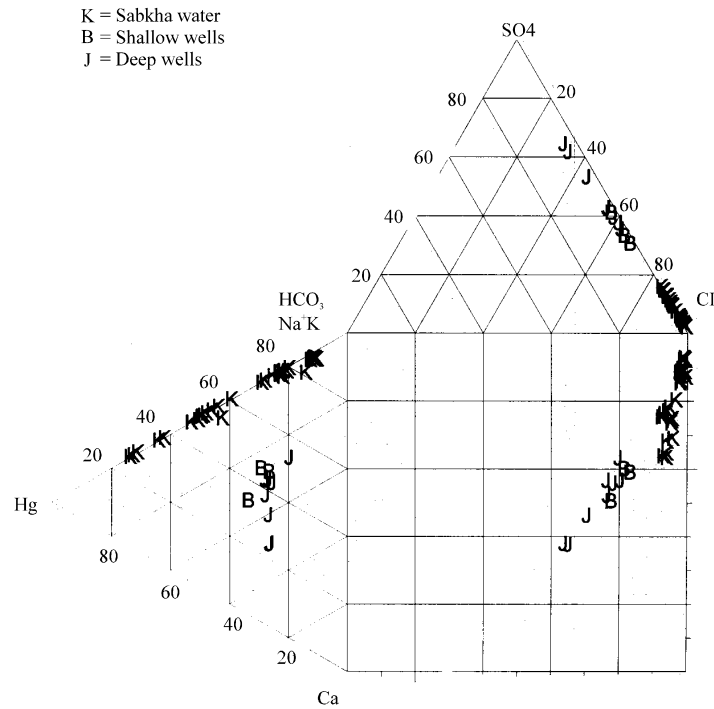


Fig. 5: Durov diagram of sabkha water and wells water samples

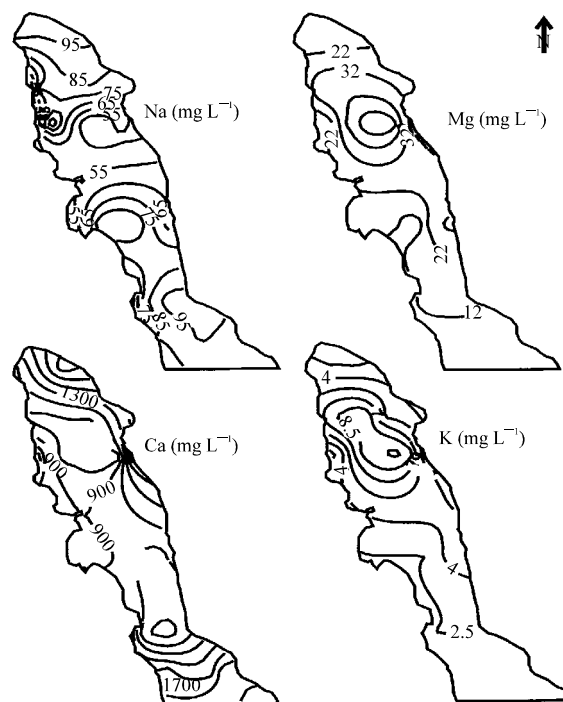


Fig. 6: Cations distribution on Sabkha water

Saturation Indices

Saturation Indices (SI) were calculated for the Sabkha water samples to determine the saturation status of different minerals. A positive SI indicates super-saturation or precipitation of secondary minerals such as calcite, dolomite, gypsum and halite minerals with SI value of 1, 4.2, 0.09 and 0.12, respectively.

Isochronal map of cations of the Sabkha water indicated that cations such as Na^+ , Mg^{++} and Ca^{++} increased toward the margin of the basin while the K^+ concentration increased toward the centre of the basin (Fig. 6). The isochronal map of anions showed that the concentration of anions increased toward the centre of the Sabkha (Fig. 7).

Ion Inter-Relationship

A very poor relationship was found between Cl^- and Na^+ ($R = 0.013$), Cl^- and Ca^+ ($R = 0.477$), Cl^- and Mg^{++} ($R = 0.425$) and Cl^- and K^+ ($R = 0.399$) for the Sabkha water (Fig. 8). There is a tendency of higher Mg^{++} values with increased Cl^- in the Sabkha water. The relationship between Cl^- and Na^+ was made on the total dissolved ion concentration obtained from speciation analysis.

The Sabkha water $\delta^{18}\text{O}$ ranged between 4.38-17.52‰ with an average value of 13.06‰ and $\delta^2\text{H}$ ranged from 12.91-70.53‰ with an average value of 50.8‰ (Fig. 9). The distribution of isotopic contents in the Sabkha water and its enrichment of stable isotopes probably resulted from intense evaporation in study area.

Shallow and Deep Groundwater

The Concentration order of dominant cations and anions is $\text{Na}^+ > \text{Ca}^{++} > \text{Mg}^{++} > \text{K}^+$ and $\text{Cl}^- > \text{SO}_4^{--} > \text{NO}_3^- > \text{HCO}_3^-$, respectively in the shallow wells water and $\text{Na}^+ > \text{Ca}^{++} > \text{Mg}^{++} > \text{K}^+$ and SO_4^{--}



Fig. 7: Anions distribution of sabkha water

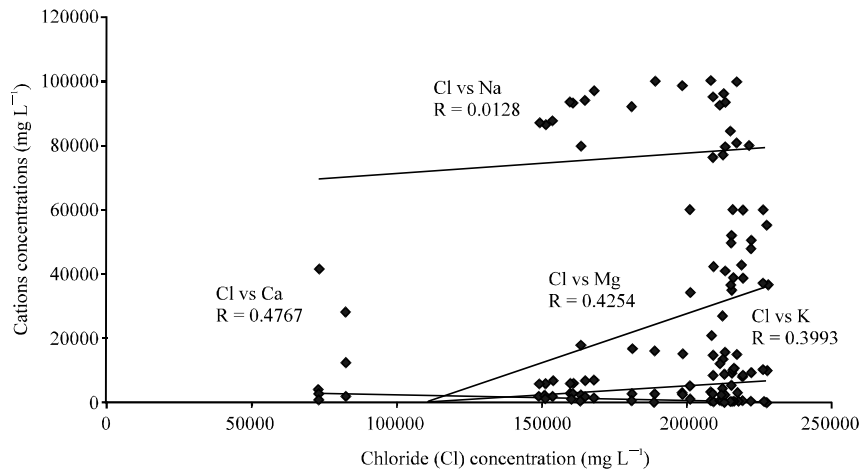


Fig. 8: Bivariate plot of chloride and cations of sabkha water

$>Cl^- >NO_3^- >HCO_3^-$, respectively in the deep wells water (Table 2). The total dissolved solids (TDS, $mg L^{-1}$) ranged from 7184-9952 with an average value of 8982 $mg L^{-1}$ in the shallow wells water and 4340-8580 with an average value of 6265 $mg L^{-1}$ in the deep wells water.

The concentration of sodium (Na^+) ranged from 921-1690 with an average value of 1430 $mg L^{-1}$ in the shallow wells. Chloride (Cl^-) ion is the dominant anion followed by SO_4^{2-} and HCO_3^- and ranged from 2350-3745 with an average value of 3235 $mg L^{-1}$ in the shallow well water. The Na^+ ion

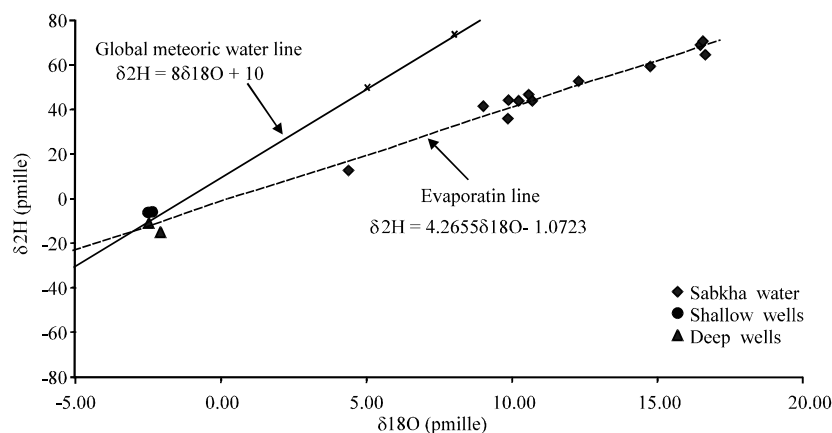


Fig. 9: Isotopic compositions of sabkha water, shallow and deep wells water

Table 2: Isotopic, chemical composition and ionic ratio of shallow and deep wells water

| Sample No. | TDS | Ca | Mg | K | Na | HCO ₃ | Cl | NO ₃ | SO ₄ | δ ¹⁸ O | δD | Mg/Ca | Na/K | Cl/SO ₄ |
|----------------------|------|-----|-----|----|------|------------------|------|-----------------|-----------------|----------------------------------|--------|-------|-------|--------------------|
| | | | | | | | | | | -----(%o)--- | | | | |
| | | | | | | | | | | -----(mg L^{-1})----- | | | | |
| Shallow wells | | | | | | | | | | | | | | |
| AW3 | 7184 | 800 | 491 | 32 | 921 | 156 | 2350 | 217 | 2265 | -2.35 | -5.99 | 0.61 | 28.78 | 1.04 |
| AW5 | 9952 | 852 | 583 | 58 | 1690 | 220 | 3612 | 541 | 2473 | -2.54 | -5.72 | 0.68 | 29.14 | 1.46 |
| AW7 | 9810 | 920 | 522 | 59 | 1681 | 183 | 3745 | 501 | 2251 | - | - | 0.57 | 28.49 | 1.66 |
| Deep wells | | | | | | | | | | | | | | |
| AW1 | 8580 | 760 | 326 | 32 | 1681 | 137 | 2950 | 310 | 2426 | -2.48 | -9.39 | 0.43 | 52.53 | 1.22 |
| AW2 | 4820 | 634 | 248 | 31 | 569 | 144 | 1162 | 196 | 1876 | -2.42 | -10.96 | 0.39 | 18.35 | 0.62 |
| AW4 | 6294 | 710 | 345 | 30 | 890 | 156 | 2016 | 110 | 2085 | -2.36 | -10.4 | 0.49 | 29.67 | 0.97 |
| AW6 | 6176 | 596 | 335 | 38 | 956 | 156 | 1880 | 318 | 1950 | -2.09 | -15.49 | 0.56 | 25.16 | 0.96 |
| AW10 | 7838 | 820 | 396 | 36 | 1251 | 173 | 2525 | 419 | 2270 | - | - | 0.48 | 34.75 | 1.11 |
| AW11 | 4340 | 680 | 218 | 14 | 384 | 178 | 755 | 112 | 2051 | - | - | 0.32 | 27.43 | 0.37 |
| AW12 | 4426 | 696 | 224 | 17 | 385 | 178 | 835 | 138 | 2004 | - | - | 0.32 | 22.65 | 0.42 |
| AW14 | 7648 | 864 | 461 | 59 | 1378 | 181 | 3012 | 478 | 2270 | - | - | 0.53 | 23.36 | 1.33 |

in the deep wells ranged from 384-1681 with an average value of 936.75 mg L⁻¹, while the Cl⁻ ion ranged from 755-3012 with an average value of 1892 mg L⁻¹ (Table 2).

Earth-alkaline water type with the dominance of sulphate -chloride is the dominate water type in the shallow and deep well water (Fig. 4). The well water samples were also plotted on Durov diagram (Fig. 5). It was found that all the shallow wells water and some of the deep wells water samples fall in field 8 indicating a possible reverse ion exchange.

Ion Inter-Relationship

A regression analysis was run to develop relationship between Cl⁻ and Ca⁺⁺, Na⁺, Mg⁺⁺, K⁺, SO₄⁼⁼ and Cl⁻+SO₄⁻ for the shallow and deep wells (Fig. 11). A very strong correlation was found between Cl⁻ vs Na⁺ (r = 0.955, shallow wells; R = 0.991, deep wells), Cl⁻ vs Ca⁺⁺ (R = 0.758, shallow wells; R = 0.488 deep wells) and Cl⁻ vs Mg⁺⁺ (R = 0.800, shallow wells; R = 0.489, deep wells). It was noticed that the correlation is poor for Cl⁻ vs Ca⁺⁺ and Cl⁻ vs Mg⁺⁺ for the deep wells (Fig. 10). Similarly, the correlation is very strong for Cl⁻ vs Cl⁻+SO₄⁻ (R = 0.932) for the shallow well waters and very poor (R = 0.568) for the deep well waters. The correlation between Cl⁻ and

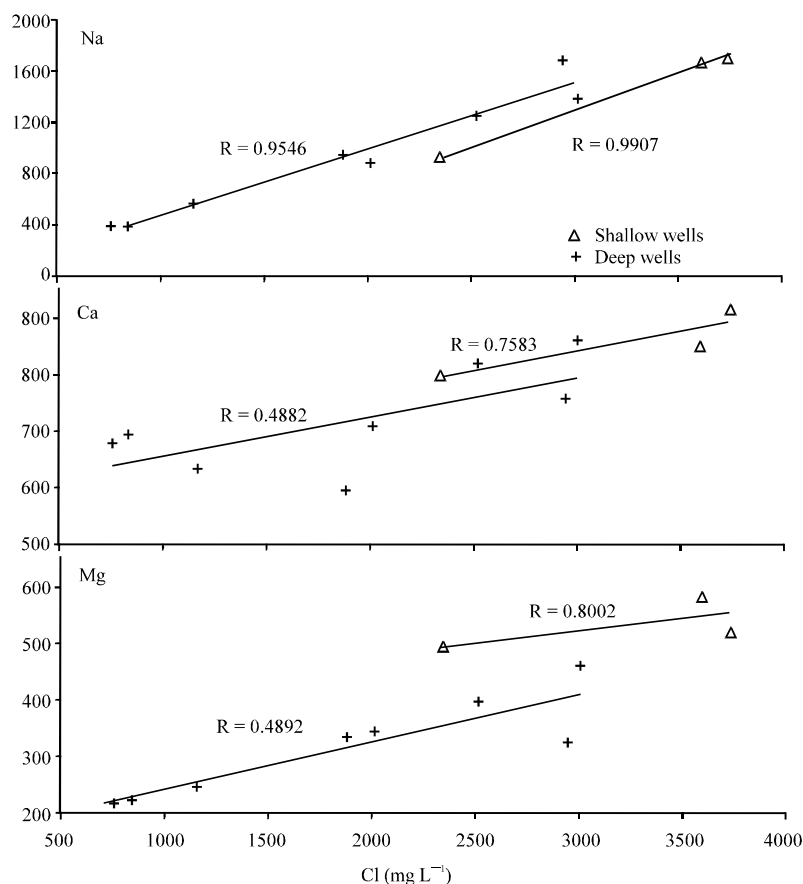


Fig. 10: Plot of Cl concentration with Na, Ca and Mg of shallow and deep wells

SO_4^{--} is good ($R = 0.657$) for the shallow well waters and very poor ($R = 0.138$) for the deep well waters. However, the relationship between Cl^- vs K^+ is very strong ($R = 0.997$) and poor ($R = 0.631$) for the shallow and deep well waters, respectively (Fig. 11).

The mean values of ionic ratios for $\text{Mg}^{++}/\text{Ca}^{++}$, Na^+/K^+ and $\text{Cl}^-/\text{SO}_4^{--}$ ranged from 0.57-0.68, 28.4 -29.14 and 1.04-1.66 in the shallow wells, respectively. Whereas, it ranged between 0.32-0.56, 18.35- 52.53 and 0.37-1.33 in the deep well waters, respectively (Table 2).

Saturation Indices

The mean Saturation Indices (SI) of calcite, dolomite, gypsum and halite for shallow and deep waters were -0.03, 0.10, -0.18, -4.12 and -0, 06, -0.13, -0.08, -4.60, respectively. The negative values of SI indicate that the minerals are in unsaturated state and will dissolve more ions when in contact with the solid phase minerals. The positive values of SI show that the minerals are in supersaturated state and will not dissolve any further ions from the solid phase minerals.

The stable isotopic compositions of shallow well water ranged from $\delta^{18}\text{O}$ -2.35 to 2.54‰, with an average value of -2.34 and δD from -5.72 to -5.99‰ with an average value of -5.86, while in the deep well waters, these ranged from $\delta^{18}\text{O}$ -2.09 to -2.48‰, and δD ranged from -9.39 to -15.49‰ (Table 2 and Fig. 9).

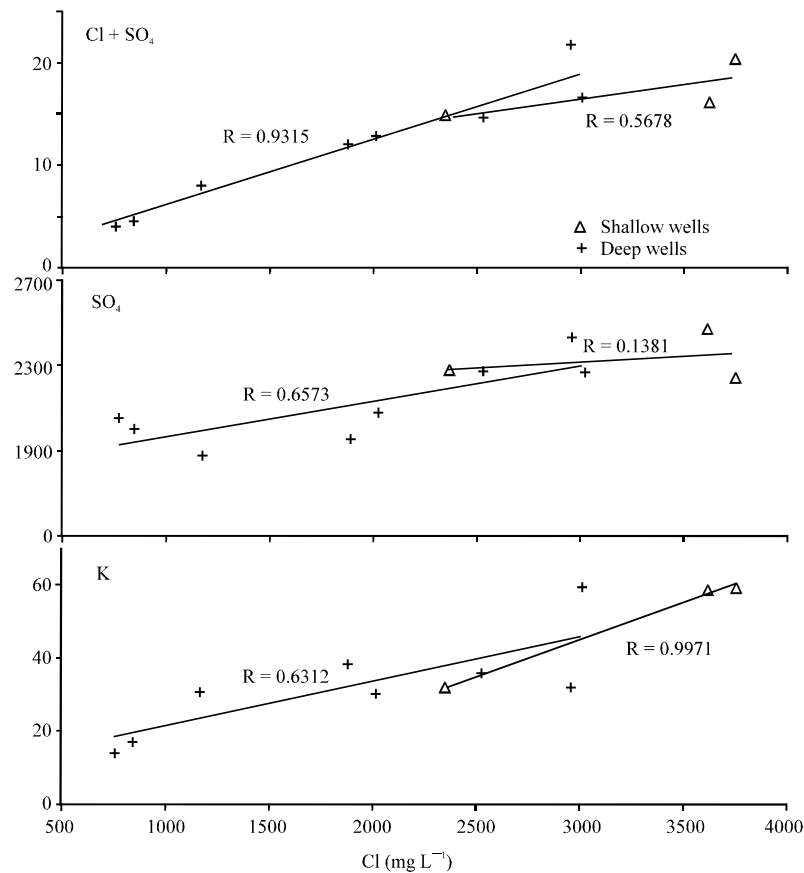


Fig. 11: Plot of Cl concentration with K_1 SO_4 and $Cl+SO_4$ of shallow and deep wells

DISCUSSION

The impact of inland Sabkha water bodies was an evidence of mixing between meteoric groundwater and evaporated reservoir water. It seems to be one of the recharge sources for shallow wells (4-13 m deep) through flood water especially in rainy season and discharge water either in the form of sabkha water or capillary fringe in the summer season. Detailed study of Sabkha sediments and water showed strong similarity between the parent rocks and groundwater. The ground water chemistry also supported significant rock-water interaction (Al-Harbi *et al.*, 2006).

The Total Dissolved Solids (TDS, $mg L^{-1}$) ranged from 124860-464750 $mg L^{-1}$ in the Sabkha water (Table 1); 7184-9952 and 4340-8580 $mg L^{-1}$ for shallow and deep wells, respectively (Table 2). It is observed that the TDS values are low in those parts of the Sabkha where thin salt layers were observed on the top of the soil surface. The TDS values of shallow and deep wells are high which might be due to the presence of high concentration of NaCl (Hsu and Siegenthaler, 1969).

High TDS and the domination of Na^+ and Cl^- ions both in the Sabkha water and the well water could be the results of several factors. Evaporation is the main factor of brines in most of the Sabkha lands in an arid environment. Apart from evaporation, water interacts with the surrounding parent rocks during its flow and dissolves minerals depending on the SI value for that particular mineral.

An earlier study showed that the concentration of dissolved ions in Sabkha water of arid and semi-arid regions generally depends on the level of concentration subject to evaporation, geology, quality of water flow, inter-change of ions, besides human activities (Karanath, 1991, 1997; Bhatt and Saklani, 1996). Since the water table is very shallow in the Sabkha basin (0-100 cm), hence much evaporation takes place especially during hot and dry summer season.

The mean sodium (Na^+) concentration in the Sabkha water ranged from 28420-100000 mg L^{-1} (Table 1). The contour map (Fig. 5) of Sabkha water shows that Na^+ distribution has a unique pattern. This suggests an apparent mixing of Sabkha water with the fresh water, especially during the rainy season through surface runoff from the adjoining outcrops of the area with the help of different drainage patterns thus resulting in the dilution of Sabkha water. Sodium bearing minerals like albite and other minerals of plagioclase feldspar are not very common in the nearby outcrops. However, little contribution from the weathering of these minerals can not be ruled out.

The concentration of cations such as Na^+ , Mg^{++} , Ca^{++} and K^+ is very low in the shallow and deep well waters (Table 2) except shallow well No. 5 (Fig. 3), where the concentration of Na^+ (1690 mg L^{-1}) and Mg^{++} (583 mg L^{-1}) is higher than the other well waters. The exceptionally high concentration of Na^+ and Mg^{++} ions in well water indicated that most probably these wells are situated on limestone or gypsiferous formations, a major source of carbonate minerals.

The chloride (Cl^-) concentrations in the Sabkha water ranged from 82383-227696 mg L^{-1} . The contour map of the Sabkha water showed that Cl^- concentration is significantly low in the shallow water table area (Fig. 7). Similar to the Na^+ ion, the Cl^- ion is highly soluble and is the least to be precipitated. Therefore, the Cl^- anion dominated the super saturated brine. Most of the chloride in the Sabkha water seems to be present as sodium chloride, but the chloride concentration exceed to sodium in the present case which could be attributed to base exchange phenomena and to the thickness of salt layer at the soil surface. The main composition of saturated salts in the Sabkha water mainly consists off NaCl, so whenever there is high evaporation process, NaCl will reach super-saturation state and precipitate thus reducing the Cl^- ions in the Sabkha water. The major anions such as Cl^- , SO_4^{--} and HCO_3^- are dominant in the well waters (Table 2). The data indicate that most of these ions decrease or increase in identical manner in all wells. The dissolution of surrounding carbonates minerals is responsible for the increase of Cl^- in the wells. The high concentration of NaCl salt both in the Sabkha brine and the well waters seems to be the result of dissolution of limestone and dolomite minerals (Aqrawi, 1995).

The nitrate (NO_3^-) concentration in Sabkha water ranged from 15.4-1750 mg L^{-1} . The contour map of the Sabkha water shows that NO_3^- concentration was appreciably low in the whole Sabkha except north and extreme south part (Fig. 7). The NO_3^- contents are exceptionally high in all the well waters (Fig. 2). High concentration of nitrate (NO_3^-) in the Sabkha and well water showed that there is a possibility of NO_3^- ion intrusion into the Sabkha water and well waters from the adjacent agricultural areas receiving excess nitrogen fertilizers (such as urea and ammonium nitrate) to increase agricultural production.

The positive correlation between Na^+ , Mg^{++} , K^+ and Cl^- (Fig. 7, 8, 10, 11) in both the sabkha and wells water suggest that these ions are part of a buried evaporate body in the Sabkha basin. Dissolution of halite also increases level of salinity in the Sabkha. Field and mineralogical evidences from the same Sabkha areas suggest that evaporite of the Sabkha basin is predominantly composed of halite (NaCl) mineral (Al-Harbi *et al.*, 2006). For example, in Dead Sea area, the precipitation of halite (NaCl) from the original seawater is responsible for the present composition of the brine, where Na/Cl ratio is much lower (0.27) in Dead Sea brine as compared to the sea water (0.86). The Cl-Na correlation shows a linear trend, which describes the behaviour of most waters (Fig. 10). The linear trend also seems to reflect the evaporation or mixing processes that might occur in the wells (Portugal and Romero, 2006).

When the salt concentration increases, the precipitation sequence of different minerals is calcite >gypsum >halite. The ions such as Ca^{++} , K^+ , Mg^{++} and SO_4^{--} are also contribute to the sabkha brine (Hamdi-Aissa *et al.*, 2004). The results suggest an atmospheric source, evaporation chemistry of the original source solutions and to some extent the water-rock interaction.

The ionic ratios of the Sabkha water such as $\text{Mg}^{++}/\text{Ca}^{++}$ ranged from 1.68-3.45 (Table 1 and 2). The $\text{Mg}^{++}/\text{Ca}^{++}$ ratios ranged from 0.57-0.68 and 0.32-0.56 in the shallow and deep well waters, respectively. The Mg/Ca ratio is more than 0.5-0.9 which reflects the water movement through limestone or dolomitic limestone (Hsu, 1963; Hem, 1992). White *et al.* (1963) stated that Na^+/K^+ ratio is more than that of natural waters (15-25). This may probably be due to the cationic exchange process between sodium and potassium ions.

The relative concentration of ions was plotted on piper diagram (Fig. 4), which suggests a mixture of cations ranging from SO_4^{--} type to NaCl ions which basically depends on the sub-stratum lithology and its degree of evaporation. Well waters and the Sabkha water are dominated by Na^+ and Cl^- ions. The salinity increases with depth in the Sabkha and the shallow well waters. Such type of salinity in the closed basin complex was reported in arid zone environments (Duffy and Al-Hasan, 1988; Rodriguez-Rodriguez, 2002; Andreo, 2004).

The Durov diagram (Fig. 4) shows that dominant anion was Cl^- and the dominant cation was Na^+ . However, where dilution and mixing might have occurred, the samples indicate reverse ion exchange of NaCl without domination of cation and anion, the dominance of Cl^- and Na^+ ions indicated the end-point water (Lloyd and Heathcote, 1985).

The concentration of $\delta^{18}\text{O}$ and δD of the sabkha water is aligned to the right of the global meteoric water line following the equation $\delta\text{D} = 4.21 \delta^{18}\text{O} - 0.687$ ($R^2 = 0.0574$) based on $\delta\text{D} \%$ v/s $\delta^{18}\text{O} \%$ plots. The intersection of global meteoric and evaporation line at -2.0 indicates that sabkha water is probably the outcome of discharge from the shallow well water (Fig. 9). It is further corroborated by well inventory studies in near basin. The well inventory data along the sabkha brine (well No. 3, 5 and 7) shows 4-13 m and deep wells away from the sabkha ranges from 40-100 m. The gradient of water flow of the shallow wells is towards the sabkha basin. The sabkha water showed enrichment of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ and this might be due to the evaporation process. It's shifted from Global Meteoric Water Line (GMWL) along line with slope 4.27 and intersects with GMWL at isotopic composition of the shallow and deep well water, which indicated that majority of the sabkha water and well waters are meteoric water origin (Fig. 9) (Rodriguez *et al.*, 2006).

CONCLUSIONS

The results showed that the hydrological regime of Sabkha is characterized by dissolution of rocks of Permian-Early Triassic (Khuff Formation and Sudair Formation) which has decisive influence on the hydro-geological evaluation. A very strong correlation was found between Cl^- vs Na^+ ($R = 0.955$, shallow wells; $r = 0.991$, deep wells), Cl^- vs Ca^{++} ($R = 0.758$, shallow wells; $R = 0.488$ deep wells) and Cl^- vs Mg^{++} ($R = 0.800$, shallow wells; $R = 0.489$, deep wells). Sabkha water is dominant by sodium-magnesium chloride, magnesium-sodium-chloride and sodium-chloride water types. Halite is the most abundant evaporate mineral which is an economic source of NaCl salt in the region. High concentration of nitrate (NO_3^-) in the Sabkha and well water showed that there is a possibility of NO_3^- ion intrusion into the Sabkha water and well waters from the adjacent agricultural areas receiving excess nitrogen fertilizers to increase agricultural production. Based on the major ion chemistry and the isotopic analysis, the Sabkha water is of meteoric origin and the process of excessive evaporation led to the development of inland Sabkha in Al-Qaseem area having arid and semi arid climatic conditions. The data of Sabkha water suggest that the water flow regime is towards the Sabkha basin especially

during the rainy season and high flood conditions. The close basin complex of Sabkha, in which the aquifer limits are indeterminate due to variety of the materials and complexity of the geological setup and the groundwater discharge, followed a centripetal pattern towards the Sabkha basin.

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