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Research Paper

Impact of A Paleochannel on Hydrogeochemistry of A Quaternary Aquifer: Case Study From Umm Al Quwain Area, United Arab Emirates

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ABSTRACT: *This study investigated the influence of Wadi Lamhah paleochannel on hydrogeochemistry of the Quaternary aquifer in Umm Al Quwain area, United Arab Emirates (UAE). Results show that the groundwater temperature in water wells affected by Wadi Lamhah channel was 3 to 7°C less than the groundwater temperature in rest of the study area. Groundwater salinity in the channel-affected wells ranged from 803 to 5,407 mg/L and averaged 3,219 mg/L, while the groundwater salinity in rest of the study area was higher, reaching 11,643 mg/L in well 24, which suffered from salt-water intrusion from the sea. Except* HCO_3^- *(329 mg/L), average concentrations of major ions in the channel-controlled wells were lower than their average concentrations in all wells within the study area. Average concentrations of detected trace elements B, Fe and Zn were lower in channel-affected wells than the rest of the study area. The high total hardness in channel-affected wells reflected the flux of Ca and Mg-rich recharge water moving into the aquifer through its southern boundary. The calculated SAR values indicated that the groundwater is good for irrigation along the course of Wadi Lamhah channel and harmful to plant and soil in the rest of the study area.*

Keywords: *Hydrogeochemistry, Quaternary aquifer, Umm Al Quwain area, United Arab Emirates, Wadi Lamhah paleochannel*

I. INTRODUCTION

Umm Al Quwain Emirate is located in northern UAE, overlooking the southern rim of Arabian Gulf, and covering an area of 800 square kilometers (km^2). The emirate is bounded by the 2801 and 2848 North, and 354 to 389 East, on the Universal Transverse Mercator (UTM) grid system (Fig. 1).

Old or ancient river channels often infilled with course fluvial deposits can store and transmit appreciable quantities of water. Below the water table, these geomorphological features are often targeted for water supply. Potentiometric surface maps for the gravel aquifer in the Al Ain area, UAE, show the influence of paleochannels of groundwater chemistry and quality [1, 2, 3]. Oil exploration uphole seismic data were used for construction a potentiometric surface map of the gravel aquifer in Al Ain area [4]. This map suggests that buried paleodrainage network contain saturated alluvial fill and may constitute major fresh water aquifers in Al Ain area.

Most of the buried channels in the Nile Delta of Egypt area are undetected, and thousands of private water wells and key municipal urban supplies wells are tapping the groundwater of these buried channels [5]. Integrating remote sensing data, soil analyses, geophysical methods, and hydrochemical analyses of water samples are required to map paleochannels and assess their impacts on groundwater chemistry and quality. Results of mechanical and petrofabric analyses indicate that the sediments along the course of the Saitic branch of the ancient Nile River, east of the Rosetta Nile branch in the Nile Delta area, are characterized by low clay and silt contents, high effective porosity (θ_e), and high sand content [5]. The geochemistry of studied sediment samples shows that the sediments of this old Nile channel possess lower SO_4^{2-}, PO_4^{3-}, Fe, Mn, Pb and Zn contents than the surrounding sediments. Water chemistry, on the other hand, revealed that this channel is characterized by low contents of TDS, Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, PO_4^{3-}, Fe, Mn, Pb, Zn, Cu and Cd. In addition to good water quality and high hydraulic conductivity (K), the channel the outlined Saitic branch of the ancient

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Nile River is expected to have short water residence time and high groundwater potentiality. However, the sandy nature of this channel makes its water more susceptible to contamination [5].

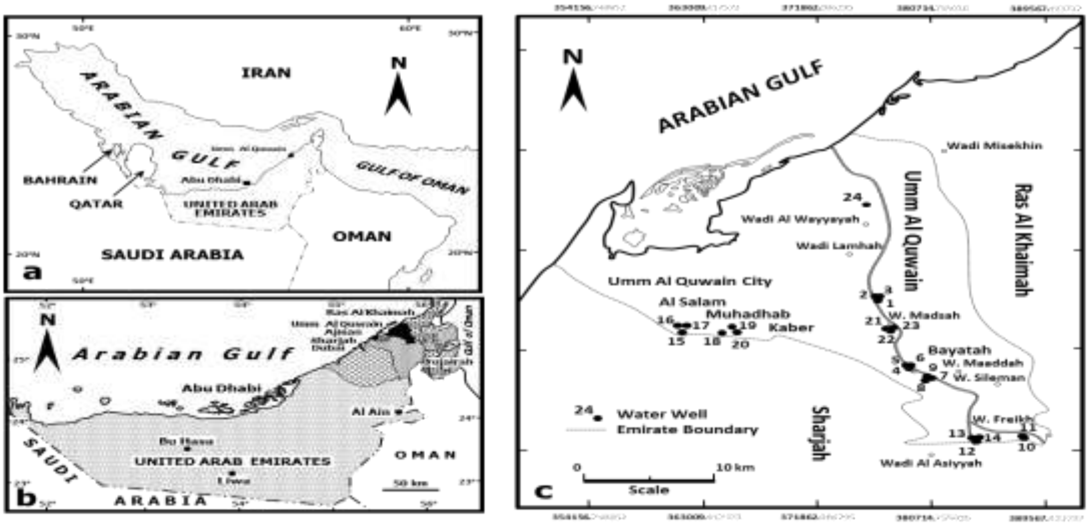

Figure 1. Location maps of the United Arab Emirates (a), Umm Al Quwain Emirate (b) and the study area (c). Black circles on Figure 1c represent water wells sampled for this study during April 2008 and May 2009.

Results of pumping tests, borehole logs, electromagnetic (EM) survey, soil classification, sandpits and vegetation cover were used for investigating the Riverine plain shallow aquifers [6]. The majority of aquifers identified in this study were found along paleo-stream courses. These aquifers are paleochannels of small spatial extent, limited thickness, shallow depth, and heavy clays cover. The Cobram sandy loam soil is strongly associated with paleochannels and the Calytris pines vegetation are generally aligned along the path of paleo-streams. All boreholes in close proximity to the sand pits are closely related to paleochannels and thick alluvial sediments [6].

The highly productive parts of the Quaternary sands and gravels in the Eastern Region of the UAE are found in coarse-grained deposits which were laid down in paleochannels which are now buried at depth [7, 8, 4, 9]. The old alluvial channels also extend underneath the aeolian sand west of Al Ain area. These channels are tapped by most of the farm wells in Al Khazna and Remah areas. The alluvial sediments are 40 to 50 m thick and the groundwater salinity ranges from 1,500 to 10,000 mg/L, and the transmissivity (T) averages 594 m^2/d.

A management model for planning groundwater development in costal deltas with paleochannels was presented [10]. The transmissivity (T) and storativity (S) values of the aquifer along paleochannels are normally higher than those of the aquifer in surrounding areas. Therefore, the results of this study are consistent with the intuition that paleochannels are best locations for groundwater development in terms of quality and quantity. It also demonstrated that paleochannels are the best locations for locating the wells for large-scale pumping.

Relict fluvial channels that are infilled with high permeability sediments act as preferred pathways for groundwater flow and solute transport. In coastal regions, such paleochannels can provide a hydraulic connection between freshwater aquifers and the sea, facilitating saltwater intrusion landward or freshwater discharge offshore. The impact of the presence of paleochannels in offshore sediments on groundwater-seawater exchange was simulated [11]. Model results revealed that when these channels breach confining units, the channels enhance fluid exchange, resulting in an increase in both inflow from and outflow to the sea. This enhanced fluid exchange occurred for all hydrogeologic conditions simulated except for the lowest confined aquifer hydraulic conductivity. In all simulations seawater inflow to the aquifer occurs largely along the channel axis whereas discharge from the aquifer to the sea occurs along the channel margins. Coastal water resource managers should consider offshore geologic conditions when considering modes of intrusion and water-resource vulnerability to intrusion. Along similar lines, studies of submarine groundwater discharge in the presence of paleochannels should be aware of varying flow conditions across the channel, particularly during sampling. Paleochannels are likely to be significant modes of salt-water intrusion into confined aquifers when excess freshwater extraction occurs on land.

Geophysical methods were used to determine groundwater flow in an integrated pattern inherited from a pre-existing paleochannel network formerly active in the underlying basement rocks in Botswana, western Zambia, southeastern Angola and north western Namibia, as well as parts of western Zimbabwe [12]. The implication of the presence of groundwater flow in paleo-drainage lines in the bedrock are enhanced hydraulic conductivity and higher well yields, rapid replenishment from upstream sources and fresher water quality, and better groundwater exploration strategies in these areas.

Investigated of groundwater resources in the Niles Cone basin, southern Alameda County, California, United States, indicated the presence of two paleo-stream channels; Alameda Creek and the smaller Dry Creek [13]. These channels act as a migration pathway for surface contaminants into the underlying aquifers, which are the main source of water supply in the basin.

II. WADI LAMHAH PALEOCHANNEL

Al Dhaid super basin in the UAE, traced from topographic sheets scale 1:50,000 and 1:100,000, is composed of five sub-basins, namely: Al Dhaid, Kadrah, Shawkah, Meleiha and Hamdah (Fig. 2). These sub-basins originate in the Northern Oman Mountains in the east, transverse central UAE and merge into a single wadi channel (Wadi Lamhah), which runs towards north, joining the Arabian Gulf in the northwestern part of the study area [14].

The Quaternary deposit forming Wadi Lamhah channel is alluvial gravel, with fine sand and silt. Aeolian sand covers the rest of Wadi Lamhah area (Fig. 3). Large conventional agricultural areas extend along the Wadi course, and a single limestone outcrop exists in the south (Fig. 3). The 2D Dc-resistivity field-data inversions, resistivity models and synthetic-data inversions for Wadi Lamhah profile is shown in Figure 3. The profile is located in the central part of the study area. The depth of penetration is approximately 450 m and did not reach the top surface of the deep limestone aquifer. The cross section of the true resistivity beneath the profile of Wadi Lamhah represents the variation in the lithology and degree of saturation of the Quaternary sand and gravel aquifer within the study area as well as the water quality (Fig. 3).

The depth to water table (the layer colored in light blue in the depth-true resistivity section shown in Figure 3) increases from 20 m in the north to more than 60 m in the south. The true resistivity ranges from 40 to 50 Ωm, indicating slightly brackish groundwater. The saturated thickness of the Quaternary aquifer is greatly reduced along this profile due to excessive groundwater pumping. Therefore, upconing of saline water (dark blue) can be seen in several areas long the profile. Drilling groundwater wells is not recommended in this profile area because it is underlain by a thick clay layer. However, detailed geophysical survey is recommended for the area south of 1160 m from the start of the profile in the north (Fig. 3).

The northwestern gravel aquifer in the study area occurs as thin lenses under the sands, and in places, as buried alluvial channels entrenched in the bedrock. The presence of these channels is associated with low-salinity groundwater. An example of these channels was pointed out by Rizk et al. (1997) in their studies on Al Ain area [15]. Deposits of gravel have been penetrated within the Quaternary sands in nearly all boreholes drilled in the gravel plain at depths of 60 m below the ground surface and at distances up to 70 km from the eastern mountains [16]. Under the study area, several alluvial channels are concealed under sand dunes. These channels, such as the channel of Wadi Lamhah, are excellent aquifers because they carry fresh recharge water, from high mountains in the east, further west where most groundwater has poor quality. In the Emirate of Umm Al Quwain, gravel plain deposits exist in low interdune areas and from the channel of Wadi Lamhah, which crosses the study area from south to north (Fig. 1). The main drainage line within the study area is Wadi Lamhah, which starts outside the study area in the southeast [14]. This drainage channel connects five east-west trending wadis near Al Dhaid area and moves to the north reaching the Arabian Gulf near the northeastern corner of the study area (Fig. 1). Flash floods on dry drainage basins have a major role in groundwater recharge, given favorable topographic and lithologic conditions in these basins.

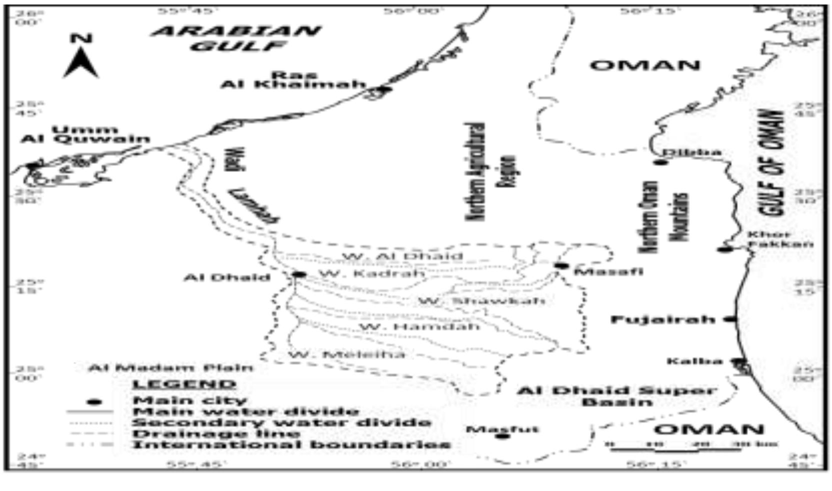

Figure 2. Al Dhaid super basin and its sub-basins, traced from topographic sheets scale 1:50,000 and 1:100,000 [14].

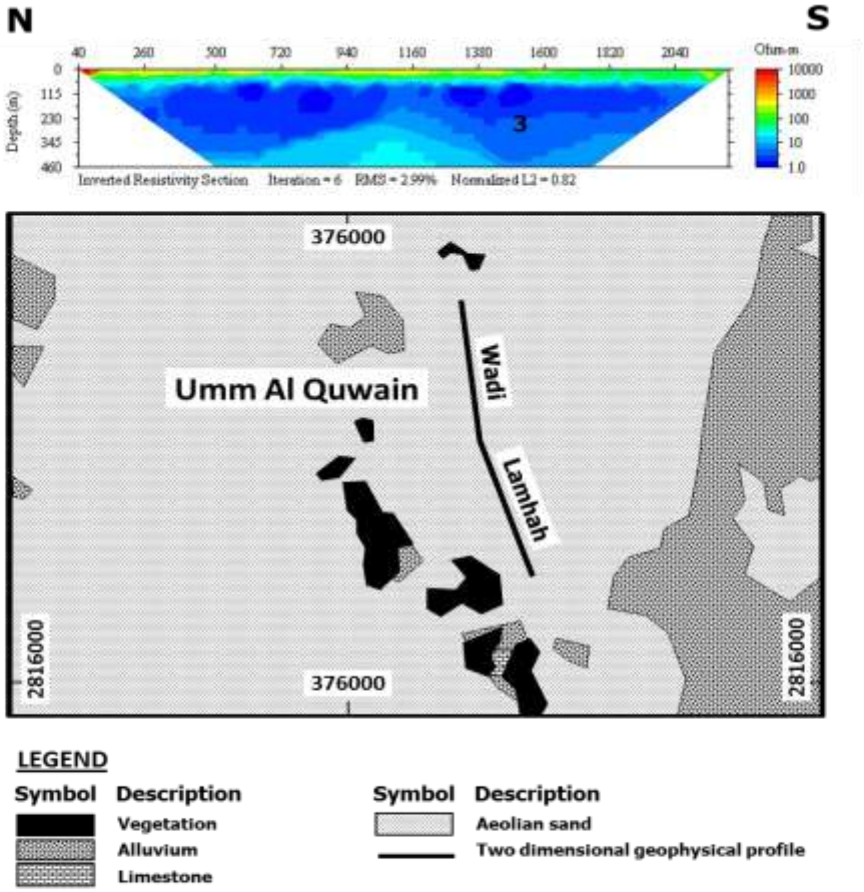

Figure 3. Results of 2D dc-resistivity data and modeling for the profile of Wadi Lamhah area. The geologic map of Wadi Lamhah area, Umm Al Quwain Emirate is (modified from [17]).

III. MATERIALS AND METHODS

1. Field Work

Field work for the present study was conducted in April 2008 and May 2009. Groundwater samples were collected from Al Surra and Muhadab well fields, in addition to Yemha, Biyatah, Al Rashidiya and Falaj Al Mualla urban centers (Fig. 1). Table 1 shows the numbers and locations of water samples collected for this study.

Table 1. Number of groundwater samples collected from Umm Al Quwain Emirates in April 2008 and May 2009.

Location	Number of groundwater Samples		
	April 2008	May 2009	Total
Yemha	3	3	6
Bayatah	3	3	6
Al Rashidiyah	3	3	6
Falaj Al Mualla	2	2	4
Surra well Field	3	3	6
Muhadab well Field	3	3	6
Farms	7	5	12
Total	24	22	46

The groundwater temperature (°C), electrical conductivity (EC) in microsiemens per centimeters (μS/cm), hydrogen ion concentration (pH), total dissolved solids (TDS) in milligrams per liter (mg/L) and total hardness (TH in mg/L) were directly measured in the field because they change after sample collection [18].

2. Laboratory analyses

The chemical analysis of the collected water samples was conducted in two laboratories, namely: the Umm Al Quwain Desalination Plant Laboratory that belongs to Umm Al Quwain Water Department, and the Food and Environment Laboratory of Ajman Municipality and Planning Department. Standard analytical techniques described in [19, 20, 21, 22, 23] were applied. Chemical analyses of major, minor and trace chemical constituents were performed using titration methods, ion chromatography [24], atomic absorption spectrophotometry (AAS) [25], and inductively coupled plasma-atomic emission spectrometry (ICP-AES) [26]. For measurement of TDS, a 100 ml of well-mixed water sample was filtered through a standard glass fiber. The filtrate was evaporated to dryness in a weighed dish and dried to a constant weight at 180°C. The increase in dish weight represented the total dissolved solid [22]. For determination of alkalinity, soluble carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) anions were measured by titration of 50 mL water sample against 0.02 N HCl solution using phenolphthalein and methyl orange indicators [23]. Total hardness was measured by addition of 2 mL of the buffer solution pH-10 and 3 to 4 drops of Erichrome Black T indicator to 10 mL water sample, and titration with standard 0.01 M EDTA solution. Ion chromatograph, model Dionex-2020i, was used for the analysis of the anions; chloride (Cl^-), nitrate (NO_3^-), and sulphate (SO_4^{2-}). The Dionex-2020i ion chromatograph is a dual-channel, high-performance chromatographic system featuring two precision analytical pumps, a dual-channel advanced chromatography module with optional column heater and two conductivity detectors. The operating conditions were 10-40°C temperature range and 1,900 psi (129 atm.) maximum pressure. A calibration curve was prepared for each anion using aliquots anion concentrations higher than detection limits. The detection limits in mg/L of Cl^-, NO_3^- and SO_4^{2-} were 0.03, 0.13 and 0.03, respectively. Prior to the determination of total metal concentrations by AAS or ICP-AES, each water sample was acidified with nitric acid (8 mL/L Analar grade), boiled for 4-5 minutes to ensure complete solubility of metal ions [23], and then filtered. Filtrate was used for both AAS and ICP-AES measurements. Atomic absorption spectrophotometry (AAS) was used for the determination of the cations; calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), and potassium (K^+) by measuring their absorbance at the maximum wavelengths, against reagent blank [25]. Measurements were carried out using the AAS (GBC 906), equipped with autosampler and background corrector. ICP-AES was used for determination of trace elements iron (Fe), lead (Pb), cadmium (Cd), chromium (Cr), manganese (Mn), copper (Cu), nickel (Ni), and zinc (Zn).

IV. RESULTS AND DISCUSSION

The following discussion is based on the results of field-measured groundwater temperature (°C) and salinity (mg/L), chemical analyses of major and minor ions, trace elements (mg/L), and calculated water-dissolved salts (%) and sodium adsorption ration (SAR).

1. Temperature

The temperature of the collected groundwater samples exhibits a marked variation between April 2008 and May 2009. The temperature of groundwater samples collected in April 2008 ranged from 24.7°C in Well 14 to 31.8°C in Well 20 and averaged 28.5°C (Table 2). The average groundwater temperature dropped from 28.5°C in April 2008 to 24.4°C in May 2009, decreasing 4.1°C and ranging from 23.5°C in Wells 18-22 to 26.5°C in Well 10 (Table 2). Figure 4 shows the areal distribution of groundwater temperatures during 2008 and 2009. Generally, the low-temperature groundwater is located in the southern part of the study area, while the temperature increases to north and northwest, in the direction of groundwater flow. The groundwater temperature in water wells affected by Wadi Lamhah paleochannel (24-27°C) was 4 to 5°C less than the groundwater temperature in rest of the study area (28-32°C). Additionally, the groundwater recharging the Quaternary aquifer within the study is moving from lower temperature and higher altitude mountains in the east and southeast. The increase in groundwater temperature in the north (31°C) and northwest (30°C) can be attributed to salt-water intrusion from the Arabian Gulf into the aquifer in both areas.

2. Total Dissolved Solids

The TDS of groundwater samples collected in April 2008 increased from 803 mg/L in Well 12 near the Sharjah-Umm Al Quwain borders in the south to 11,643 mg/L near Well 24 in the northern part of the Emirate. Figure 5 shows the areal distribution of groundwater salinity in Umm Al Quwain Emirate in 2008 and 2009. The Groundwater in the Quaternary aquifer within the study area varies from fresh water (TDS <1,000 mg/L in Well 12 in the south) to brackish (TDS >1,000 to <10,000 mg/L in the majority of the study area) to saline water (TDS >10,000 mg/L in the north and northwest). The increase of groundwater salinity from south to north and northwest occurs in the direction of groundwater flow towards the discharge area in the Arabian Gulf. Groundwater salinity in the paleochannel-affected wells ranges from 803 (Well 12) to 5,407 mg/L (Well 13) and averages 3,090 mg/L, while the groundwater salinity in rest of the study area is higher, reaching 11,643 mg/L in well 24, which suffers from salt-water intrusion from the Arabian Gulf, and averages 3,791 mg/L.

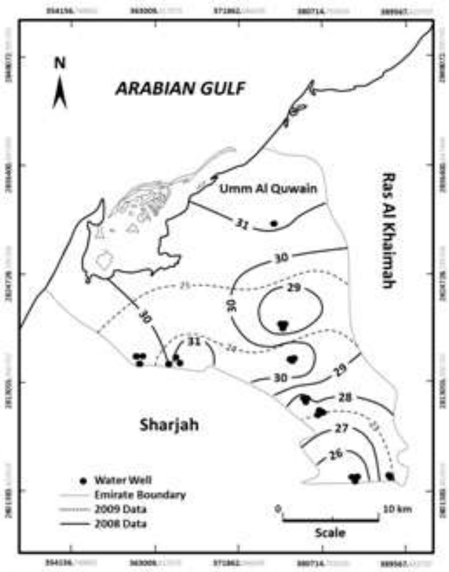

Figure 4. Iso-temperature (°C) contour map of groundwater in the Quaternary aquifer within Umm Al Quwain Emirate in April 2008 (solid lines) and May 2009 (dashed lines).

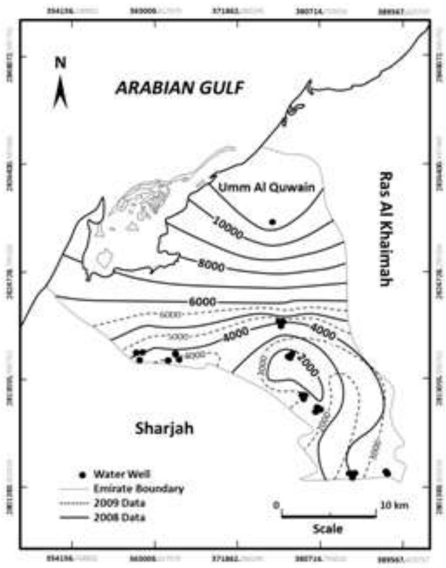

Figure 5. Iso-salinity (mg/L) contour map of groundwater in the Quaternary aquifer within Umm Al Quwain Emirate in April 2008 (solid lines) and May 2009 (dashed lines).

3. Major Ions

The sequence of cations dominance in groundwater of the Quaternary alluvial aquifer in the study area has the order: $Na^+ > Mg^{2+} > Ca^{2+} > K^+$. This sequence reflects the hydrogeologic setting of Umm Al Quwain Emirate in the UAE. The dominance of Na^+ points out to salt-water intrusion from the sea into the aquifer within the study area. Similarly, the second dominant cation is Mg^{2+}, which is a major ion in sea water. The long distance between Umm Al Quwain Emirate in the west and the Northern Oman Mountains in the east, the main recharge area for groundwater in the UAE, explains the relatively low concentration of Ca^{2+} and K^+ in the study area. Average concentrations of cations in paleochannel-controlled wells (Na^+ = 858 mg/L; (Fig. 6), Mg^{2+} = 151 mg/L, Ca^{2+} = 68 mg/L and K^+ = 21 mg/L) are lower than their average concentrations in all wells within the study area (Na^+ = 1,033 mg/L, Mg^{2+} = 162 mg/L, Ca^{2+} = 75 mg/L, and K^+ = 24 mg/L). The sequence of anions dominance in groundwater of the Quaternary alluvial aquifer in the study area has the order: $Cl^- > SO_4^{2-} > HCO_3^- > CO_3^{2-}$. This sequence also reflects the hydrogeologic setting of the Umm Al Quwain Emirate in the UAE. The dominance of Cl^- points out to salt-water intrusion from Arabian Gulf into the aquifer within the study area. Similarly, the second dominant anion is SO_4^{2-}, which is a major ion in sea water. The long distance between the Umm Al Quwain Emirate in the west and the Northern Oman Mountains in the east, the main recharge area for groundwater in the UAE, explains the relatively low concentration of HCO_3^- in the aquifer within study area. Except HCO_3^- (329 mg/L), average concentrations of anions in paleochannel-controlled wells (Cl^- = 1,432 mg/L (Fig. 7), SO_4^{2-} = 517 mg/L, and HCO_3^- = 167 mg/L) are lower than their average concentrations in the other wells within the study area (Cl^- = 1,622 mg/L, SO_4^{2-} = 680 mg/L, and HCO_3^- = 188 mg/L).

4. Minor Ions

Nitrate ion (NO_3^-) concentrations in groundwater sampled collected in 2008 varied between 1.1 mg/L in Well 13 in the south and 16 mg/L in Well 24 in the north. In 2009, NO_3^- increased from 5.1 mg/L in Well 15 in the west to 16.1 mg/L in Well 10 in the extreme south. The average NO_3^- concentration increased from 3.6 mg/L in 2008 to 9.5 mg/L in 2009. The higher nitrate ion in groundwater within the study area during May 2009 than April 2008 may reflect the influence of recharge water moving into the study area from the south and east, carrying more oxygen (O_2), nitrate (from the agricultural areas in the east) and low-salinity recharge water. Because of intensive agricultural activities along the course of Wadi Lamhah, average NO_3^- concentration in the paleochannel wells (3.5 mg/L) is close to average level (3.6 mg/L) in the study area. According to the WHO standards for drinking water, fluoride ion (F^-) concentration varies between 1.4 and 2.4 mg/L [27], according to prevailing temperature. Fluoride ion levels in groundwater sampled collected in April 2008 ranged from 0.2 mg/L in Well 4 in the south to 1.9 mg/L in Well 17 in the west. In 2009, the minimum F^- of 0.11 mg/L was recorded in Well 10 in the south and 1.02 mg/L in Well 20 in the west. The average F^- in the Quaternary aquifer of Umm Al Quwain Emirate was the same as 0.7 mg/L in 2008 and 2009. Figure 8 shows the areal distribution of F^- concentration in groundwater within the study area in 2008 and 2009. The iso-F^- concentration contour lines in 2008 and 2009 reflect its increase from south to north and northwest in the direction of groundwater flow (Fig. 8). The average F^- content increases, from (0.4 mg/L) in Wadi Lamhah channel wells to (0.7 mg/L) in the study area, with increasing groundwater salinity.

5. Trace Elements

Iron (Fe) concentration in 2008 ranged from 0.01 mg/L in the south to 2.55 mg/L in the middle and averaged 0.23 mg/L. The Fe content exceeded the WHO recommended limit in Wells 1, 5 and 9, and exceeded the maximum permissible limit for drinking water in Well 2. Average concentrations of detected trace elements B (boron), Fe, Zn and Cr are 0.7, 0.3, 0.1 and 1.0 mg/L, respectively, in paleochannel wells, and 0.9, 0.2, 0.1 and 0.4 mg/L, respectively, in the study area. The concentrations of the trace metals Cu, Pb, Mn, Ni and Cd were below their detection limits in groundwater samples collected from the Quaternary aquifer in Umm Al Quwain Emirate during April 2008 and May 2009.

6. Water-Dissolved Salts

In 2008, the percentage of $Ca(HCO_3)_2$ salt was generally low throughout the study area, ranging from 0.6% in Well 12 in the south to 10.1% in Well 7 near the middle, and averaging 4.3%. In 2009, the minimum percentage of $Ca(HCO_3)_2$ salt remained unchanged in Well 12 (0.6%), while the maximum decreased to 5.8% in Well 17 in the northwest. The $Ca(HCO_3)_2$ percentage generally increases along the Wadi Lamhah paleochannel (8% in 2008 and 4% in 2009) and decreases everywhere else (Fig. 9). The 2008 minimum (0.1%) and maximum (12%) of $Mg(HCO_3)_2$ salt in the Quaternary aquifer within the study area were calculated in the Well 20 in the northwest and Well 22 in the center, respectively. The average percentage of $Mg(HCO_3)_2$ was (1.6%) in 2008. The 2009 percentage of $Mg(HCO_3)_2$ increased from 0.1% in Well 20 in the northwest to 5% in Well 9 in the center and averaged 1.3%. The $Mg(HCO_3)_2$ increases along the Wadi Lamhah channel, which brings Mg-rich recharge water from the main recharge areas in the south and east of Umm Al Quwain Emirate.

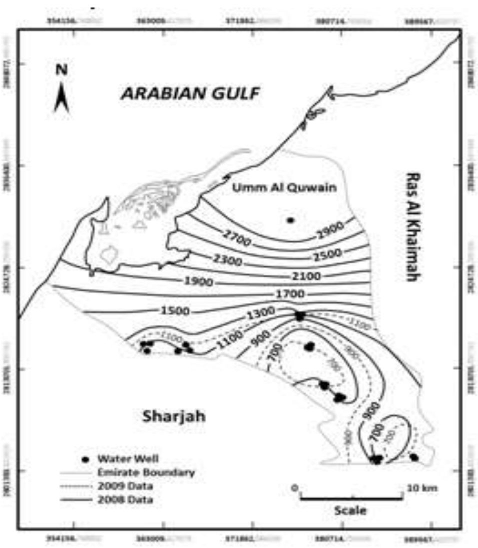

Figure 6. Iso-concentration (mg/L) contour map of sodium ion (Na^+) in groundwater of the Quaternary aquifer within Umm Al Quwain Emirate in April 2008 (solid lines) and May 2009 (dashed lines).

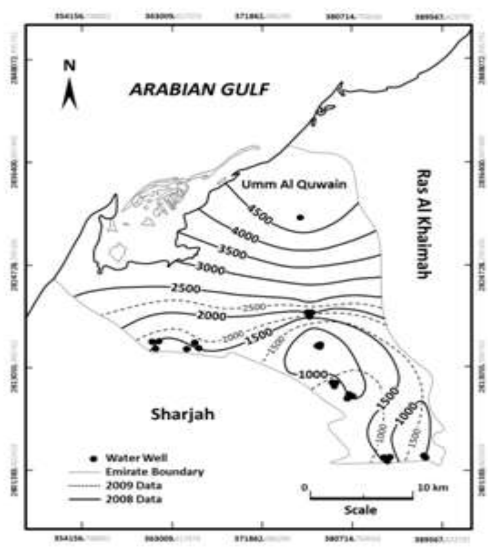

Figure 7. Iso-concentration (mg/L) contour map of chloride ion (Cl^-) in groundwater of the Quaternary aquifer within Umm Al Quwain Emirate in April 2008 (solid lines) and May 2009 (dashed lines).

The percent of $Ca(SO_4)$ is low in the west, and increases to the north, south and along the course of Wadi Lamhah paleochannel. The northward increase returns to the influence of salt-water intrusion from the Arabian Gulf. In the middle, Wadi Lamhah channel represent an avenue for active solute movement from south to north through the aquifer, including calcium and sulphates. In April 2008, the percentage of $Ca(SO_4)$ increased from 1% in Wells 2, 7 and 17 in the middle to 6% in Well 14 in the south. During May 2009, the percentage of $Ca(SO_4)$ increased from 2% in Wells 12 and 14 in the south to 18% in Well 7 in the middle. The average $Ca(SO_4)$ was 1% in 2008 and increased to 3% in 2009. The $MgSO_4$ is the second dominant water-dissolved salt within the study area. In 2008, the percentage of this salt increases from 1% in Well 12 in the south to 25% of the total dissolved salts in Well 23 in the middle. In 2009, the percentage of $MgSO_4$ increases from 1% in Well 12 in the south to 33% of the total dissolved salts in Well 7 in the middle. The average $MgSO_4$ percentage was 16% in 2008 and 13% in 2009. The highest percentages $MgSO_4$ mark the course Wadi Lamhah, from which percentages decrease to the west and east (Fig. 10). The average percentage of $Na_2(SO_4)$ was generally higher in April 2008 than in May 2009, while the minimum and maximum percentages remained the same. In 2008, the $Na_2(SO_4)$ increased from 1% in Well 5 in the middle to 38% in Well 12 in the south, and the average was 6%. In 2009, the salt ranged from 1% in Well 13 in the south to 38% in Well 12 in the south, and averaged 3%. High concentration coincides with the location of an old desalination plant, which used to dispose high-salinity reject brine on the land surface. This practice may have contributed to the high Na salts in this area, which is relatively far from the direct influence of sea-water intrusion from the Arabian Gulf in the north.

The 2008 $MgCl_2$ percentages ranged from 1% in Well 23 in the middle to 21% in Well 13 in the south, and averaged 3.2%. The 2009 $MgCl_2$ percentages varied between 1% in Well 1 in the middle and 28% in Well 6 in the middle, and averaged 10%. The $MgCl_2$ salt is high in the middle central part of the study area, reflecting the impact of human activities on salt concentration in this area (Fig. 11). The NaCl is the most dominant water-dissolved salt in the Quaternary aquifer within the study area. The NaCl salt percentage and distribution reflects the influence of salt-water intrusion into the Quaternary aquifer in Umm Al Quwain Emirate. Wadi Lamhah channel, on the other hand, represent the relatively lower salinity area within the Emirate. In 2008, NaCl percentage increased from 51% in Well 12 in the south to 73% in Well 5 in the middle, and averaged 66%. In 2009, NaCl salt percent jumped from 35% in Well 6 in the middle to 73% in Well 18 in the northwest, and averaged 60%. The iso-NaCl contour map illustrates a progressive increase of NaCl salt from south to north, in the direction of groundwater flow, towards the Arabian Gulf. Wadi Lamhah channel has the lowest NaCl percentage in the study area. Because of the dynamic nature of groundwater in Wadi Lamhah channel, the percentages of water-dissolved salts in near channel wells $MgCl_2$ (8.6%), Na_2SO_4 (13.4%), $CaSO_4$ (3.2%) and $Mg(HCO_3)_2$ (3.6%) were higher than their percentages in the rest of the study area (2.7%, 7.3%, 1.5% and 2.9%, respectively).

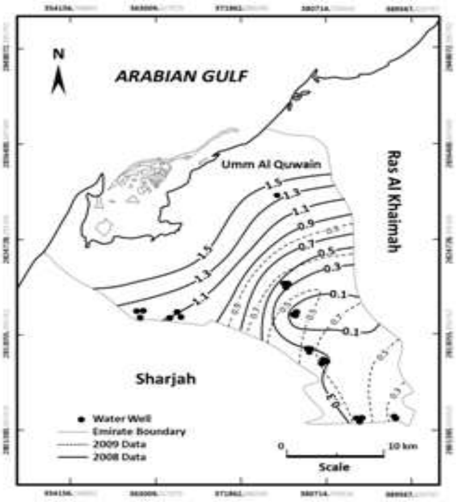

Figure 8. Iso-concentration (mg/L) contour map of fluoride ion (F) in groundwater of the Quaternary aquifer within Umm Al Quwain Emirate in April 2008 (solid lines) and May 2009 (dashed lines).

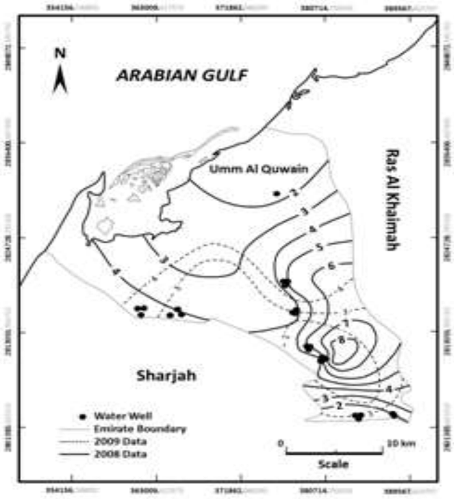

Figure 9. Percentage distribution of the hypothetical salt $Ca(HCO_3)_2$ in the Quaternary aquifer within Umm Al Quwain Emirate during April 2008 (solid lines) and May 2009 (dashed lines).

Water is classified according its hardness into soft water (<60 mg/L), moderately hard water (61-120 mg/L), hard water (121-180 mg/L) and very hard water (>180 mg/L) [18]. According to this classification, groundwater in the Quaternary aquifer of Umm Al Quwain area is soft in Well 12 in the south (TH ranged from 23 mg/L in April 2008 to 25 mg/L in May 2009), moderately hard in Well 22 (TH was 75 mg/L in 2008 and 74 mg/L in 2009) and Well 21 (TH = 102 mg/L in 2008) and Well 7 (TH = 91 mg/L in 2009), and hard in Wells 4 (TH = 150 mg/L), 5 (TH = 177 mg/L), 7 (TH = 125 mg/L) and 9 (TH = 122 mg/L) in April 2008, and Wells 4 (TH = 139 mg/L) and 9 (TH = 128 mg/L) in May 2009. Groundwater was very hard in the rest of the wells in 2008 and 2009. Figure 12 shows the spatial distribution of groundwater hardness in Umm Al Quwain Emirate in 2008 and 2009. Except for a few wells, groundwater is mostly very hard throughout the study area, with a marked increase from south to north. Water hardness between 700 and 800 mg/L reflected the influence of salt-water intrusion in the aquifer in the northern part of the study area. The high total hardness in channel affected wells, such as wells 10 (271 mg/L), 11 (275 mg/L), 13 (433 mg/L) and 14 (381 mg/L) reflects the flux of Ca and Mg-rich recharge water entering the aquifer through its southern boundary.

7. Sodium Adsorption Ratio

For evaluating the suitability of groundwater in the study area for agricultural uses, the SAR is used for classification of irrigation water. Sodium reacts with soil and reduces its permeability, which adversely affects plants and soils. According to the SAR values, groundwater along Wadi Lamhah paleochannel between the southern boundary of Umm Al Quwain Emirate and Well 1, 2, and 3 is good for irrigation can cause a limited harmful effect to soil and plants when used for irrigation (Fig. 13). Between contours 12 and 18 in, groundwater can be moderately harmful to soil and plants, and between contours 18 and 26 groundwater can be harmful to soil and plants and north of contour 26 groundwater can be highly harmful to soil and plants if this water were to be used for irrigation of traditional crops.

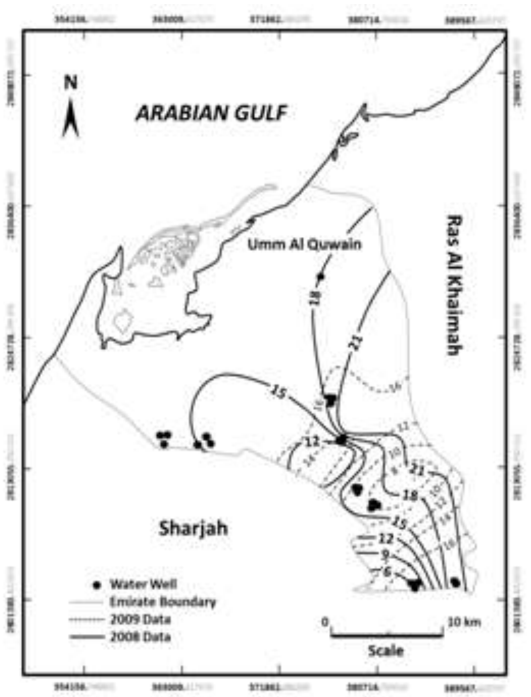

Figure 10. Percentage distribution of the hypothetical salt $Mg(SO_4)$ in the Quaternary aquifer within Umm Al Quwain Emirate during April 2008 (solid lines) and May 2009 (dashed lines).

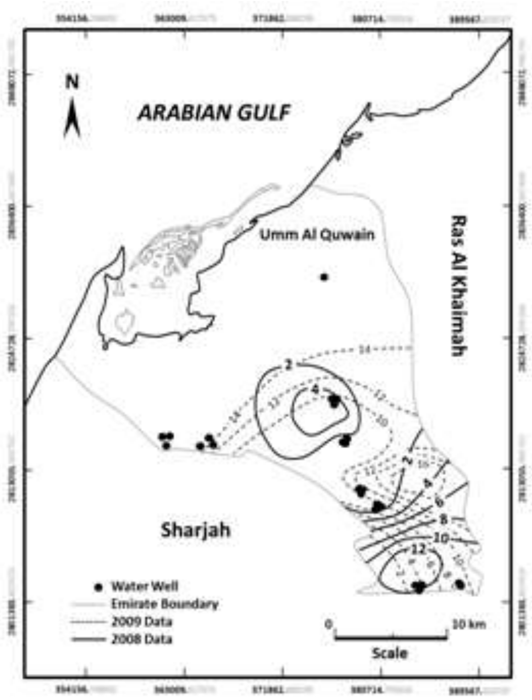

Figure 11. Percentage distribution of the hypothetical salt $MgCl_2$ in the Quaternary aquifer within Umm Al Quwain Emirate during April 2008 (solid lines) and May 2009 (dashed lines).

V. CONCLUSIONS

Wadi Lamhah drainage line is superimposed on a paleochannel combining five wadis, that originate in the Northern Oman Mountains in the east, and reaches the Arabian Gulf in the northwest. In addition good quality, groundwater in the channel has short water residence time and high groundwater potentiality. However, the unconfined nature of groundwater in this channel makes it more susceptible to contamination form surface pollution sources.

Results of field work and chemical analyses revealed that the groundwater temperature in wells affected by Wadi Lamhah channel was 3 to 7°C less than the groundwater temperature in rest of the study area. The groundwater temperature increases from south to north and northwest, in the direction of groundwater flow. The groundwater temperatures in April 2008 ranged from 24.7 to 31.8°C and averaged 28.5°C, decreasing to 23.5-26.5°C, with an average of 24.4°C in May 2009. The low-temperature groundwater in the south (23.5-24.7°C) reflects the movement of recharge water into the aquifer from the south and east, while the high-temperature groundwater in the north (26.5-31.8°C) is attributed to salt-water intrusion from the Arabian Gulf.

In 2008, the groundwater salinity increased from 803 mg/L in the south to 11,643 mg/L in the north and averaged 3,791 mg/L. In 2009, the groundwater salinity increased from 833 mg/L in the south to 8,281 mg/L in the north and averaged 3,555 mg/L. In 2008 and 2009, the groundwater in the Quaternary aquifer within the Emirate of Umm Al Quwain varied from fresh water (TDS <1,000 mg/L in the south) to brackish (TDS >1,000 to <10,000 mg/L in the majority of the study area) to saline water (TDS >10,000 in the north and northwest). The groundwater salinity increased from south to north and northwest in the direction of groundwater flow towards the discharge area in the Arabian Gulf. Groundwater salinity in the paleochannel-affected wells ranges from 803 (Well 12) to 5,407 mg/L (Well 13) and averages 3,219 mg/L, while the groundwater salinity in rest of the study area reaches 11,643 mg/L in well 24, which suffers from salt-water intrusion from the Arabian Gulf, and averages 3,791 mg/L.

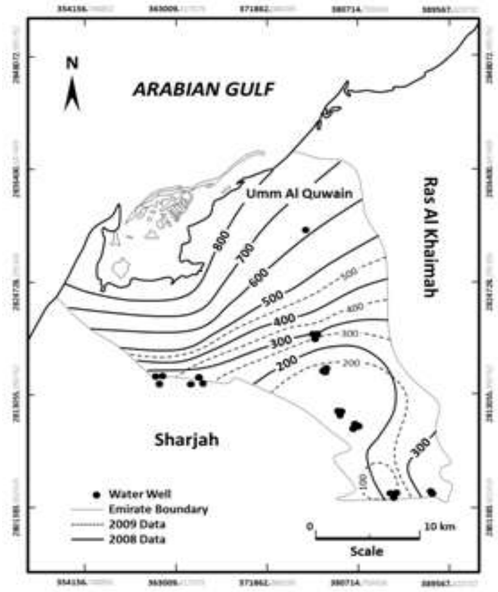

Figure 12. Iso-concentration (mg/L) contour map of total hardness (TH) in groundwater of the Quaternary aquifer within Umm Al Quwain Emirate in April 2008 (solid lines) and May 2009 (dashed lines).

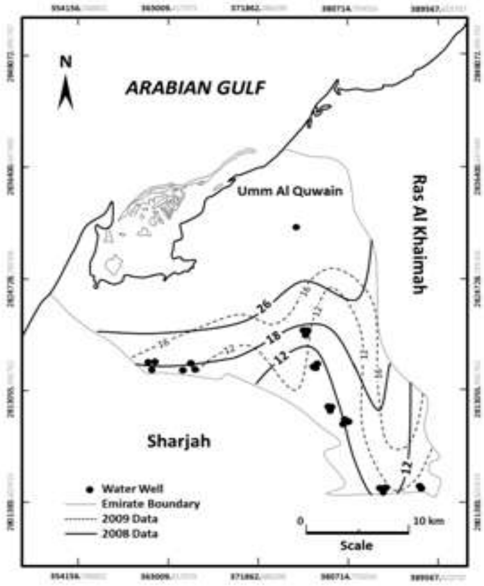

Figure 13. Iso-sodium adsorption ratio (SAR) contours calculated for groundwater samples collected from the Quaternary aquifer in Umm Al Quwain Emirate during April 2008 (solid lines) and May 2009 (dashed lines).

The sequence of cations dominance is $Na^+ > Mg^{2+} > Ca^{2+} > K^+$, while the sequence of anions dominance is $Cl^- > SO_4^{2-} > HCO_3^- > CO_3^{2-}$, reflecting influence of salt-water intrusion form the Arabian Gulf into the Quaternary aquifer within the study area. Concentrations of Ca^{2+}, Mg^{2+}, Na^+ and K^+ in 2008 and 2009 increased from south to north in the directions of groundwater flow. Local high anomalies in Na^+ and Cl^- occur in areas where heavy groundwater pumping for agricultural and domestic purposes is taking place. Opposite of all cations and anions, HCO_3^- levels is high in the south (159 mg/L in 2008 and 256 mg/L 2009) decreasing in the direction of groundwater flow towards the Arabian Gulf in the north and northwest (58 mg/L in 2009). Except HCO_3^-, average concentrations of cations and anions in the paleochannel-controlled wells (Na^+ = 858 mg/L , Mg^{2+} = 151 mg/L , Ca^{2+} = 68 mg/L and K^+ = 21 mg/L ; and Cl^- = 1,432 mg/L, SO_4^{2-} = 517 mg/L and HCO_3^- = 167 mg/L) are lower than their average concentrations in other wells within the study area (Na^+ = 1,033 mg/L, Mg^{2+} = 162 mg/L, Ca^{2+} = 75 mg/L and K^+ = 24 mg/L ; and Cl^- = 1,622 mg/L, SO_4^{2-} = 680 mg/L and HCO_3^- = 188 mg/L).

In 2008, concentration of NO_3^- varied between 1.1 mg/L in the south and 16 mg/L in the north, and averaged 3.6 mg/L. In 2009, NO_3^- increased from 5.1 mg/L in the west to 16.1 mg/L in the south and averaged 9.5 mg/L. The higher nitrate ion in 2009 than 2008 reflects the influence of recharge water moving from the south and east carrying more NO_3^- from the agricultural areas in the south and east. Because of intensive agricultural activities along the course of Wadi Lamhah, average NO_3^- concentration in the paleochannel wells (3.5 mg/L) is close to average level (3.6 mg/L) in the study area. But, the average F^- content increases, from (0.4 mg/L) in channel wells to (0.7 mg/L) in the study area, with increasing groundwater salinity.

Iron (Fe) concentration in 2008 ranged from 0.01 mg/L in the south to 2.55 mg/L in the middle and averaged 0.23 mg/L. The Fe content exceeded the WHO recommended limit in Wells 1, 5 and 9 [27], and exceeded the maximum permissible limit for drinking water in Well 2. Average concentrations of the detected trace elements B, Fe, Zn and Cr are 0.7, 0.3, 0.1 and 1.0 mg/L, respectively, in channel-affected wells, and 0.9, 0.2, 0.1 and 0.4 mg/L, respectively, in the study area.

The average $Ca(HCO_3)_2$ was generally low in 2008 (4.3%) and 2009 (2.4%) throughout the aquifer. The average $Mg(HCO_3)_2$ was also low in 2008 (1.6%) and 2009 (1.3%). However, relatively high percentages of $Ca(HCO_3)_2$ (10% in 2008 and 6% in 2009) and $Mg(HCO_3)_2$ was (12% in 2008 and 5% in 2009) were encountered along Wadi Lamhah channel, which brings recharge water rich in both salts from outside the study area in the south and east. The $MgSO_4$ is the second dominant water-dissolved salt within the study area. The average $MgSO_4$ was 16% in 2008 and 13% in 2009 and maximum was 25% in 2008 and 33% in 2009. The $MgC\ell_2$ averaged 3.2% in 2008 and 10% in 2009, and reached 21% in 2008 and 28% in 2009. High percentages of $MgSO_4$ and $MgCl_2$ in the middle of the study area and along the course of Wadi Lamhah channel are related to human activities. The average $Na_2(SO_4)$ was 6% in 2008 and 3% in 2009 and the maximum was generally higher in April 2008 than in May 2009, while the minimum was 38% in 2008 and 2009. High $Na_2(SO_4)$ near recharge area is against the hydrogeologic logic, but was a result of disposal of high-salinity reject brine from a private desalination plant on land surface in this area. The NaCl is the most dominant water-dissolved salt in the Quaternary aquifer within the study area. The average NaCl was 66% in 2008 and 60% in 2009, and the maximum percentage was 73% in 2008 and 2009. High NaCl indicates salt-water intrusion form the Arabian Gulf into the aquifer in the northern part of the study area. In contrast, the course of Wadi Lamhah channel has the lowest NaCl percentage in the study area. Because of the dynamic nature of groundwater in Wadi Lamhah paleochannel, the percentages of water-dissolved salts in near-channel wells $MgCl_2$ (8.6%), Na_2SO_4 (13.4%), $CaSO_4$ (3.2%) and $Mg(HCO_3)_2$ (3.6%) were higher than their percentages in the rest of the study area (2.7%, 7.3%, 1.5% and 2.9%, respectively).

Groundwater in the Quaternary aquifer within the study varies from fresh in the south (TDS <1,000 mg/L) to brackish in the middle and along the course of Wadi Lamhah channel (TDS >1,000 to <10,000 mg/L) to saline in the north (TDS >10,000 mg/L). Groundwater is soft in the south (TH = 23 mg/L in 2008 and 25 mg/L in 2009), moderately hard (TH = 75-102 mg/L in 2008 and 74-91 mg/L in 2009) to hard (TH = 122-177 mg/L in 2008 and 128-139 mg/L in 2009) in the middle, and very hard (TH = 186-1,320 mg/L in 2008 and 181-543 mg/L in 2009) in the north. Except for a few wells, groundwater is mostly very hard throughout the study area, with a marked increase from south to north. Water hardness between 700 and 800 mg/L reflected the influence of salt-water intrusion from the Arabian Gulf in the aquifer in the northern part of the study area.

The SAR values <12 of groundwater in the southern part of the study area and along Wadi Lamhah channel indicate its suitability for irrigation, with little harm to plants and soil. Groundwater in the middle of the study area, with SAR between 12 and 26, is moderately to highly harmful to soil and plants. Groundwater with SAR >26 is highly harmful to soil and plants if this water were to be used for irrigation of traditional crops.

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