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Hydrogeochemical Processes of Alkhobar Aquifer in Eastern Region, Saudi Arabia

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Abstract: A field investigation was carried out to determine the Physical and chemical characteristics of Al-Khobar aquifer in the Eastern region of Saudi Arabia. Total Dissolved Solids (TDS) varies from 4400 mg L^{-1} along the Gulf coast on the eastern side to around 1800 mg L^{-1} on the western side. Sodium (Na) is the dominant cation followed by Mg, Ca and K in descending order. Whereas, the anion concentration order is $Cl > SO_4 > HCO_3$. Nitrate concentration was found to be higher than the recommended limit for drinking purposes. The Saturation Indices (SI) indicated that the regional groundwater is under-saturated with respect to calcite, dolomite, gypsum, anhydrite, halite, pyrite and aragonite minerals and oversaturated with respect to goethite and hematite minerals. The hardness of groundwater is very high as compared to the established standards. The F contents are within permissible limits for drinking. The nitrate contents are within permissible limits for domestic use. Two water types i.e., Na-Ca-Cl-SO_4 and Na-Ca-Mg-Cl-SO_4 dominate the Al-Ahsa whereas Na-Ca-Cl and Na-Ca-Cl-SO_4 water types are dominant in Al-Dammam, Al-Khobar and Al-Qatif areas. Overall, the study provided useful information on some important hydrogeochemical processes in groundwater of the eastern region. Further studies are required to determine heavy trace metals concentration for multiple uses.

Key words: Alkhobar aquifer, Dammam formation, turbidity, total-hardness, total-dissolved-solids, saturation indices, nitrate, fluoride

INTRODUCTION

Water quality is important for the development of civilization and to establish database for planning future water resources development strategies. In Saudi Arabia, water resources are limited, non-renewable and vary from region to region. The groundwater contains dissolved salts and other constituents depending on the geochemistry of the underlying aquifer. The presence of different chemical and physical constituents in excess of their permissible limits for various uses can create health hazards and environmental problems. The Eastern Province lies in the west of Arabian Gulf and extends up to 400 km.

Previously, many studies have been conducted in Saudi Arabia on groundwater quality in Al-Qaseem Region (Faruq *et al*., 1996), Al-Ahsa Oasis, Eastern Province (Hussain and Sadiq, 1991; Al-Hawas, 2002), Saudi groundwater chemistry (Mee, 1983; Allael Din *et al*., 1993) and Wadi Al-Yamaniyah (Bazuhair and Alkaff, 1989). Hussein and Bazuhair (1992) studied the groundwater in Hddat Al-Sham-Al-Bayada Area, Western Saudi Arabia. They found that each of the aquifers is characterized by its own water quality. Also, the groundwater occurs in the area within two geological units: the alluvial deposits of the wadi system and the classic coarse members of the Cretacceous-Tertiary sedimentary succession. Recently, Omar *et al*. (2006) evaluated water quality in Wadi Malal, Al-Madinah Al-Munawarah and found that the salinity and nitrate concentration are much higher than the established standards for various uses. Furthermore, well waters in Wadi Malal along its flow path are too saline and the nitrate levels are too high to be used as drinking water. Information on groundwater quality in the Eastern Region, Saudi Arabia is limited for its efficient utilization and management. This study was, therefore, conducted to determine important physical and chemical characteristics of groundwater for planning future management options in the Eastern Region.

MATERIALS AND METHODS

Hydrogeology of the study area: The geology and hydrogeology of the aquifers in the Eastern Province of Saudi Arabia were described by Naimi (1965). The ground water potential of the area has been investigated in great details for Ministry of Agriculture and Water (MAW) during the last two decades by Italconsult (1969), BRGD (1976, 1977) and GDC (1980).

The Dammam Formation, which mainly consists of carbonate rocks with inter- bedded shales and marls, is

Age		Formation	Member	Generalized lithologic description	Range of thickness	Hydrogeology
Quaternary		Surficial deposits		Gravel, sand and slit	Generally less than 30 m	Variable productivity, depending on recharge.
Tertiary	Neogene	Hofuf		Sandy marl and sandy limestone	0-95 m	Generally called Neogene Aquifer Irregular occurrences of water. Prolific aquifer in Al-Ahsa.
		Dam		Marl and shale; subordinate sandstone; limestone	0-125 m	
		Hadrukh		Marly sands, siltstones and sandy limestone	0-90 m	
	Eocene	Dammam	Alat	Limestone with sandy fissures; orange marl at the base	0-85 m	Moderate aquifer
			Khobar	Skeletal-detrital limestones, dolomitic limestones, marls at the base	0-60 m	Aquifer
			Alveolina Limestone	Limestone interbeded with marls or shales	0-20 m	Aquitard
			Salla Shale	Dark-coloured fissile shales and marls with small gypsiferous lenses	0-25 m	Aquitard
			Midra Shale			
		Rus		Marl, chalky limestone, anhydrite	10-200 m	Aquitard
	Paleocene	Umm Er Radhuma		Limestone, dolomitic limestone and dolomite	200-600 m	Aquifer
Cretaceous	Aruma			Limestone; subordinate dolomite and shale	400-600 m	Poor aquifer

Fig. 1: Generalized litho-stratigraphic sequence of Tertiary in Eastern Saudi Arabia (After Italconsultant, 1969)

bounded at the base by the chalky limestones of the Rus Formation and at the top by the Eocene-Neogene unconformity. The Formation is subdivided into five members: the Midra Shale, the Saila Shale, the Alveolina Limestone, the Khobar and the Alat Member (Fig. 1). The last two members consist of an upper limestone unit and a lower unit and they are the most economically exploitable aquifers in the Dammam Formation.

The Midra and Saila Shale members are considered a single lithological unit in view of the great lithological similarity between them. They constitute the basal level of the Dammam Formation and consists of blue to blue gray marl or shales and the limestones. Their combine thickness over the whole study area ranges from zero on the top of the Ghawar anticline west of Hofuf, to 20-25 m in the coastal belt area, the average thickness being 15-20 m. These two members, together with the underlying Rus Formation, form the hydraulic separation between the Dammam and Umm Er Radhuma Formations.

The Alveolina Limestone Member overlies the Midra and Saila Shales and is bounded at the top by the Khobar Member. The thickness of this member ranged from zero to about 20 m. The Khobar member overlies the Alveolina Limstone Member. It is bounded at the top by the marls of the Alat Member and it consists mainly of skeletal-detrital limestones, dolomitic limestone and a basal marl unit. The limestones and dolomitic limestones of the Khobar Member form the most productive reservoir in the Dammam Formation. The thickness of the Khobar limestone member ranges from a minimum of zero meter to a maximum of about 60 m.

Previous investigations by Italconsult (1969) and BRGD (1977) have shown that the transmissivity of the Khobar aquifer is extremely variable, ranging from a minimum of 3.0×10^{-6} $m^2 sec^{-1}$ to a maximum of 3.0×10^{-1} $m^2 sec^{-1}$. Storage coefficient (10^{-3} to 10^{-5}) are low, indicating a confined aquifer behaviour.

The quality of water in Al-Khobar aquifer is frequently suitable for domestic and agricultural usages. Generally, good quality waters are found in places where the transmissivities are higher. The salinity data (Italconsult, 1969) show two main areas of low salinity water where the total dissolved solids are less than 2000 mg L^{-1}. One of these areas extends from the southwest to the northeast more or less along the Ghawar anticline and the other extends from the western outcrop zone towards the coastal belt. They join in an area along the coastal belt which extends from Qatif towards Jubail. To the north of the latitude 27°N and east of the longitude 84°E, the salinity values increase very rapidly reaching up to 12,000 mg L^{-1}. The Alat member overlies the Khobar and is bounded at the top by the continental clastics and shales of the Hadrukh Formation. The quality of water in the Alat aquifer is similar to that in the Khobar aquifer and in both cases two extensive low salinity zones exist. However, in the Alat aquifer the low salinity zone in the coastal belt occupies a much larger area which extends towards Al-Khobar (Italconsult, 1969).

Water sample collection: A total of 121 groundwater samples were collected from 4 different locations namely Al-Ahsa (51), Al-Khobar (38), Al-Dammam (18) and Al-

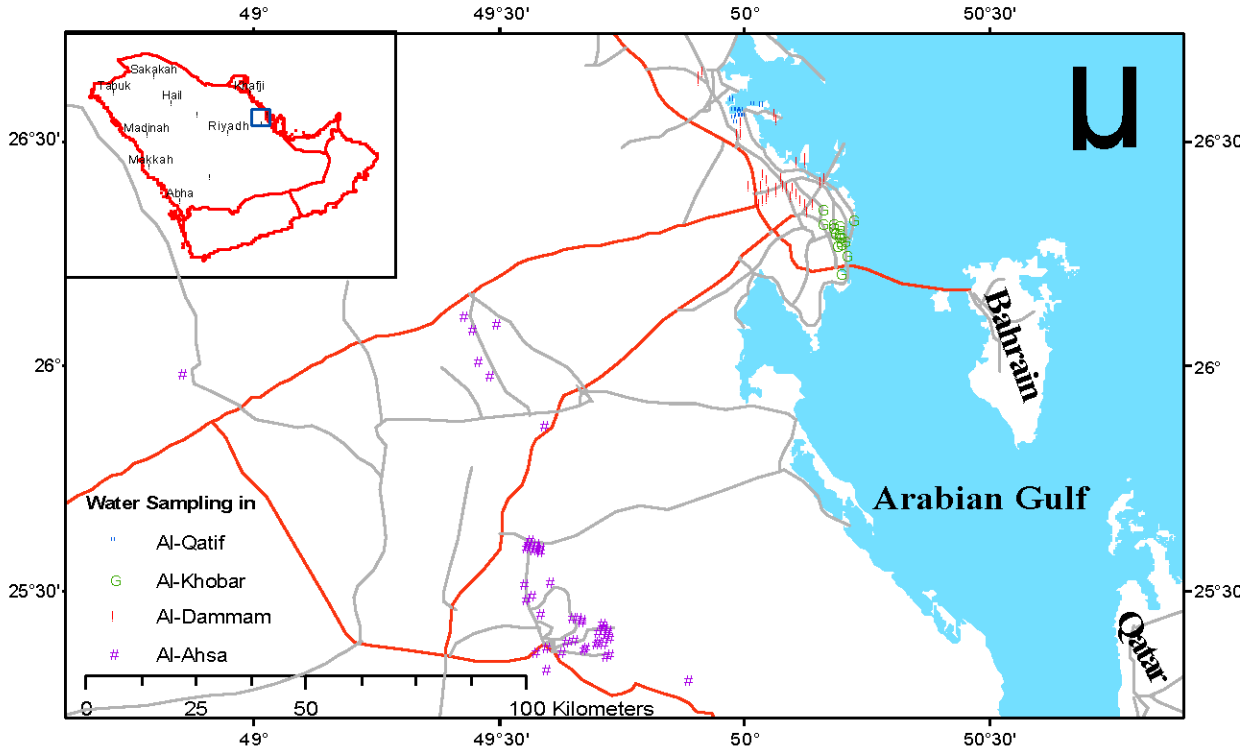

Fig. 2: Location map of study area

Table 1: Permissible limits of different ions (mg L^{-1}) in water for domestic uses

Parameters	Permissible/recommended upper limits
pH	6.5-8.5
Total Dissolved Solids	1000
Alkalinity/Hardness	500
Nitrate (as NO_3)	45
Fluoride	1.5-2.0
Magnesium	150
Calcium	200
Sodium	200
Chloride	250

Qatif (14) in the Eastern Region, Saudi Arabia during the year 2003 (Fig. 2). The water samples from the selected wells were collected after purging the wells by pumping for about two to three hours until the Electrical Conductivity (EC) and the pH of water stabilized. The water is used mainly for agriculture, domestic and industrial purposes. The water samples were collected in sterile bottles and preserved in an ice-chest before transporting to analytical laboratory for analysis. The depth of each well was also recorded at different locations.

Measurement of physical parameters: Parameters such as temperature, pH, turbidity, odor, taste, total alkalinity and Dissolved Oxygen (DO) were measured instantly at the time of collection of samples.

Chemical analysis: The water samples were analyzed for EC, TDS, alkalinity, total hardness, Ca, Mg, Na, K, Cl, F, HCO_3, SO_4, fluoride (F) and NO_3 by following the United States of America's Environmental Protection Agency's Method 2007 (USEPA, 1979).

Water quality classification: The data were evaluated by different mathematical models and equations. The results were compared with the established water quality standards (National and or International) for safe multiple use of groundwater with minimal pollution problems (Table 1). The most important elements considered were NO_3, F and Cl, because their concentration in water above the permissible limits is harmful for the living organisms.

Saturation Index (SI) and cations/anions ratios: These calculations provided information on various dissolution/precipitation reactions taking place between different cations and anions on the solute chemistry of the ground water, magnitude of rock-water interaction and its source of origin. A comparison of chemistry of well waters along the coastal line with the wells in the inland areas determined the level of seawater intrusion into freshwater of this alluvial aquifer extending from coastal area to around 400 km inland westward.

RESULTS AND DISCUSSION

Physical parameters

Aquifer depth: Important water bearing aquifers in the eastern region of Saudi Arabia are Wasia, Umm-Er-Radhuma, Alat, Alkhobar and Neogene. Generalized Litho-stratigraphic sequence of Tertiary in Eastern Saudi Arabia is shown in Fig. 1. The water quality varied within each aquifer as well as between different aquifers. It generally increases in the direction of the hydraulic gradient ranging from 2000-6000 mg L^{-1} (Wasia) and 100-3500 mg L^{-1} (Neogene). The total depth of wells in various locations ranged from 128-250 m, 62-170 m, 92-170 m and 120-160 m in Al-Ahsa, Al-Dammam, Al-Khobar and Al-Qatif, respectively (Table 2).

pH of water: The pH ranged between 6.8-7.3 (Al-Ahsa), 6.63-7.4 (Al-Dammam), 6.5-7.29 (Al-Khobar) and 6.72-7.4 (Al-Qatif) in the study area (Table 2). The permissible limit of pH in waters is between 6.5-8.5 for drinking purposes without causing any health hazards. The groundwater is in neutral state and a good solvent. Because any significant variation in pH above or below the neutral value of 7 can affect the solubility of some salt ions present in the soil-water system or water-rock interaction.

Turbidity: Turbidity is a principal physical characteristic of water and is an expression of the optical property that causes light to scattered and absorbed by the particles and molecules rather than transmitted in straight lines through a water sample. It is caused by suspended matter or impurities that interfere with the clarity of water. These impurities include clay, silt, finely divided inorganic and organic matter, soluble colored organic compounds and plankton and other microscopic organisms (American Public Health Organization, 1998). Mean turbidity values of groundwater (expressed as NTU) ranged between 0.28-6.95 (Al-Ahsa), 0.58-12.20 (Al-Dammam), 0.48-9.30 (Al-Khobar) and 0.52-2.71 (Al-Qatif) in the study area (Table 2).

Interpretation of groundwater chemistry

Electrical Conductivity (EC): Mean EC (expressed as dS m^{-1}) ranged from 1.23-5.05 (Al-Ahsa), 2.20-8.6 (Al-Dammam), 3.23-5.2 (Al-Khobar) and 0.96-5.26 (Al-Qatif) in the study area (Table 2). The EC values show that the ground water of the area is medium to highly saline. The high salt concentration of water shows that significant dissolution and or precipitation reactions are taking place in the aquifer depending upon the solubility constants of different minerals present in the limestone aquifer. This phenomena is being explained exclusively from the saturation indices of the ground water.

Water salinity varies from 4400 mg L^{-1} (total dissolved solids, TDS) along the Gulf coast on the eastern side to around 1800 mg L^{-1} on the western side of the study area. The high level of TDS on the eastern side could be due to: High pumping rate causing deterioration of groundwater quality and possible seawater intrusion into the adjoining aquifer through natural drainage to the depleting zone (Fig. 3a, b). Overall, the TDS of well waters showed decreases from east to west direction, but the water quality improved in the middle (western part) and the south-east corner of the study area. This improvement in water quality with respect to total salinity (TDS) could be attributed to shallow well depth and minimum influence of seawater intrusion.

The chemical analysis indicate that Na is the dominant cation followed by Mg, Ca and K in descending order. Whereas, the anion concentration order is $Cl > SO_4 > HCO_3$ (Table 3). The data also show that Na and Cl ions dominate the total salinity of water suggesting the presence of NaCl compound more than others in the groundwater.

Total hardness: Total hardness is defined as the sum of the concentration of calcium and magnesium ions, expressed as calcium carbonate in mg L^{-1}. Because hard waters take a large amount of soap to produce a lather or foam. Hardness is an important criterion for determining the suitability of water for domestic, drinking and industrial purposes. Mean hardness of water ranged from 460-1420 (Al-Ahsa), 872-1660 (Al-Dammam), 762-1196 (Al-Khobar) and 132-1248 (Al-Qatif) in different locations (Table 2). Overall, the groundwaters in the study area are very hard and unfit for domestic use unless treated to remove hardness. The concentration of $CaCO_3$ dissolved in water by its degree of hardness is presented below:

Table 2: Mean Ranges of Some Physical and Chemical Characteristics of Groundwater of Eastern Region.

Aquifer	Total samples (No.)	Depth (m)	pH	EC (dS m^{-1})	Turbidity (NTU)	NO_3 (mg L^{-1})	F (mg L^{-1})	T. hardness (mg L^{-1})
Al-Ahsa	51	128-250	6.8-7.3	1.23-5.05	0.28-6.95	6.3-73.8	1.0-1.8	460-1420
Al-Dammam	38	62-170	6.63-7.4	2.20-8.6	0.58-112.20	11.4-26.4	1.1-1.4	872-1660
Alkhobar	18	92-170	6.5-7.29	3.23-5.2	0.48-9.30	8.5-20.7	1.0-1.4	762-1196
Al-Qateef	14	120-160	6.72-7.4	0.96-5.26	0.52-2.71	3.1-21.3	0.5-1.3	132-1248

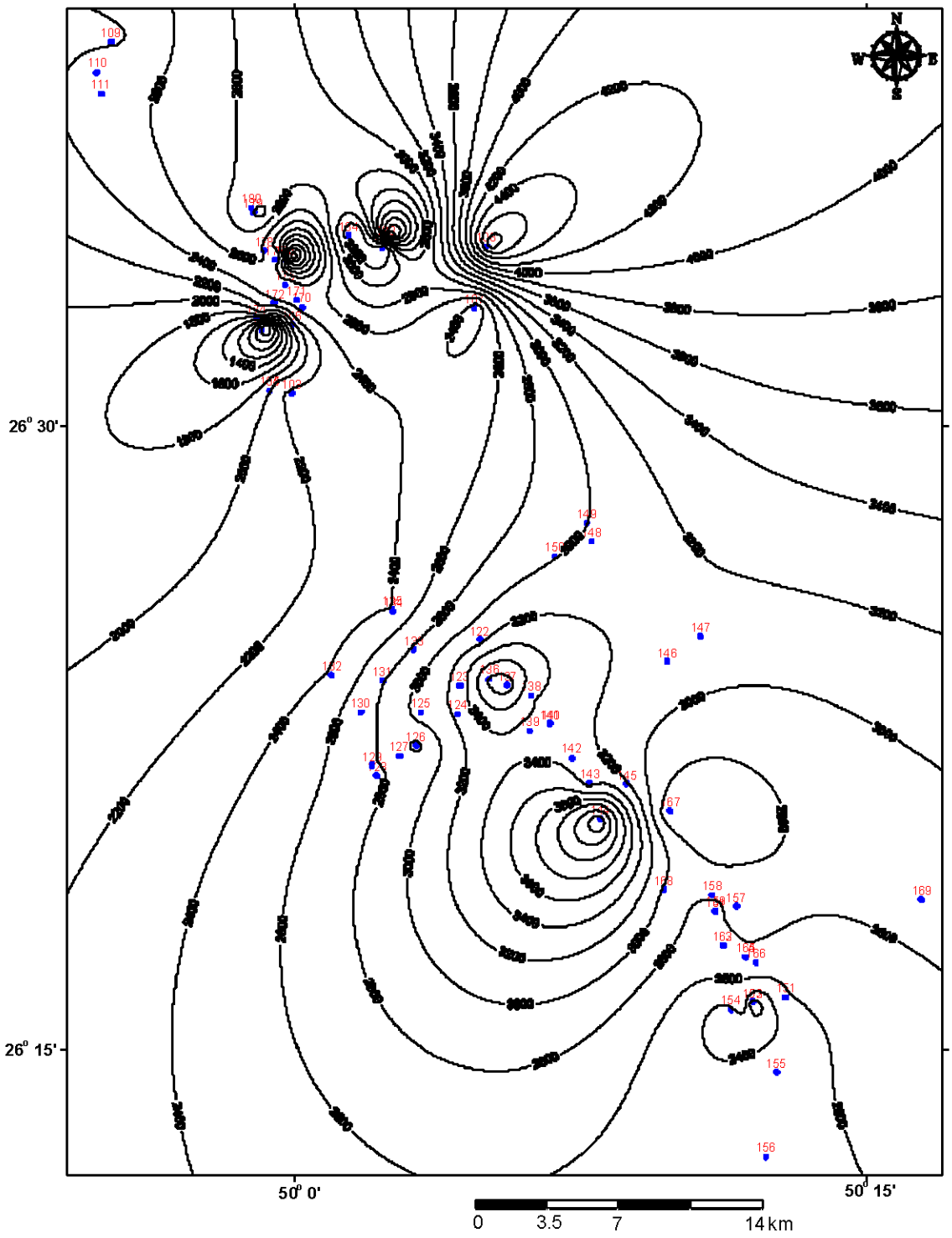

Fig. 3a: TDS contour map for wells in Al-Dammam, Al-Khobar and Al-Qatif areas

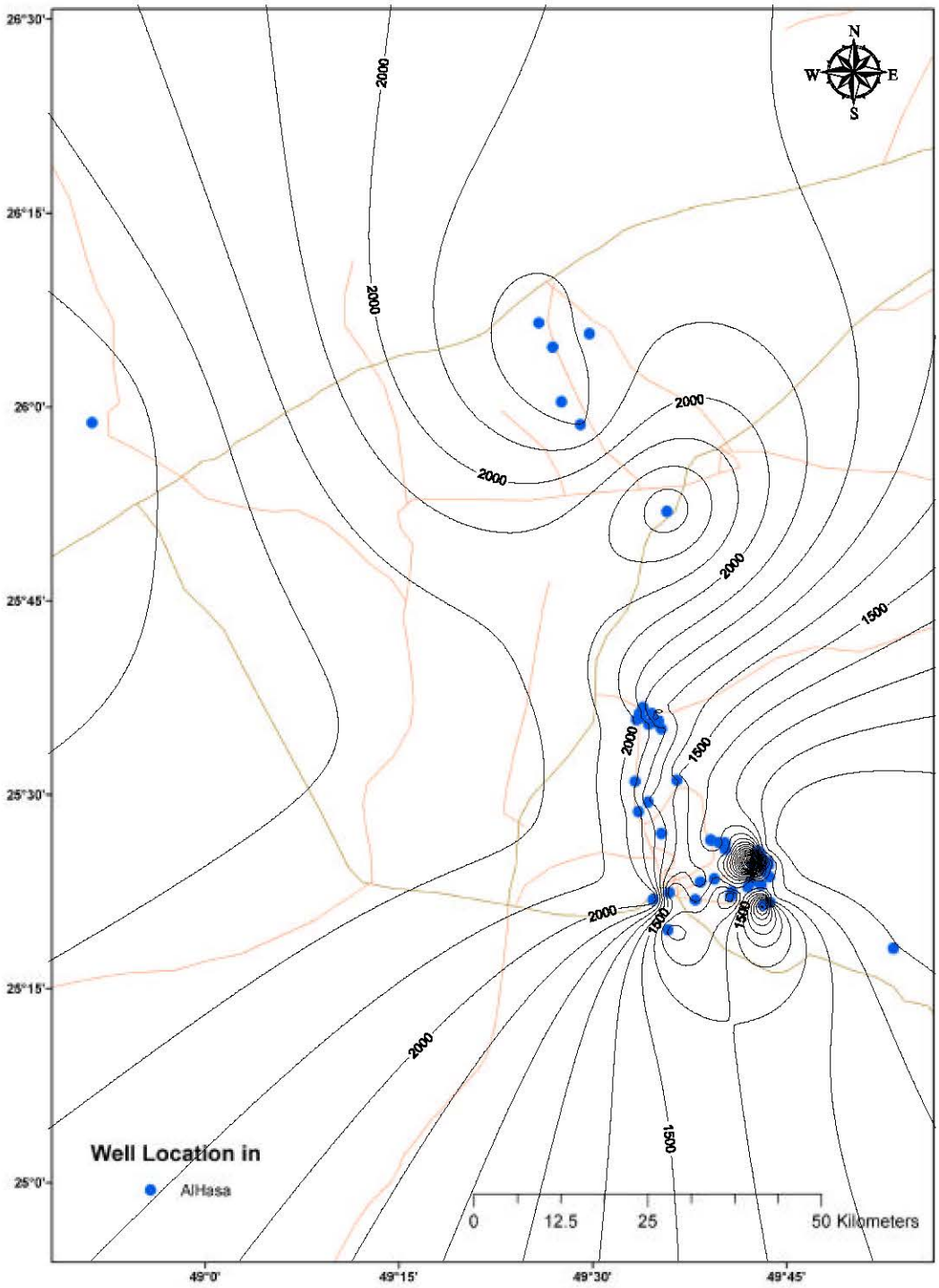

Fig. 3 b: TDS contour map for wells in Al-Ahsa area

Degree of hardness	mg L^{-1} as $CaCO_3$
Soft	0-60
Moderately hard	60-120
Hard	120-180
Very Hard	Greater than 180

Nitrate (NO_3) in groundwater of Al-Khobar aquifer: Most of the nitrogen in the groundwater is probably derived from the biosphere. The nitrogen originally fixed from the atmosphere, is mineralized by soil bacteria into ammonium, which is converted into nitrate by nitrifying bacteria under aerobic conditions (Tindall *et al*., 1995). Mean nitrate concentration (mg L^{-1}) ranged from 6.3-73.8 (Al-Ahsa), 11.4-26.4 (Al-Dammam), 8.5-20.7 (Al-Khobar) and 3.1-21.3 (Al-Qatif) in the study area (Table 2). The maximum permissible limit of nitrate concentration in water for various purposes especially for drinking is 50 mg L^{-1} according to WHO (1984). It was also found that majority of groundwater samples contain low level of nitrate which is within permissible limits of WHO (1984) for safe use of water and will not create health hazards upon consumption.

Fluoride (F) in groundwater of Al-Khobar aquifer: Fluoride exists fairly abundantly in earth's crust and can enter groundwater by natural processes. Mean fluoride concentration (mg L^{-1}) ranged from 1.0-1.8 (Al-Ahsa), 1.1-1.4 (Al-Dammam), 1.0-1.4 (Al-Khobar) and 0.5-1.3 (Al-Qatif) in the study area (Table 2). According to WHO (1984), fluoride is an effective agent for preventing dental caries if taken in optimal amounts. Water is a major source of fluoride intake. The WHO (1984) suggested that in areas with a warm climate, the optimal fluoride concentration in drinking water should remain below 1 mg L^{-1}, while in cooler climate it could go up to 1.2 mg L^{-1}. The guidelines value (permissible upper limit) for fluoride was set at 1.5 mg L^{-1}. However, the F concentration in groundwater of study area is within permissible limit according to WHO (1984). The SI value of fluorite mineral is negative in all the well waters at four different locations. This infers more F dissolution in water due to water-rock interaction when water passes through the fluoride bearing mineral rocks.

Saturation indices: The chemical composition of natural waters is derived from many different sources of solutes including both gases and aerosols from the atmosphere and the weathering and erosion of rocks and soils. Dissolution and precipitation reactions of minerals occur below the soil surface where their concentration is influenced by many environmental factors, especially the position and the solubility of rock strata (water-rock interaction) (Lin and Clemency, 1980; Ronge and Cleasson, 1982).

Table 3: Mean values of water quality parameters in eastern region of Saudi Arabia

Parameters	Al-Ahsa	Al-Khobar	Al-Dammam	Al-Qatif
Depth (m)	123.00	123.00	141.00	154.00
Temp. (°C)	32.72	32.72	35.46	34.40
pH	7.31	6.95	6.88	6.87
EC (dS m^{-1})	2.45	4.31	4.59	3.67
Turbidity, UTV	2.11	3.35	----	1.35
DO (mg L^{-1})	6.63	7.74	7.20	7.19
Alkalinity	156.00	159.00	155.00	143.00
T. Hardness	713.00	1012.00	1049.00	914.00
Ca (mg L^{-1})	167.00	262.00	267.00	237.00
Mg (mg L^{-1})	72.00	92.00	93.00	78.00
Na (mg L^{-1})	306.00	554.00	682.00	481.00
K (mg L^{-1})	21.00	25.50	27.70	19.20
NO_3 (mg L^{-1})	19.63	15.51	19.11	17.50
Cl (mg L^{-1})	602.00	1123.00	1372.00	996.00
SO_4 (mg L^{-1})	368.00	461.00	420.00	377.00
F (mg L^{-1})	1.31	1.28	1.29	1.12
TDS (mg L^{-1})	1666.00	2651.00	2995.00	2311.00
SAR	4.95	7.52	9.09	6.67
Calcite	-0.19	-0.24	-0.113	-0.26
Dolomite	-0.34	-0.51	-0.25	-0.57
Gypsum	-1.04	-0.89	-0.91	-0.96
Anhydrite	-1.23	-1.07	-1.07	-1.13
Halite	-5.42	-4.89	-4.77	-5.02
Pyrite	-95.30	-92.71	-94.10	-91.85
Aragonite	-0.33	-0.38	-0.25	-0.40
Goethite	9.87	9.86	9.49	9.39
Hematite	21.77	21.77	21.03	20.84
Fluorite	-0.83	-0.74	-0.76	-0.85

Saturation Indices (SI) were calculated for all the water samples from Al-Ahsa, Al-Dammam, Al-Khobar and Al-Qatif aquifers using the speciation code WATEQ4 (Ball and Nordstrom, 1992) and the PHREEQC model developed by Parkhurst (1995). Mean saturation indices of different minerals are given in Table 3. All the aquifers are under-saturated (negative SI) with respect to certain minerals (for example: calcite, dolomite, gypsum, anhydrite, halite, pyrite and aragonite) and oversaturated (positive SI) with respect to some other minerals (For example: goethite and hematite). Actually, the SI is a measure of the thermodynamics state of a solution relative to the equilibrium with a specified solid-phase mineral. In the study area, most of the groundwater is under-saturated with respect to calcite, dolomite, gypsum, anhydrite, halite, pyrite and aragonite, the groundwater flow is capable of dissolving the aquifer rock thus increasing both its porosity and permeability. The underground water is oversaturated with respect to goethite and hematite (SI is positive), these minerals will precipitate and adversely affect the aquifer properties.

Water classification: The chemistry data was plotted on Durov, Piper, Ternary and Giggenbach Triangle Diagram (Fig. 4-7). Two water types namely Na-Ca-Cl-SO_4 and Na-Ca-Mg-Cl-SO_4 dominate the Al-Ahsa whereas Na-Ca-Cl and Na-Ca-Cl-SO_4 water types are dominant in Al-Dammam, Al-Khobar and Al-Qatif areas. This variation

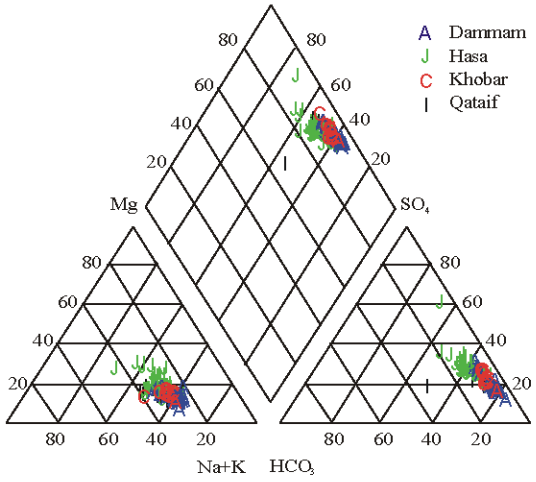

Fig. 4: Piper diagram for Al-Dammam, Al-Ahsa, Al-Khobar and Al-Qatif samples

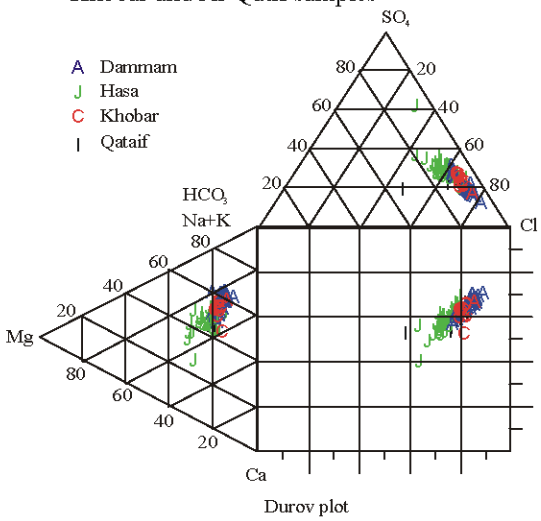

Fig. 5: Durov plot for Al-Dammam, Al-Ahsa, Al-Khobar and Al-Qatif samples

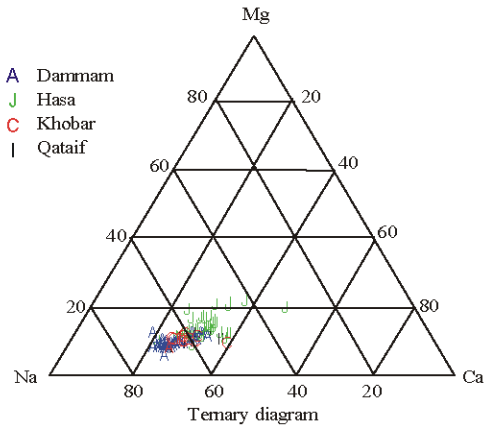

Fig. 6: Ternary diagram for Al-Dammam, Al-Ahsa, Al-Khobar and Al-Qatif samples.

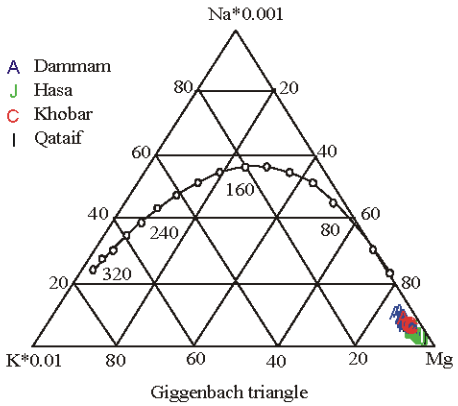

Fig. 7: Ternary diagram for Al-Dammam, Al-Ahsa, Al-Khobar and Al-Qatif samples

in the water types could be due to the difference in depth of the wells and the geochemistry of the aquifer. This aquifer is predominantly consisted of limestone and alluvial types rocks mainly composed of $CaCO_3$ and limestone rock formation.

CONCLUSIONS

The groundwater salinity ranged from 4400 mg L^{-1} (Total dissolved solids, TDS) along the Gulf Coast on the eastern side to around 1800 mg L^{-1} on the western side. Sodium (Na) is the dominant cation followed by Mg, Ca and K in descending order. Whereas, the anion concentration order is $Cl>SO_4>HCO_3$. Nitrate concentration is within permissible limits for drinking purpose according to WHO (1984). The regional groundwater is under-saturated with respect to calcite, dolomite, gypsum, anhydrite, halite, pyrite and aragonite minerals and oversaturated with respect to goethite and hematite minerals. The hardness of waters is very high as compared to the established standards. The F contents are within permissible limits for drinking. The nitrate contents are very high and require pretreatment for domestic use. Two water types namely Na-Ca-Cl-SO_4 and Na-Ca-Mg-Cl-SO_4 dominate the Al-Ahsa whereas Na-Ca-Cl and Na-Ca-Cl-SO_4 water types are dominant in groundwater of Al-Dammam, Al-Khobar and Al-Qatif areas. Overall, the study provided useful information on some important hydrogeochemical processes of groundwater in the eastern region and the chemistry of different groundwater aquifers.

REFERENCES

Al-Hawas, I.A., 2002. Irrigation water quality evaluation of Al-Hassa springs and its predictive effects on soil properties. Pak. J. Biol. Sci., 5: 651-655.

Allael-Din, M.N., I.M. Madany, A. Al-Tayaran, A.H. Al-Jubair and A. Gomaa, 1993. Quality of water from some well in Saudi Arabia. Water, Air Soil Pollut., 66: 135-143.

American Public Health Organization, 1998. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Water Environment Federation, American Water Works Association. 20th Edn. APHA, AWWA, WEF, Washington, D.C.

Ball, J.W. and D.K. Nordstrom, 1992. Geochemical Model to Calculate Speciation of Major, Trace And Redox Elements in Natural Waters. U.S. Geological Survey. Int. Groundwater Modeling Center, pp: 189.

Bazuhair, A.S. and A. Alkaff, 1989. Evaluation of ground water quality in Wadi Al-Yamaniyah Saudi Arabia. Arab Gulf J. Sci. Res., 7: 21-38.

BRGD., 1976. Hydrogeological investigations of the Al-Wasia aquifer in the Eastern province of Saudi Arabia. Unpublished Report, Ministry of Agriculture and Water, Riyadh, Kingdom of Saudi Arabia.

BRGD., 1977. Al-Hassa development project: Groundwater resources and management program. Unpublished Report, Ministry of Agriculture and Water, Riyadh, Kingdom of Saudi Arabia.

Faruq, I.M., M. Jahangir and A.S. Al-Shareef, 1996. Chemical characteristics of Saudi ground water, Al-Qassim. Biol. Soc. (Saudi Biol. Soc. J.), 4: 123-140.

GDC., 1980. Umm Er Radhuma Study. Bahrain Assignment, Demeter House, Station Road Cambridge, CBI 2Rs.

Hussain, G. and M. Sadiq, 1991. Metal chemistry of irrigation and drainage waters of Al-Ahsa Oasis of Saudi Arabia and its effects on soil properties. Water, Air Soil Pollut., 57-58: 773-783.

Hussein, M.T. and A.S. Bazuhair, 1992. Groundwater in Haddat Al Sham- Al Bayada Area, Western Saudi Arabia. Arab Gulf J. Sci. Res., 10: 23-43.

Italconsult, 1969. Water and agricultural development studies for area IV. Unpublished Report, Ministry of Agriculture and Water, Riyadh, Kingdom of Saudi Arabia.

Lin, F. and C. Clemency, 1980. The kinetics of dissolution of muscovites at 25°C and 1 atm CO_2 partial pressure. Proceedings of 3rd International Symposium on Water-Rock Interaction, Edmonton.

Mee, J.M., 1983. Saudi ground water chemistry and significance. Arab Gulf J. Sci. Res., 1: 113-120.

Naimi, A.I., 1965. The groundwater of Northeastern Saudi Arabia. Fifth Arab Petroleum Congress, Cairo, Egypt.

Omar, A., Al-harbi, G. Hussain, M.M. Khan, M.A. Moallim and I.A. Al-Sagaby, 2006. Evaluation of groundwater quality and its recharge by isotopes and solute chemistry in Wadi Malal, Al-Madinah Al-Munawarah, Saudi Arabia. Pak. J. Biol. Sci., 9: 260-269.

Parkhurst, D.L., 1995. User's guide to PHREEQC: A computer program for speciation, reaction path, advective transport and inverse geochemical calculations. USGS Water Resources Investigation Report, 38(8).

Ronge, B. and T. Cleasson, 1982. Bergarters och minerals L. slight I hetvatten [Water-rock interactions at elevated temperatures]. Stiftelsen Bergteknish Forskining- BeFo Nr 72:1/82. Swedish Rock Engineering Research Foundation. (BeFo in Swedish with English summary).

Tindall, J.A., R.L. Petrusak and P.B. McMohan, 1995. Nitrate transport and transformation processes in unsaturated porous media. J. Hydrol., 169: 51-94.

USEPA., 1979. Methods for chemical analysis of water and wastes. Document NO. EPA-600/4-79-020 (revised in 1983). United States Environmental Protection Agency, Environmental Monitoring Systems Laboratory, Cicinnati, USA.

WHO., 1984. Guidelines for drinking water quality. Health criteria and other supporting information. Geneva: World Health Organization. Vol. 2.