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Chemical and Isotopic Investigation of Groundwater in Eastern United Arab Emirates (UAE)

Ahmed Ali Abdalla Murad
Western Michigan University

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CHEMICAL AND ISOTOPIC INVESTIGATION OF GROUNDWATER IN EASTERN UNITED ARAB EMIRATES (UAE)

by

Ahmed Ali Abdalla Murad

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Ahmed Ali Abdalla Murad

CHEMICAL AND ISOTOPIC INVESTIGATION OF GROUNDWATER IN EASTERN UNITED ARAB EMIRATES (UAE)

Ahmed A. Murad, Ph.D.

Western Michigan University, 2004

UAE is located at the southeast of Arabian Peninsula. Two main aquifers occupy the study area: the Eastern Gravel Plain and Ophiolite aquifer. Increasing salinity of groundwater and depletion of aquifers are a major concern in the UAE. Previous studies suggest that groundwater, particularly in the Eastern Gravel Plain aquifer, is affected by seawater intrusion and evaporation. Isotopes of oxygen, hydrogen, carbon and chlorine, and chemical analyses were used to investigate this problem in detail. Samples of groundwater from the Eastern Gravel Plain aquifer have $R^{36}Cl$ values in the range of 13.3 to 17.4 $\times 10^{-15}$ while those from the Ophiolite aquifer have $R^{36}Cl$ values in the range of 20 to 118 $\times 10^{-15}$. These values indicate the presence of bomb-produced ^{36}Cl and are consistent with recent (post 1950) recharge of most of the samples.

δD - $\delta^{18}O$ relationship plots on a typical evaporation line, which suggests potential primary and secondary evaporation of the recharging waters prior to infiltration. The $R^{36}Cl$ values of the coastally- bound Eastern Gravel Plain aquifer are lower than the Ophiolite aquifer. Seawater intrusion is absent or minimal based on oxygen-hydrogen isotopes, $R^{36}Cl$ and Cl/Br ratio. Measurements of bromide concentrations support the contention that organically bound Cl is being released into

this environment. Agricultural practices, which are extensive in this region, are a possible source.

Samples of groundwater from Eastern Gravel Plain aquifer have $\delta^{13}C$ and DIC values in the range of –10 to -17‰ and 12 to 100 mg C/l respectively. While samples from Ophiolite aquifer have $\delta^{13}C$ and DIC values in the range of –11 to –16.4‰ and 16 to 114 mg C/l respectively. The calculated $\delta^{13}C$ of CO_2 source ranges from –16.6 to –24.3‰ and –18.4 to –23.2‰ with an average of -20.5 and –20.8‰ for Eastern Gravel Plain and Ophiolite aquifers respectively. This suggests that the control on DIC is via soil cover vegetated by C-3 and C-4 plants.

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CHAPTER I

INTRODUCTION

Water has played a major role in establishing civilizations and has been a source of conflicts between nations throughout history. Groundwater is a main source of water in the United Arab Emirates (UAE) and other Gulf Council Countries (GCC). UAE is located to the southeast of the Arabian Gulf and in the southern part of the Arabian Peninsula. Lack of adequate rainfall during the year and inequality between recharge and groundwater withdrawal rates is a crucial problem facing UAE. Life in the UAE has changed dramatically in the last few decades. Development, together with increasing population and standard of living during the last 20 years has resulted in increased consumption of large quantities of groundwater for irrigation and domestic uses.

Salinity problems in the groundwater supply have developed over time. The salinity of groundwater is a limiting factor for different uses; this problem may also restrict development in the country. Distillation plants have been built in different emirates to make-up for the deficit of fresh water. Building and operating distillation plants is very costly. As an alternative to salinized groundwater, these types of plants will increase in the country because of the growing population and industrialization. The UAE depends mainly on major aquifers, desalinated water and treated sewage water for water resources. There is about a 10% annual increase in the conversion of sewage water to potable water due to the shortage of groundwater and increasing population (Alsharhan et al., 2001). The groundwater withdrawn from most aquifers is not replenished (over human time-scales) because of the arid climate in the country (Schyfsma, 1978). The high demands for water in the country have resulted in declining groundwater levels and rising salinity in several areas.

Statement of the Problem

During the previous decades, drinking water in the UAE was extracted exclusively from groundwater. Agricultural activities are a major way of life for the people in the country and the water used for irrigation purposes was drawn from Falajs (canals constructed for irrigation). Recently, the demand for groundwater for different purposes such as drinking, irrigation of agriculture areas, water supply for industrial facilities, amongst many other uses, has led to the depletion of major aquifers, resulting in deterioration of groundwater quality.

The great challenge affecting the UAE and other Arab countries is how to manage the depleting groundwater resources. Due to the lack of rainfall, many wells have gone dry and farmers have either drilled new wells or deepened the existing ones. Groundwater in the UAE is becoming progressively more saline with time. The salinity of the groundwater along the east coast may suffer from salt-water intrusion problems, but other sources may contribute to increasing groundwater salinity as well.

Objectives

This research is designed to investigate different sources of salinity in groundwater from the eastern part of the UAE. This study includes measurements of chlorine and stable isotopes (oxygen, hydrogen and carbon) in groundwater from the eastern part of the country. Major ion analyses were performed to help provide insights into the different sources of salinity.

Project Goals

The goals of this study aimed to determine different sources of groundwater salinity in the eastern part of the UAE. The goals as follows:

- Use of geochemistry and chemical measurements for collected groundwater samples to understand the behavior of different major ions in regional groundwater.
- Conduct radioactive and stable isotope analyses for collected groundwater samples to visualize the problem of salinization.

The approach of this study is to determine the natural and anthropogenic sources of groundwater salinity in the region using isotopes analyses in conjunction with chemical data. The natural sources of salinity could be evapotranspiration, distribution of the stratrigraphy such as presence of halite and gypsum layers. The anthropogenic sources introduced to groundwater by human activities, such as agriculture activities and over pumping of groundwater, also will lead to seawater intrusion especially in areas located in the coast.

CHAPTER II

GEOMORPOLOGY, GEOLOGY AND HYDROGEOLOGY

Location

UAE is one of the Gulf Council countries, which lies to the south of the Arabian Peninsula. It is located between 22° 40′ and 26° 00′ N latitudes, and 51° 00′ and 56° 00′ E longitudes. To the east, it is bound by the Gulf of Oman and the Sultanate of Oman, and it is bound by the Kingdom of Saudi Arabia on the south and west. Also, the country is bound to the north by the Arabian Gulf and by Qatar on the west (Figure 1).

The country has an area of approximately 83,000 km^2 and a population of about 3.1 million people. The UAE is comprised of seven emirates including: Abu Dhabi, Dubai, Sharjah, Ras Al-Khima, Ajman, Umm Al-Queen and Fujairah. The area, where this study was conducted, is located in eastern part of the UAE at north of 24° 56′ 46″ latitude and west of 56° 16′ 02″east longitude. The study area includes the Emirate of Fujairah and parts of the Sharjah Emirate.

Climate

The climate in the UAE is influenced by the Arabian Gulf with respect to temperature, humidity and the occurrence and distribution of precipitation (Ministry of Agriculture and Fisheries, 1981). Alsharhan, Rizk, Narin, Bakhit and Alhajri (2001) indicated that cyclonic depressions and summer monsoons affect the climate in the Arabian Peninsula. In general, precipitation in the region is associated

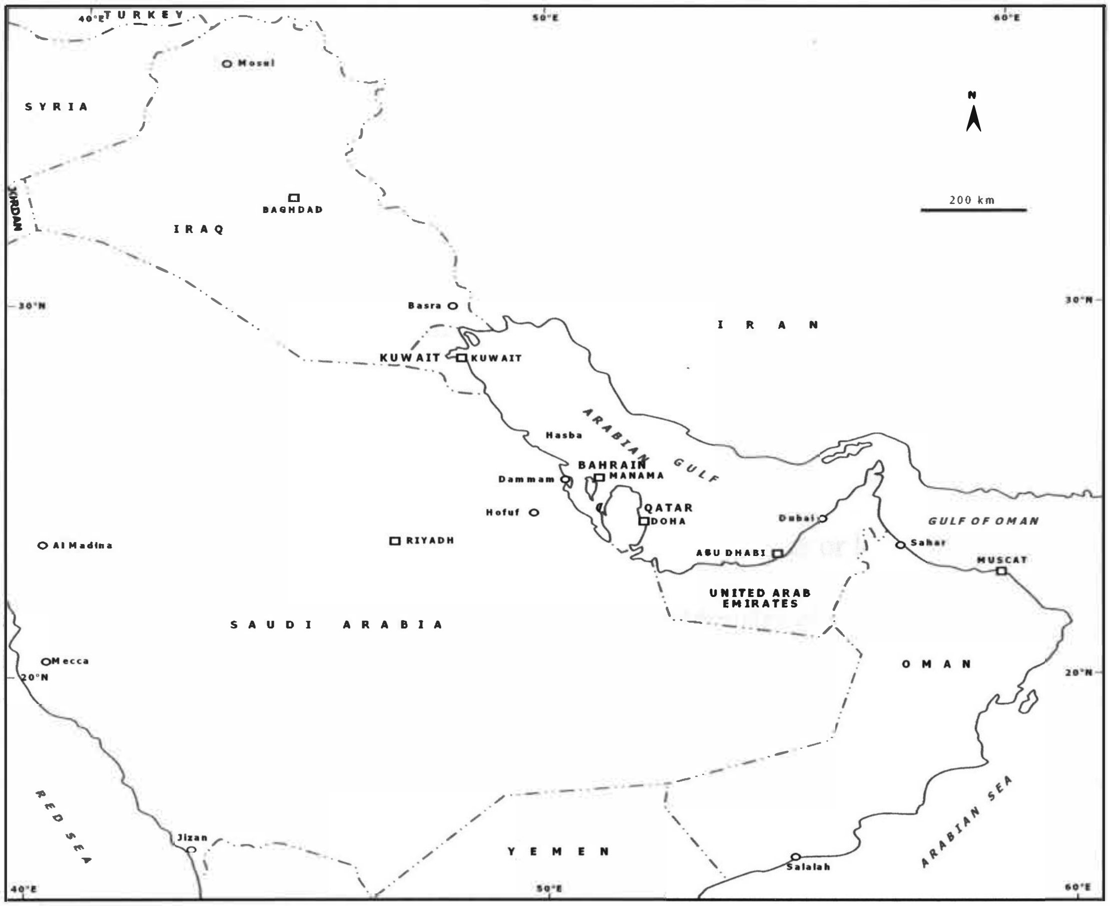

Figure 1. Arabian Peninsula Showing the Location of the United Arab Emirates and Adjacent Countries (modified from Alsharhan et al., 2001).

with frontal, orographic and cyclonic effects (Stanger, 1986).

There are essentially two seasons: hot and dry summer between May and September during which the temperature can reach more than 43 °C, and a winter spanning October and April with average temperature of 14 °C (Ministry of Agricultural and Fisheries, 2001). Precipitation, which is the main source of groundwater recharge, is rare. The annual rainfall amount is highly variable due to the effects of topography. Precipitation in the country averages 150 to 160 mm/yr in the higher elevations (mountainous areas), whereas the average precipitation in the coastal area is between 110 to 130 mm/yr (Bakhit, 1998). The coastal area receives most of its precipitation in the winter months, whereas mountainous areas and adjacent plains receive some rain in summer and winter (Jones and Marrei, 1982). Small storms can produce rainfall during the summer season during July and August, but this precipitation evaporates in the atmosphere before it reaches the ground (Stanger, 1986). A study by Rizk, Alsharhan, and Shindo (1997) indicates that there is a 10-year cycle during which above average (120 mm/yr) precipitation may occur. Also, the pattern of rainfall in the UAE shows a trend of higher or lower amounts of precipitation that alternate every three or four years (Ministry of Agriculture and Fisheries, 1981).

The cities, which are mostly located along the Arabian Gulf, experience the highest temperatures. Garamoon (1996) shows that the highest solar incident radiation is in June and the lowest in December. Humidity is high in the coastal areas and decreases inland. The relative humidity in the study area varies between 35% and 61%. The summer has high humidity compared with the winter months (Ministry of Agriculture and Fisheries, 2001).

The UAE is characterized by high rates of evaporation (>2000 mm/yr) (Jones and Marrei, 1982). This rate includes all water sources that may be evaporated such as precipitation and return flow. Evaporation rates range from 10 to 11 mm/day at higher elevations (the mountainous areas) and gravel plains (Alsharhan et al., 2001). The average evaporation in the Eastern Gravel Plain in 1999/2000 ranged from 5.5 mm/day (December and January) to 13.6 mm/day (May). The average evaporation rate for the mountainous areas ranged from 3.9 mm/day (January) to 16.9 mm/day

(June) (Ministry of Agricultural and Fisheries, 2001). Table 1 shows meteorological information for different weather stations in the study area.

Table 1: Meteorological Parameters (Yearly Mean) for Different Weather Stations in the Study Area. Source: Ministry of Agriculture and Fisheries, Climatological Data, 2001.

Parameters	**Masafi Station**	**Fujairah Int. Airport Station**	**Dibba Station**	**Kalbah Station**
Maximum air Temperature in Deg. C	32.3	32.4	33	----
Minimum air Temperature in Deg. C	21.6	24.6	23.1	----
Maximum relative humidity (%)	77	----	81	----
Minimum relative humidity (%)	25	----	34	----
Class A Pan Evaporation (mm)	10.7	----	9.1	9.3
Wind speed (km/hr) in 2m a.g.l	6.8	----	7.9	----
Yearly average Rainfall (mm)	175.9	158.6	138.2	140.6

---- indicates no data.

Geomorphology and Geology

A variety of geomorphologic features in the eastern part of the UAE characterize the study area and are significant in controlling the movement of groundwater. These features include mountains, gravel plains and coastal areas. The mountains are an extension of the Northern Oman Mountains (Figure 2). The area under study is a composite of a wadi flat that adjusted to the Northern Oman Mountains. Many wadi channels cross the study area from the mountains toward the

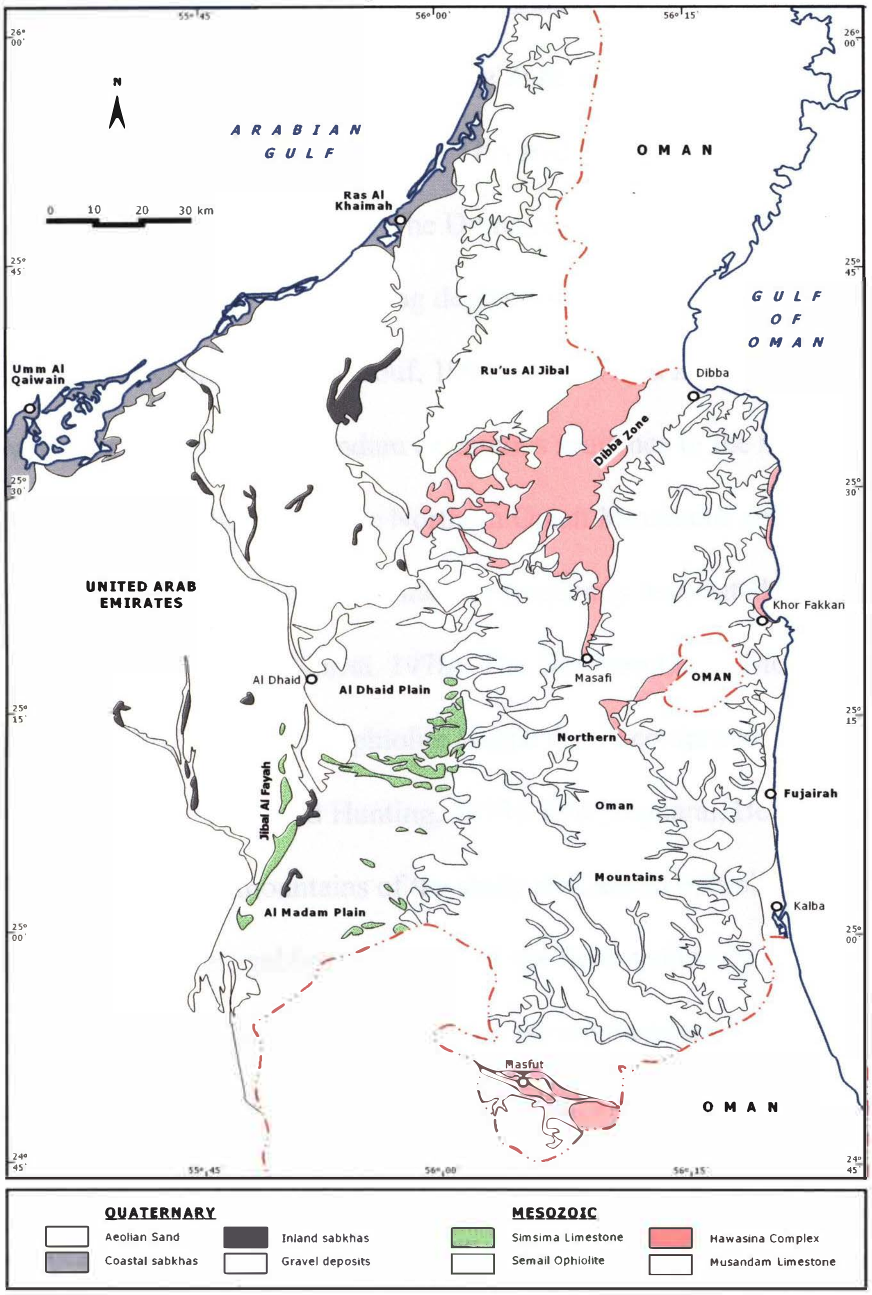

Figure 2. Geologic Map of the Eastern Area of the UAE (modified from the UAE National Atlas, 1993).

east coast. Generally, the mountains in the area are very rugged and almost inaccessible. Recently, modern roads have been constructed through these areas.

According to Finzi (1973), the eastern mountains can be divided into the Ru'us Al Jibal massif in the north, the Dibba Zone in the middle and the Northern Oman Mountains in the south (Figure 2). This study is focused on the Dibba Zone and the Northern Oman Mountains. The Dibba zone is a series of thrust sheets and an elongated northeast-southwest trending depression. The Dibba Zone is 10 km wide and 20 km long (Khattab and Maarouf, 1993). The Dibba zone acts as a tectonic window that separates the Musandam calcareous sequence in the north and the ophiolite complex in the south. The Northern Oman Mountains are a thick sequence of metamorphic and ophiolitic rocks that are frequently associated with large and small scale tectonic events (Marrei, 1978). The Northern Oman Mountains constitute the northern part of the Semail Ophiolite Nappe that is composed of plutonic igneous rocks (Glennie et al., 1974 and Hunting, 1979). Eyre, Samarai, Beer and Wetherelt (2001) indicate that the mountains of the study area are an ophiolite complex composed of periodites, gabbros, basalts and sea floor sediments.

This range of mountains is located on the southeastern part of the Arabian Peninsula adjacent to Gulf of Oman. Glenni, Bœuf, Hughes Clarke, Moody-Stuart, Pilaar, and Reinhardt (1974) describe six major rock sequences with the Northern Oman Mountains.

The sequences from the bottom to the top include: (1) granites, gneisses, partly metamorphosed siliciclastic and carbonate sediments, (2) shallow marine carbonate, (3) Sumeini group, (4) Hawasina ophiolites, (5) a thick sheet of basic and ultrabasic rocks (Semail Ophiolites) and (6) shallow marine Maastrichtian and Early Tertiary carbonates. Before these two studies (Glennie et al., 1974 and Hunting, 1979), Lees (1928) considered that Hawasina and Semail Ophiolites were thrust into Oman Mountains. He stated that the age of Hawasina is Upper Jurassic to Lower Cretaceous.

The wadis in the study area overlie the ophiolite formation of the Semail Suite. This ophiolite suite is composed of medium-grained gabbro and fine to medium diorites. The outcrops of Ophiolite appear on the sides of the wadis and also as isolated hills. These outcrops have been weathered extensively (Electrowatt, 1981). The ophiolite was formed approximately 95 Ma ago and belongs to the Cenomanian age (Tilton et al., 1981, and Tippiti et al., 1981). The ophiolite in the Khorfakkan, which is located in the north of Fujairah, consists of 10-100 m metaluminous to peraluminous granitic intrusions, ranging from cordierite-andalusite-biotite monzogranites to garnet-tourmaline leucogranites (Cox et al., 1999).

The Ophiolite sequences are jointed, fractured and faulted (Figure 3). Faults typically strike northwest southeast (Entec, 1995). The Ophiolite metamorphic sole, which is described in detail by Allemann and Peters (1972), Searle and Malpas (1982), and Gnos and Kurz (1994), is located to the south of the study area. It is mainly composed of garnet and diopside amphibolite at the contact of periodite down into hornblende and plagioclase amphibolites then epidote and quartz amphibolites and finally into quartzites (Searle and Cox, 2002). According to Glennie et al. (1974), the metamorphic sole is classified as: (1) a greenschist facies of metamorphosed cherts, siliceous shales and basalts, and (2) a polymetamorphic series that consists of amphibolites, quartzites and calc-silicate rocks.

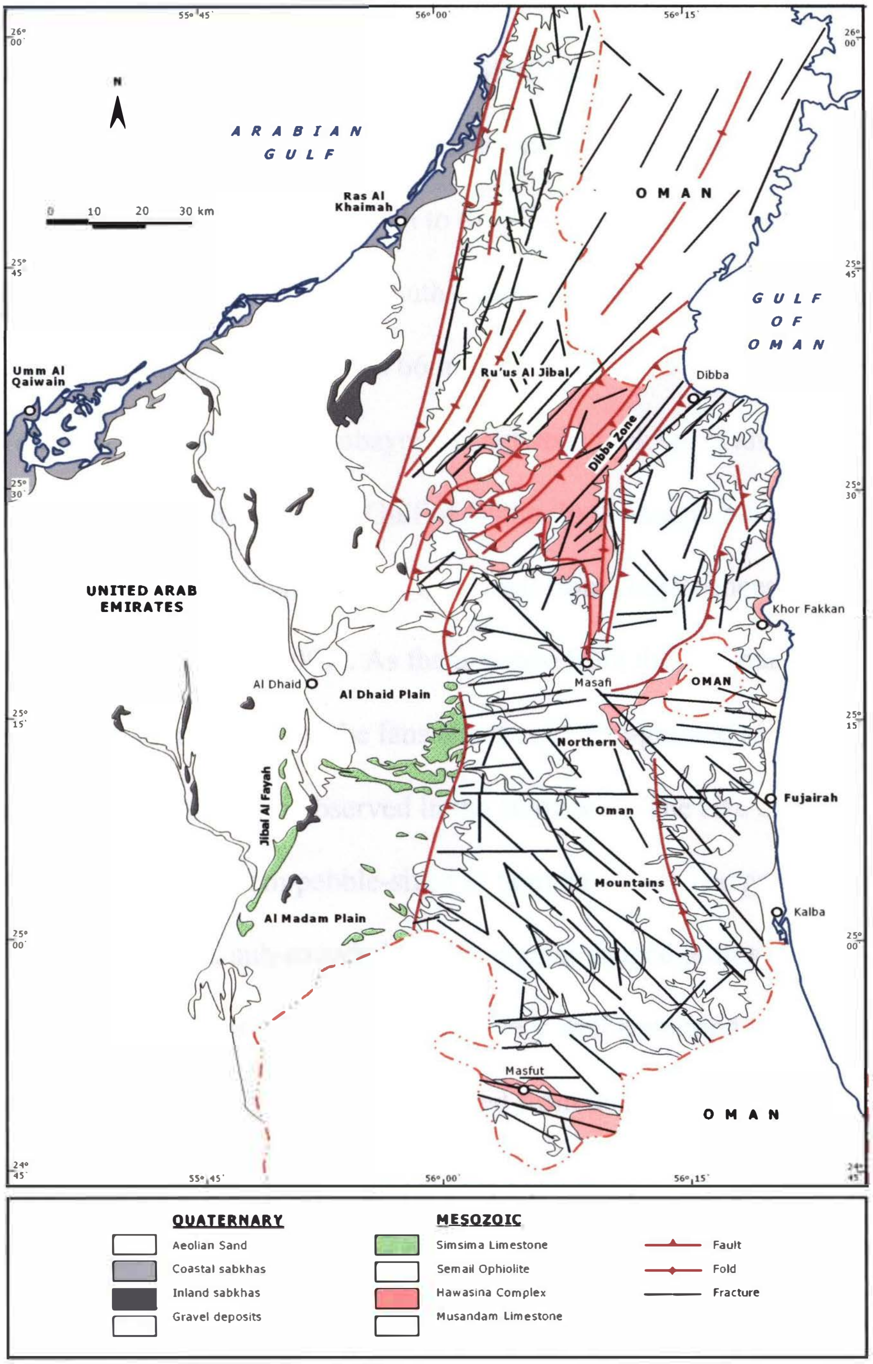

Figure 3. Structural Geologic Map of the Eastern Area of the UAE (modified from the UAE National Atlas, 1993).

Garzanti, Vezooli, and Ando (2002) indicated that sand which formed from Ophiolite sequences consists of cellular serpentinite grains and enstatite from residual mantle harzurgites.

The gravel plain is bounded by the Gulf of Oman to the east and the Northern Oman Mountains to the west (Figure 4). The gravel plain is situated along the east coast of the area from Dibba in the north to the Khorfakkan in the south. The gravel plain is about 22 to 25 m thick in the south of the study area (approximately 8.5 km from the Gulf of Oman) and it reaches 66 m depth (Entec, 1995). The gravel plain is a series of alluvial flats filling the embayments between rock spurs and extends from the foothills of the mountains to the Gulf of Oman. In the south, a continuous littoral strip between the mountains and the sea is formed from coalescences of flats and wadi fans (Alsharahan et al., 2001). As the distance from the mountains towards the sea increases, the composition of the fans changes to fine-grained sands and gravels. Floodplain deposits have been observed in the study area. The size of the sediments in the gravel plain varies from pebble-sized to boulder-sized. The gravel plain consists of poorly sorted, sub-rounded to sub-angular shaped grains and also is composed of basic igneous composition, with very well cemented sandstone and conglomerates. Weathered serpentinite, derived from the Ophiolite rocks, forms most of the Gravel plain, which consists of recent to Pleistocene wadi gravels. These form the surface of wadis which overly the Ophiolite sequence. The sand beaches are different from the wadi sediments. The sand of the beach is composed of bioclasts and has higher heavy mineral concentrations, whereas shale grains are significant in the wadi sands. A possible explanation for that is the weathering and erosion of unstable components along the Gulf of Oman (Garzanti et al., 2002).

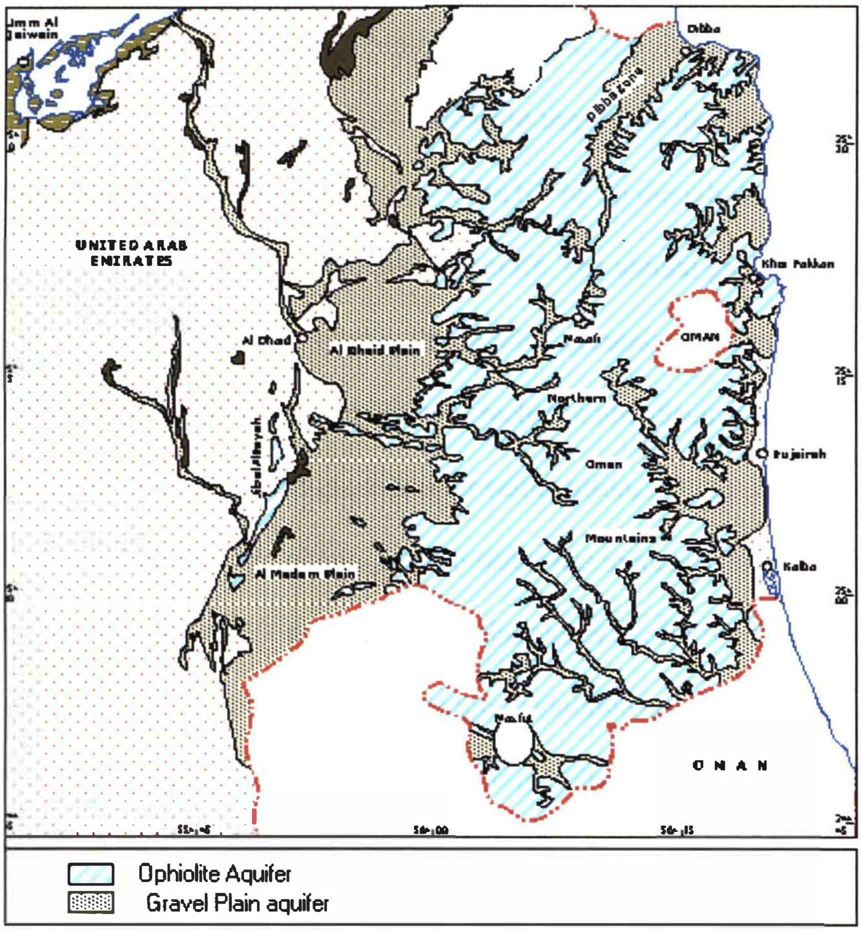

Figure 4. The Main Aquifers in Eastern UAE (modified from the UAE National Atlas, 1993).

The coastal zone is located in the east of the study area and is adjacent to the gravel plain area. The coastal zone and gravel plain are one unit, composed mainly of gravel in a series of alluvial fans.

Hydrogeology

According to the Ministry of Agriculture and Fisheries (1993), the study area is within the area classified as east coast catchments. The climate of the UAE, which is discussed in detail in chapter I, has significant impact on the hydrogeology. The main wadis can carry an annual runoff of 125×10^6 m^3 in the whole UAE. About 35 recharge dams are constructed to impound runoff. The annual groundwater recharge is 120×10^6 m^3 (Khalifa, 1995), whereas the annual groundwater extraction is about 880×10^6 m^3. There is an imbalance between recharge and discharge, which could cause depletion of aquifers and groundwater salinization. Due to aquifer depletion, desalinization of seawater to obtain potable water has increased significantly from 7×10^6 m^3 in 1973 to 694×10^6 m^3 in 2000 (Alsharhan et al., 2001). Based on the latest survey of water resources distribution, the total available surface water in the UAE is 135×10^6 m^3, while the groundwater is 128×10^6 m^3. The whole UAE uses about 915×10^6 m^3 per year, of which the distilled water is about 352×10^6 m^3 (Al-Khaleej, 2003). These statistics show that the UAE is facing a great problem that might affect development and the economy of the country.

Agricultural activity plays a vital role in problems related to the groundwater, such as depletion of aquifers and increasing groundwater salinity. Irrigated areas have increased from about 13,000 hectares in 1973 to 43,800 hectares in 1990 (United Arab Emirates National Atlas, 1993).

Aquifers

Two distinguishable aquifers in the study area include the Eastern Gravel Plain and Ophiolite aquifers (see Figure 4).

Eastern Gravel Plain Aquifer

This aquifer is situated along the eastern coast with Dibba (Figure 4) in the north to the Khorfakkan in the south. The aquifer is comprised of sequences of alluvial flats filling the embayments between rock spurs and extends from the ends of these mountains to the Gulf of Oman. South of this aquifer, a continous littoral strip between the mountains and the sea is formed by the coalescence of flats and wadi fans (Alsharhan et al., 2001). As the distance from the mountains toward the sea increases, the composition of the fans changes to fine-grained sand and gravel. This aquifer is underlain by ophiolitic rocks in the south (Fujairah) and by sedimentary deposits of marl and limestone (Tertiary) near Dibba in the north (Bakhit, 1998). The gravels in this aquifer are characterized by high permeability. At the surface, the gravels are unconsolidated, but they become cemented and consolidated with depth. There are three subdivisions of gravels. These subdivisions are recent gravels, young gravels and old gravels (Entec, 1995). Recent gravels are silty sandy gravel with some cobbles; young gravels are silty sandy gravels with many cobbles and boulders. The old gravels are silty sandy gravels with cemented and weathered cobbles and boulders. Unconsolidated gravels have hydraulic conductivities of 6 to 17 m/d, whereas the cemented gravels have 0.086 to 0.86 m/d (Elctrowatt, 1981). Generally, the Eastern Gravel Plain aquifer is characterized by high permeability and transmissivity, and the ability to transmit impounded water is high. The temperature of groundwater typically varies between 21°C and 41°C, while pH varies between 7 and 8.5. The chemical facies of groundwater in Eastern Gravel Plain aquifer is Mg-Cl which reflects the influence of Mg-rich ophiolitic rocks (Rizk et al., 1997).

Ophiolite Aquifer

The Ophiolite aquifer (Figure 4) is of good quality due to jointing, faulting and weathering of the "Semail beds" of the Northern Oman Mountains (Rizk et al., 1997). A survey by Electrowatt Engineering Services (1981) showed that the Ophiolite Suite consists of medium-grained gabbros and fine to medium-grained diorites. Another feature of this aquifer is the presence of wadi deposits at the surface. The salinity of water in the fractures increases with depth as the size of fractures decreases (Ministry of Agriculture and Fisheries, 1986) due to the slow movement of water and higher rate of mineralization (Bakhit, 1998).

The upper layer of this aquifer is weathered and therefore forms a more transmissive layer than the unweathered layer below. The transmissivity in gabbros and diorites is variable and ranges from 29.5 m^2/d to 490 m^2/d. Higher values for transmissivity are due to the highly fractured gabbro. This aquifer is confined in some places and unconfined or semi confined in other areas based on its relationship with the overlying unit. Hydrochemical data shows that the electrical conductivity is variable due to response to rainfall and runoff recharge events. Chemical data shows this to be magnesium-chloride type waters with secondary ion concentrations of sodium and bicarbonate (Entec, 1995).

Groundwater in the eastern region of the UAE, which includes Eastern Gravel Plain and Ophiolite aquifers, is characterized by dominance of the following cations: $Mg^{2+}>Ca^{2+}>Na^{+}>K^{+}$ and the dominance of the following anions: $HCO_3^{-}>Cl^{-}>SO_4^{2-}>CO_3^{2-}$. Also, both aquifers are characterized by enrichments in Ca-HCO_3 and Mg-HCO_3 dissolved in the water. The groundwater in the region occurs within local flow systems, which are characterized by short residence time and rapid flow rate (Rizk et al., 1997). Both aquifers contain high concentrations of ^{3}H (10-20 TU) and > 50 pmc (percent modern carbon) suggesting modern (post-1950) recharge (Alsharhan et al., 2001). Regional groundwater flow in the study is such that recharge takes place in the mountainous area (Ophiolite aquifer) and discharge occurs in the Gulf of Oman adjacent to the Eastern Gravel Plain aquifer.

CHAPTER III

METHODS

Sampling

Two trips were made to the study area for sampling. The first trip was between January and April of 2002, and the second trip, in August of 2002. One-hundred-twenty (120) groundwater samples were collected for major ion and metal analyses, 103 samples for oxygen and hydrogen isotope analyses, 12 samples for chlorine-36 analyses, and about 80 samples for DIC and carbon isotope analyses. Five water samples from Gulf of Oman were collected for isotope analyses. During August of 2002, additional ten samples of groundwater were collected for DIC analyses to determine if significant seasonal variations exist in the aquifers. In addition to water samples, one sample of animal waste (manure) was collected from the study area for chemical analyses in order to evaluate the effect of manure on groundwater quality.

Analyses

Different analyses in this study were conducted either in the field or in the laboratory. The measured field parameters include pH, temperature and electrical conductivity. Groundwater samples collected for laboratory analyses were stored in plastic bottles. Samples for major cation analyses were acidified and samples for anions analyses were stored at 4°C.

Field Measurements

Electrical conductivity (EC) in microsiemens per centimeter (μS/cm), pH and temperature (°C) were measured for groundwater samples during the sampling. The pH parameter was measured using a portable pH-meter, model HI-8314. The EC of collected groundwater samples was measured using a Myron-L EP-meter.

Laboratory Analyses

Chlorine-36

Twelve groundwater samples were collected from representative sites for chlorine-36 measurements. The chlorine-36 measurements conducted at PRIME Lab (Purdue University, Indiana) were using Accelerator Mass spectrometry (AMS). .

Hydrogen Isotope Analyses

Groundwater samples were collected in 20-ml scintillation vials for both oxygen and hydrogen analyses. The water was reduced to hydrogen gas using either uranium (Bigeleisen et al., 1952) or zinc (Coleman et al., 1982). The reduction reactions are as follows:

$$2H_2O_{(l)} + U_{(s)} \rightarrow UO_{2(s)} + 2H_{2(g)} \qquad (1)$$

$$2H_2O_{(l)} + 2Zn_{(s)} \rightarrow 2ZnO_{(s)} + 2H_{2(g)} \qquad (2)$$

Reaction 1 was done at 800°C, whereas reaction 2 was carried out at 400°C.

In this research, the zinc method was the preferred method to reduce groundwater samples to hydrogen gas. The extraction procedures were done in a vacuum line using 6 mm Pyrex® tubes (Figure 5).

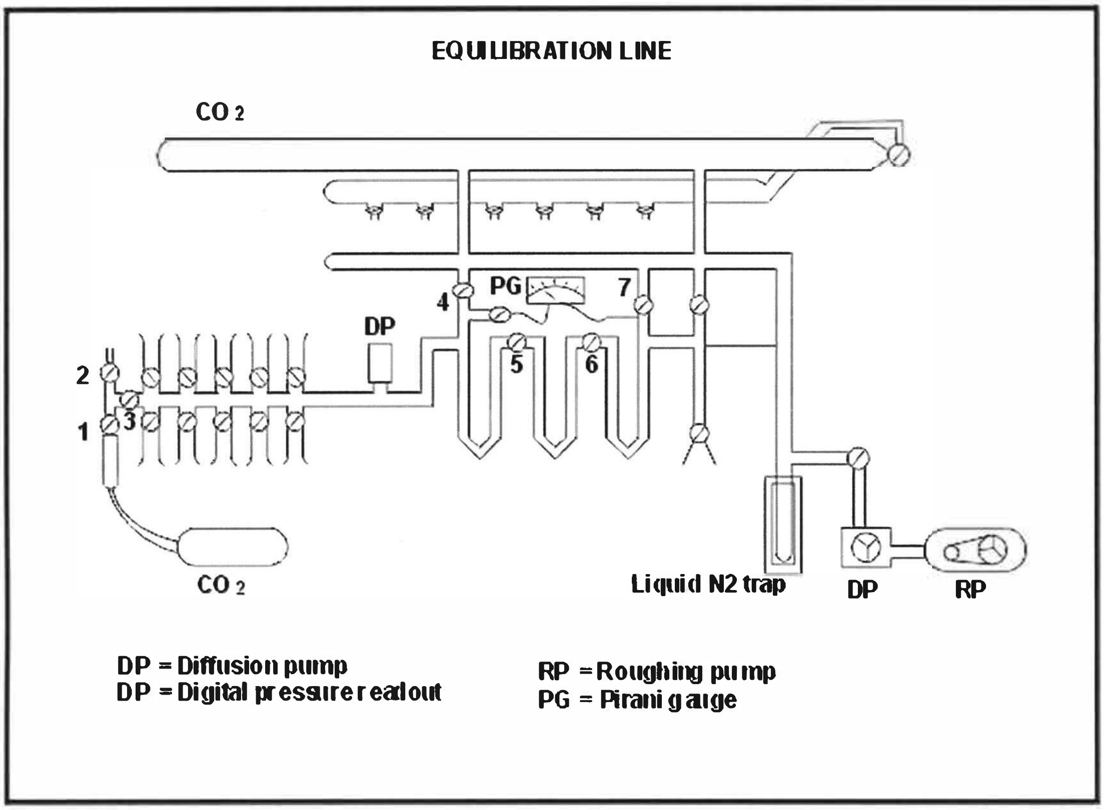

Figure 5. Diagram Showing Vacuum Line.

About 150 mg of zinc was added to the Pyrex tube, which was then connected to the vacuum line for evacuation. After that, zinc inside the tube was heated to 400°C to remove adsorbed moisture and chemisorbed hydrogen probably in the form of hydroxy groups using a master heater gun (Model: HG-501 A, 120 V.A.C., 60 Hz., 14 Amp, Master Appliance Corp.). When the heating was completed, a liquid nitrogen was used to cool the tube which was then isolated from the vacuum line by a stopcock. Immediately after isolation, 2 μl of water sample was injected using a gas tight syringe (Hamilton company).

The heated tube with water was connected to the line again five minutes after injection of the sample. Then the tube with water was sealed with the tube still under liquid nitrogen. The sealed tube was heated to 500°C for 45 minutes.

Oxygen Isotope Analyses

The stable oxygen isotope composition of water can be determined using CO_2 equilibration. This method was established by Epstien and Mayeda (1953) and is based on the equilibrium isotope exchange reactions between CO_2 and water. This reaction takes place with a given fractionation factor which depends on the temperature. The equilibration reaction takes place via hydration of CO_2 according to the following steps:

$$CO_2\,(g) \leftrightarrow CO_2\,(aq) \tag{3}$$

$$H_2O_{(l)} + CO_2\,(aq) \leftrightarrow HCO_3^-{}_{(aq)} + H^+{}_{(aq)} \tag{4}$$

The equilibrated CO_2 has an $^{18}O/^{16}O$ ratio related to the water through a fractionation factor α :

$$\alpha_{A\text{-}B} = (^{18}O/^{16}O)_A \;/(^{18}O/^{16}O)_B \tag{5}$$

where A and B are the different phases.

The isotopic exchange reaction is expressed as follows:

$$C^{16}O_2 + H_2{}^{18}O \leftrightarrow C^{16}O^{18}O + H_2{}^{16}O \tag{6}$$

This exchange reaction reaches equilibrium after a certain time, which can be reduced from one day or more to a few hours by shaking the samples. In the method used in this study, a vacutainer tube (10 ml) was used for water equilibration with CO_2 by connecting it to the vacuum line (Figure 5) and evacuating. Then the CO_2 tank was opened, and CO_2 gas was allowed to pass though the line. The CO_2 tank contains high purity CO_2, which was used for equilibration. Then stopcock #1 was opened, and for a few seconds stopcock #2 was opened. CO_2 was passed and collected in the evacuated U-trap by opening stopcock #3. A liquid nitrogen dewar was inserted into the U-trap to collect the gas. Stopcocks #4 and 6 remain closed when CO_2 is allowed to pass to the U-trap. When CO_2 was collected inside the U-trap, stopcock #6 was opened to remove any non-condensable gases. Stopcock # 6 was closed again and the liquid nitrogen dewar was removed and the CO_2 was allowed to expand in the line until it reached half atmosphere. Then stopcock #5 was closed and the vacutainer tube was allowed to equilibrate with CO_2 for five minutes. The tubes filled with CO_2 were taken off the vacuum line and 2 ml of water was injected to each tube. The water and CO_2 were allowed to equilibrate at constant temperature of 25 ± 0.01°C, CO_2 for about 27 hours.

Carbon Isotope Analyses

There are two methods for DIC analysis. These methods are direct precipitation (Pearson et al., 1978 and Bishop, 1990) and gas evolution techniques (Holt et al., 1995 and Atekwana and Krishnamurthy, 1998). The DIC in the direct precipitation method (Gleason et al., 1969) is precipitated in the form of strontium carbonate ($SrCO_3$) and then converted to CO_2 gas by reaction of precipitate with phosphoric acid under vacuum. Problems arising from this method include contamination of CO_2 from the ammoniacal strontium chloride (amm. $SrCl_2$) solution used to precipitate DIC and the heterogeneity of the precipitate used for the analysis. Also, the precipitation of $SrSO_4$ in sulfate waters can produce low CO_2 yield (Hassan, 1982). The gas evolution technique (Graber and Aharon, 1991) is a problematic technique, as well. The problems that appeared with this technique are: gain and loss of CO_2 in the container of water sample during shipping and storage prior to the analysis, lack of complete transfer of CO_2 gas to the extraction line from the sample container. During storage, the activity of bacteria may alter the DIC and the isotopic ratio of the water sample if samples are not preserved with a bactericide (Mook, 1968). Hassan (1982) stated that the critical problem of this technique is the lack of a proper sampling device and the limitations of transferring the sample due to the manner of water sampling. In this study, a modification of the gas evolution technique developed by Atekwana and Krishnamurthy (1998) was used for DIC analysis. Vacutainer tubes (Becton Dickson & Company, Franklin Lakes, NJ 07417) were used for extraction. The tube is evacuated and then the acid-DIC reaction is carried out inside the tube, and remained in the tube until CO_2 extraction was done. Prior to the analyses, a standard solution of Na_2CO_3 was prepared by dissolving 212 gram of Na_2CO_3 solid in deionized water according to the following equation:

$$Na_2CO_{3(s)} + H_2O_{(l)} \rightarrow CO_{2(g)} + 2NaOH_{(aq)} \tag{7}$$

A standard solution of Na_2CO_3 was used for optimal procedures and for calibration of the ultrasonic extraction technique. Approximately 0.5 ml of 85% phosphoric acid was added to the pre-evacuated tubes and then the septa were sealed with household adhesive. Pre-evacuated tubes with acid are connected to the line for evacuation. 5 ml of Na_2CO_3 solution was added to the tube and the solution was left for several minutes for complete reaction.

The extraction of CO_2, produced by the phosphoric acid and Na_2CO_3 reaction, was done under vacuum. The extraction needle was attached to the vacuum line (Figure 6) and the sample tube was inserted into the needle to cover the needle opening, but without penetrating inside the tube in order to evacuate the air in the needle assembly. After that, the needle is pushed through the septum and CO_2 is released and trapped and purified cryogenically under vacuum. The CO_2 yield is measured by calibrated coldfinger.

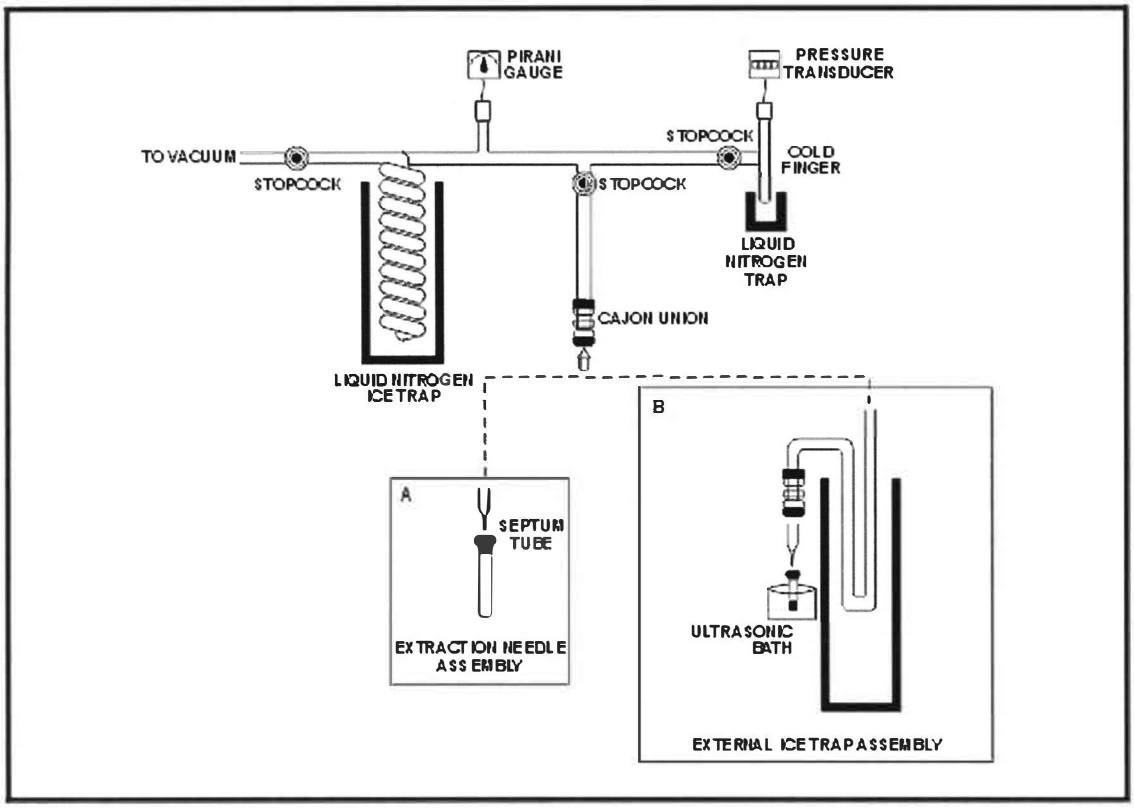

Figure 6. Schematic Diagram Showing DIC Extraction Line (modified from Atekwana and Krishnamurthy, 1998).

Three samples were extracted and collected by coil trap tubes and two other samples were collected by U-trap tube filled glass beads. The modified gas evolution technique for DIC extraction (Atekwana and Krishnmurthy, 1998) uses a heater and stirr with a magnetic bar inside the vacutainer tube (Table 2). The $\delta^{13}C$ of the standard showed a variation of 0.1 to 0.2‰.

Table 2. Results of CO_2 Yield and $\delta^{13}C$ from Na_2CO_3 Solution

DATE	**RUN #**	**CO_2(μmole)**	**$\delta^{13}C$ (‰)**
10/09/01	1	90	-7.6
10/10/01	2	78	-7.5
10/10/01	3	88	-7.7
10/10/01	4	92	-7.5
10/10/01	5	89	-7.5

Extraction of Na_2CO_3 Solution Using Ultrasonic Bath (Modified from Atekwana and Krishnamurthy, 1998). In this research, DIC extraction procedures were slightly modified. As seen from the inset B in Figure 2, an ultrasonic bath is used instead of a heater and stirrer. The procedures applied here are otherwise the same as procedures described above. Table 3 shows the results of DIC extraction produced with the modified method.

Extraction of Groundwater Samples. The preparations for groundwater samples are similar to the preparation for Na_2CO_3 solution. A plastic syringe with a 26-gauge needle was used for groundwater collection in the field. Air bubbles were removed by tapping the syringe gently and excess water was expelled to obtain the

Table 3. The Results of DIC Extraction by Using the Ultrasonic Method

DATE	**RUN #**	**CO_2(μmole)**	**$\delta^{13}C$ (‰)**
10/28/01	1	93	-7.7
10/28/01	2	95	-7.6
10/28/01	3	95	-7.5
10/29/01	4	93	-7.5
10/29/01	5	97	-7.5

desired volume of water. Before sampling, each well was purged. The collected sample was exposed to the atmosphere for less than 20 seconds from the time of collection to the injection into the prepared septum tube.

The CO_2 in the septum tube, from the reaction of water samples and phosphoric acid, was extracted using an external modification to the vacuum system (as described previously).

Chemical Analyses

The chemical analyses of the groundwater samples were conducted at the Central Laboratories Unit (CLU) in UAE University, Al-Ain. The analyses of major cations (Na^+, K^+, Mg^{+2} and Ca^{+2}) were conducted by using Atomic Absorption Spectrometry, whereas the trace metals (Al, B, Ba, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, P, Pb, Sr, Zn, Hg and SiO_2) were analyzed using Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES). Ion chromatography was used for analysis of the anions NO_3^- and SO_4^{2-}. The analyses of CO_3^{2-} and HCO_3^- were conducted using the AOAC official titration method (920.194). Chloride analysis was conducted using the titrimetic method. Confirmatory analyses for chlorine analysis for some aqueous samples were conducted at KAR Laboratories, Inc. (Kalamazoo, MI) using SM (18) 4500-Cl-E. Bromide concentrations were determined at the KAR Laboratories, Inc. (Kalamazoo, MI) using the EPA 300.0A method. In addition, one sample of animal waste was analyzed for chloride and bromide using the SM (18) 4500-Cl-E and EPA 300.0A methods respectively. The precision for aqueous samples was 0.5% for all ions, while the precision for chloride and bromide from the animal waste was 2% and 1.3% respectively.

CHAPTER IV

ISOTOPES

Introduction

Isotopes of oxygen, hydrogen, carbon and chlorine have been used in this study to assess groundwater quality in the eastern part of the UAE. In the following, a principle of each isotope method is discussed.

Oxygen and Hydrogen Isotopes

Water molecules are composed of hydrogen and oxygen, both of which have several naturally occurring isotopes. The isotopic composition of hydrogen and oxygen in water can be measured using mass spectrometry. Such measurements are typically reported with respect to the international standard Vienna Standard Mean Ocean Water (VSMOW). The isotope measurements are expressed in per mil (‰), defined as follows:

$$\delta D‰ = [({}^{2}H/{}^{1}H_{sample}/{}^{2}H/{}^{1}H_{reference} - 1)* 1000] \tag{8}$$

$$\delta^{18}O‰ = [({}^{18}O/{}^{16}O_{sample}/{}^{18}O/{}^{16}O_{reference} - 1)* 1000] \tag{9}$$

The $\delta^{18}O$ and δD variations in precipitation are controlled mainly by evaporation and condensation processes (Yurtsever, 1997). Evaporation is a process that occurs widely on earth, especially at low altitude and particularly in arid environments. Thus, surface water characterized by higher values of $\delta^{18}O$ and δD relative to meteoric precipitation results from evaporation (Alley and Cuffey, 2001). Lighter water molecules evaporate more readily than heavy ones, so this causes an isotopic enrichment in the heavy isotopes in the liquid phase. As a result, the vapor has more negative values of $\delta^{18}O$ and δD, and the residual water is enriched in heavy isotopes resulting in more positive $\delta^{18}O$ and δD values (Mazor, 1997).

Many factors affect the values of $\delta^{18}O$ and δD in natural water samples. Theses factors include: temperature, amount of precipitation, distance from the source of water vapor and altitude. The temperature effect is more in temperate region because of pronounced temperature changes during the winter and summer seasons. Decreasing temperature produces more depleted δ values. The amount of precipitation also has a significant impact on $\delta^{18}O$ and δD. Heavy precipitation produces lower (i.e. more negative) values for both oxygen and hydrogen isotopes. The continental effect results in progressively more negative values away from the coastal areas. The effect of altitude in $\delta^{18}O$ is about –0.26‰/100 m. (Clark and Fritz, 1997; Mazor, 1997 and Alley and Cuffey, 2001).

The average isotopic distribution of oxygen and hydrogen is described by the: $\delta D = 8\delta^{18}O + 10$ (Craig, 1961). This equation is known as Global Meteoric Water Line (GMWL) and this line is controlled by factors such as the origin of vapor mass, secondary evaporation and precipitation seasonality (Clark and Fritz, 1997). The $\delta^{18}O$-δD relationship of precipitation produces a linear line. Dansgaard (1964) attributed the GMWL to the condensation of water vapor under equilibrium conditions which was evaporating by the non-equilibrium conditions. In order to understand a given system, a meteoric water line (MWL) should be established. The meteoric water line constructed from the $\delta^{18}O$ and δD of the rainfall data in a given region is known as Local Meteoric Water Line (LMWL). This line is used as a reference line, which can help to explain the observed distribution of isotopic composition of samples relative to the local precipitation. Other isotopic data such as those obtained from groundwater or surface water can be plotted together with local meteoric line to help understand how these samples might be related to meteoric water. The isotopic content of oxygen and hydrogen in groundwater has been used to identify the origins of salinity (Edmunds and Droubi, 1998).

Chlorine-36

Chlorine-36 is a useful tool to trace different sources of salinity in groundwater systems (Carlson et al., 1990; Mazor, 1992; and Phillips, 2000). Chlorine-36 is produced naturally by several mechanisms: (1) atmospheric production through the spallation reaction of ^{40}Ar and neutron capture of ^{36}Ar (meteoric), (2) lithospheric production by the spallation reaction of K and Ca and neutron activation of ^{35}Cl (epigene), and (3) subsurface production via neutron activation of ^{35}Cl (hypogene) (Bentley et al., 1986a,b; Carlson et al., 1990; Commander et al., 1994; and Lyons et al., 1998). ***In situ*** production of chloride could be another source of ^{36}Cl in groundwater that is low in chloride (Yechiel et al., 1996). Also, ^{36}Cl has been produced anthropogenically in the 1950's during nuclear weapons testing (Lyons et al., 1998).

The distribution of ^{36}Cl in the subsurface is controlled by the above sources as well as by the evapotranspiration and dissolution of halite (Bird et al., 1989 and

Mazor, 1997). In general, high $^{36}Cl/Cl$ ratios are associated with areas of high precipitation, whereas low ratios are observed in regions of low precipitation (Phillips, 2000). The meteoric ^{36}Cl tends to increase from the continental interiors toward coastal areas (Bentley et al., 1986a,b). Lehmann, Loosli, and Purschert (1995) suggest several other possible external sources of chloride to groundwater system which include seawater incursion, aquitard infiltration, and mixing with high salinity water from outside the aquifer.

The aim of this study was to investigate groundwater quality in eastern UAE (Figure 7) using ^{36}Cl, oxygen and hydrogen isotopes and select chemical analyses. Published ^{14}C and ^{3}H data are compared with the present data. Several prior studies have evaluated the groundwater characteristics in the eastern part of the UAE (Jones and Marrei, 1982; Elschami, 1990; Rizk and El-Etr, 1997; Rizk et al., 1997; and Brunke and Schelkes, 1999). Based on these studies, it has been suggested that evaporation and seawater intrusion are possible sources of salinity in the groundwater of the region.

Stable Isotope of Carbon

Carbon-13 is a stable isotope that is present in all carbon compounds. The carbon isotope ratio ($\delta^{13}C$) is a useful tracer to study the carbon chemistry of natural water (Chapelle et al., 1985; Landmeyer and Stone, 1995, and Yang et al., 1996). The production rates of CO_2 concentrations in the unsaturated zone are affected by several environmental factors such as temperature, soil moisture and porosity. Several processes affect the geochemistry of $\delta^{13}C$ and dissolved inorganic carbon (DIC) in

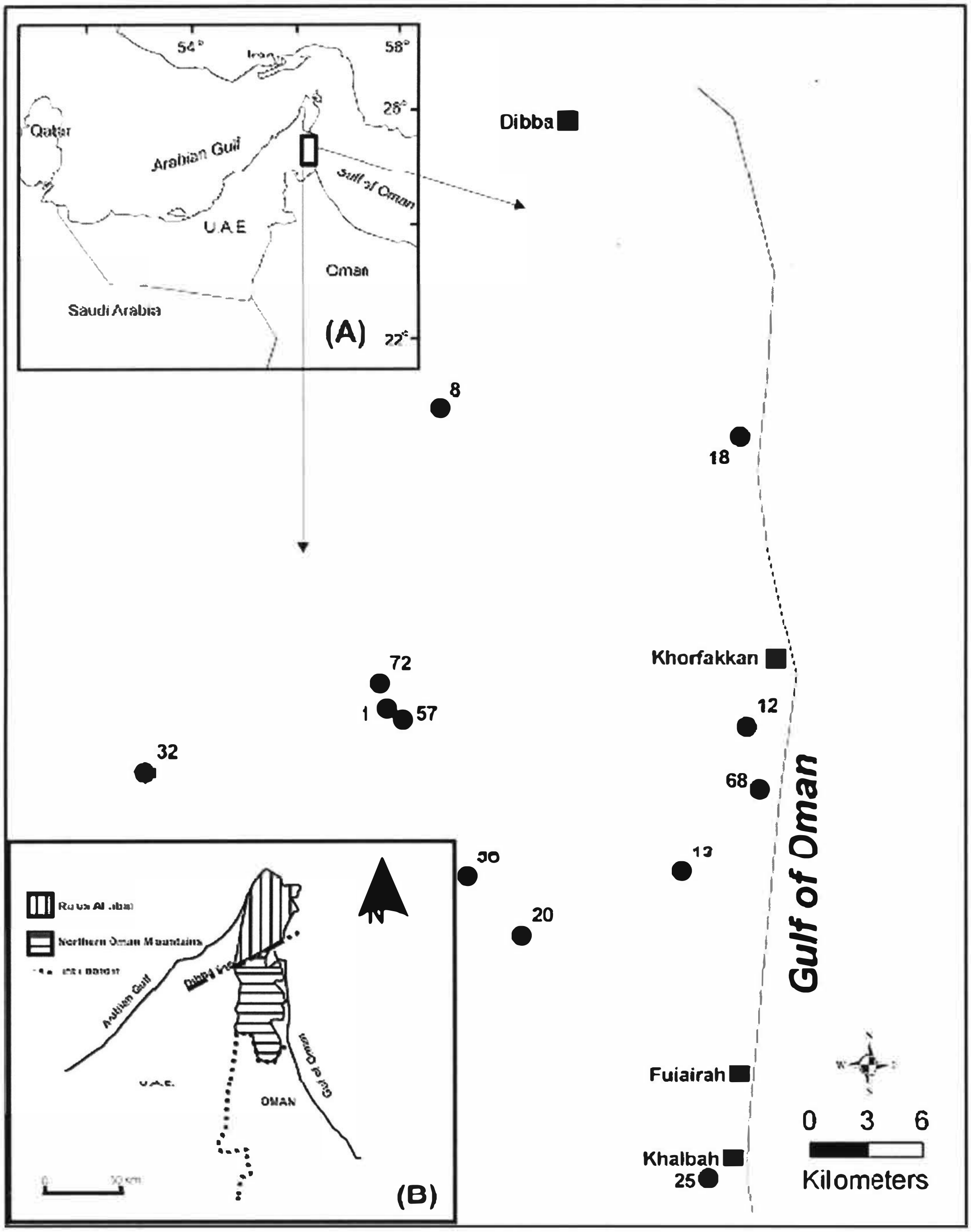

Figure 7. Map of the United Arab Emirates Showing the Study Area and Samples Locations. Insets: (A) Location of the study area. (B) Classification of eastern mountains of U.A.E. according to Finzi (1973). (Modified from Naqash and Marrei, 1983).

groundwater systems. These processes include: carbonate dissolution, oxidation and reduction of organic matter, volcanic and magmatic activity in hydrothermal systems, precipitation of secondary carbonate and the exchange between carbonate minerals and total dissolved inorganic carbon (TDIC) (Clark and Fritz, 1997; and Drever, 1997).

DIC is produced by the dissolution of gaseous CO_2 and weathering of silicates or precipitation of carbonates. For example, dissolved inorganic carbon can be produced through the following reactions (Garrels and Christ, 1965):

$$CO_2\,(g) + H_2O_{(l)} \leftrightarrow H_2CO_{3(aq)} \tag{10}$$

$$H_2CO_{3(aq)} \leftrightarrow H^+_{(aq)} + HCO_3^-{}_{(aq)} \tag{11}$$

$$HCO_3^-{}_{(aq)} \leftrightarrow H^+_{(aq)} + CO_3^{-2}{}_{(aq)} \tag{12}$$

$$HCO_3^-{}_{(aq)} + Ca^{+2}{}_{(aq)} \leftrightarrow H^+_{(aq)} + CaCO_{3(s)} \tag{13}$$

DIC is defined as the sum of all the chemical species that contain inorganic carbon and can generally be represented by the following equation (neglecting carbonae aqueous complexes):

$$CO_2\,(g) + H_2CO_{3(aq)} + HCO_3^-{}_{(aq)} + CO_3^{-2}{}_{(aq)} = DIC \tag{14}$$

And $\delta^{13}C_{DIC}$ is defined by the following equation:

$$\delta^{13}C_{DIC} = (mCO_{2(g)}\, \delta^{13}C_{CO2(g)}) + (mHCO_3^-\, \delta^{13}C_{co2(g)}) + (mCO_3^{-2}\, \delta^{13}C_{CO2(g)}) \quad (15)$$

where m= mole fraction.

The CO_2 (g) involved in reaction (10) is normally biogenic in shallow aquifers, resulting from root respiration or/and oxidation of organic matter and also can be atmospheric. Reaction (13) can originate from the precipitation of calcite in aquifers. Organic and inorganic acids and pCO_2 regulate the dissolution of carbonate minerals. Higher pCO_2 values produce more carbonate dissolution.

The degree of openness of the system between the groundwater and soil zone controls the DIC production via infiltration. Open system exists in the vadose zone where continuous supplement of CO_2 exists and the final produced DIC is high. However, a closed system exists in the recharge area where the infiltration to the aquifer is rapid. Also, saturated soil with little or no carbonate is considered as an example of a closed system. The final DIC is lower compared with that produced in an open system (Clark and Fritz, 1997). Carbonate dissolution under an open system will dissolve more carbonate compared with a closed system. The dissolution of carbonate is generally limited in closed systems by fixed values of CO_2. Weathering of silicate materials such albite and anorthite produces carbon that contributes to the DIC pool. Consumption of CO_2 by alteration of feldspars minerals such as albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$) can produce DIC. The alteration of feldspars minerals to kaolinite ($Al_2Si_2O_5(OH)_4$) can be represented by the following equation (Stumm and Morgan, 1996):

$$\underset{\text{Albite}}{NaAlSi_3O_{8(s)}} + CO_{2(aq)} + 11/2\ H_2O_{(l)} \rightarrow Na^{+}_{(aq)} + ½\ \underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_{4(s)}} + 2H_4SiO^{\circ}_{4(aq)} + HCO^{-}_{3\,(aq)} \tag{16}$$

$$\underset{\text{Anorthite}}{CaAl_2Si_2O_{8(s)}} + 2CO_{2(aq)} + 3H_2O_{(l)} \rightarrow Ca^{+2}_{(aq)} + \underset{\text{Kaolinite}}{Al_2Si_2O_5(OH)_{4(s)}} + 2HCO^{-}_{3\,(aq)} \tag{17}$$

In metamorphic and igneous rocks, the carbonate dissolution frequently takes place where calcite fills the fractures in these rocks (Clark and Fritz, 1997). In addition to the above pathways, DIC can be produced from gypsum dissolution and incongruent dissolution of dolomite as shown from the equations below:

$$\underset{\text{Gypsum}}{CaSO_4.2H_2O_{(s)}} + H_2O_{(l)} + CO_{2(g)} \rightarrow Ca^{+2}_{(aq)} + SO_4^{-2}{}_{(aq)} + H_2O_{(l)} + 2HCO^{-}_{3\,(aq)} \tag{18}$$

$$Ca^{+2}_{(aq)} + 2HCO^{-}_{3\,(aq)} + \underset{\text{Dolomite}}{CaMg(CO_3)_{2(s)}} + H_2O_{(l)} \rightarrow Ca^{+2}_{(aq)} + Mg^{+2}_{(aq)} + 2HCO^{-}_{3\,(aq)} + \underset{\text{Calcite}}{CaCO_{3(s)}} + OH^{-}_{(aq)} \tag{19}$$

The dissolution of dolomite is slow and takes place below the water table under closed system conditions. This process can lead to calcite precipitation as dolomite dissolves. Dissolution of dolomite has no effect on $\delta^{13}C_{DIC}$, whereas precipitating calcite has only a minor effect on $\delta^{13}C_{DIC}$ (Clark and Fritz, 1997).

The distribution of DIC species is based on pH of the system. H_2CO_3 is the dominant species at low pH, whereas HCO_3^- is between 6.4 and10.3. At high pH, CO_3^{-2} is the dominant DIC species. An enrichment factor (ε) arises between different aqueous species and soil gas and is defined as $\varepsilon = (\alpha-1)*1000$, where α is a fractionation factor. For example at 25°C, the enrichment factor (ε) between $CO_{2(g)}$

and $CO_{2(aq)}$ is 1.1‰, whereas between $CO_{2(aq)}$ and $HCO_3^-{}_{(aq)}$ it is 9‰. This factor between $HCO_3^-{}_{(aq)}$ and $CO_3^{-2}{}_{(aq)}$ and between $CO_3^{-2}{}_{(aq)}$ and calcite is quite small: -.04‰ and 0.9‰ respectively.

The carbon isotopic fractionations in nature follow two paths. The first path is the enrichment of ^{13}C in the carbonate reservoir through isotopic equilibrium exchange reactions such as calcite dissolution. In this type of reaction, the distribution of isotope varies between chemical substances, phases and molecules (Hoefs, 1997). The second path is non-equilibrium reactions such as the photosynthetic processes which concentrate the light isotope in organic material due to the kinetic isotope effects. The kinetic isotope effect is based on the rate of reaction of isotopic molecules (Hoefs, 1997).

The carbon cycle in groundwater systems starts with meteoric precipitation that infiltrates the aquifer. Infiltrated water along the way is equilibrated with soil CO_2 and gained DIC by root respiration and weathering of carbonate and silicate materials. The type of vegetation has a significant effect on the signature of $\delta^{13}C$ of soil CO_2. Three photosynthetic cycles can influence the value of $\delta^{13}C$ of soil CO_2. These cycles are: the Calvin or C_3, the Hatch-Slack or C_4 and the Crassulacean acid metabolism (CAM). C_3 plants are dominant in most terrestrial ecosystems. This type of plant can fix CO_2 with the Rubisco enzyme and is characterized by $\delta^{13}C$ values of –24 ‰to 30 ‰ with an average of -27 ‰ (Vogel, 1993). C_4 plants dominate in hot open ecosystem such as tropical and temperate grasslands (Ehleringer et al., 1991). C_4 plants have $\delta^{13}C$ of –10 ‰ to –16 ‰ with an average of –12.5 ‰ (Vogel, 1993). In addition, CAM plants can be found in desert environments; these plants can switch between photosynthesis by C_3 pathway during the day and use the C_4 pathway for fixation of CO_2 during the night.

Results and Discussion

All the isotopic data including oxygen, hydrogen and carbon for collected groundwater samples from eastern UAE (Figure 8) are presented in Appendix A.

Oxygen and Hydrogen Isotopes

Published groundwater $\delta^{18}O$ and δD based on about 20 groundwater samples for the entire study area range from –3 to +2 ‰ and –10 to +2 ‰ respectively (Kulaib, 1991; Wagner and Geyh, 1999; Alsharhan et al., 2001 and Machida et al., 2002). This study is based on 103 groundwater samples (see Appendix A). The observed ranges of $\delta^{18}O$ and δD for groundwater in samples from this study are –4.2 to –1.2 ‰ and –14.6 to +2.3 ‰ respectively. The ranges of isotopic compositions of oxygen for the Eastern Gravel Plain and Ophiolite aquifers are fairly small: -3.3 to –1.4 and –4.3 to –1 ‰ respectively. However, the ranges of hydrogen isotopes in Eastern Gravel Plain and Ophiolite aquifer are –10.8 to +2.3 and –14.5 to +2 ‰ respectively. The variations in $\delta^{18}O$ and δD values in groundwater samples strongly suggests that various processes such as evaporation of meteoric precipitation, and agriculture activity, particularly infiltration of irrigation water, may affect the composition of the groundwater samples. In addition to groundwater samples, water from the Gulf of Oman was collected for oxygen and hydrogen measurements. The averages of $\delta^{18}O$ and δD for the Gulf of Oman samples (5 samples) are 0.2 and 0.5 ‰

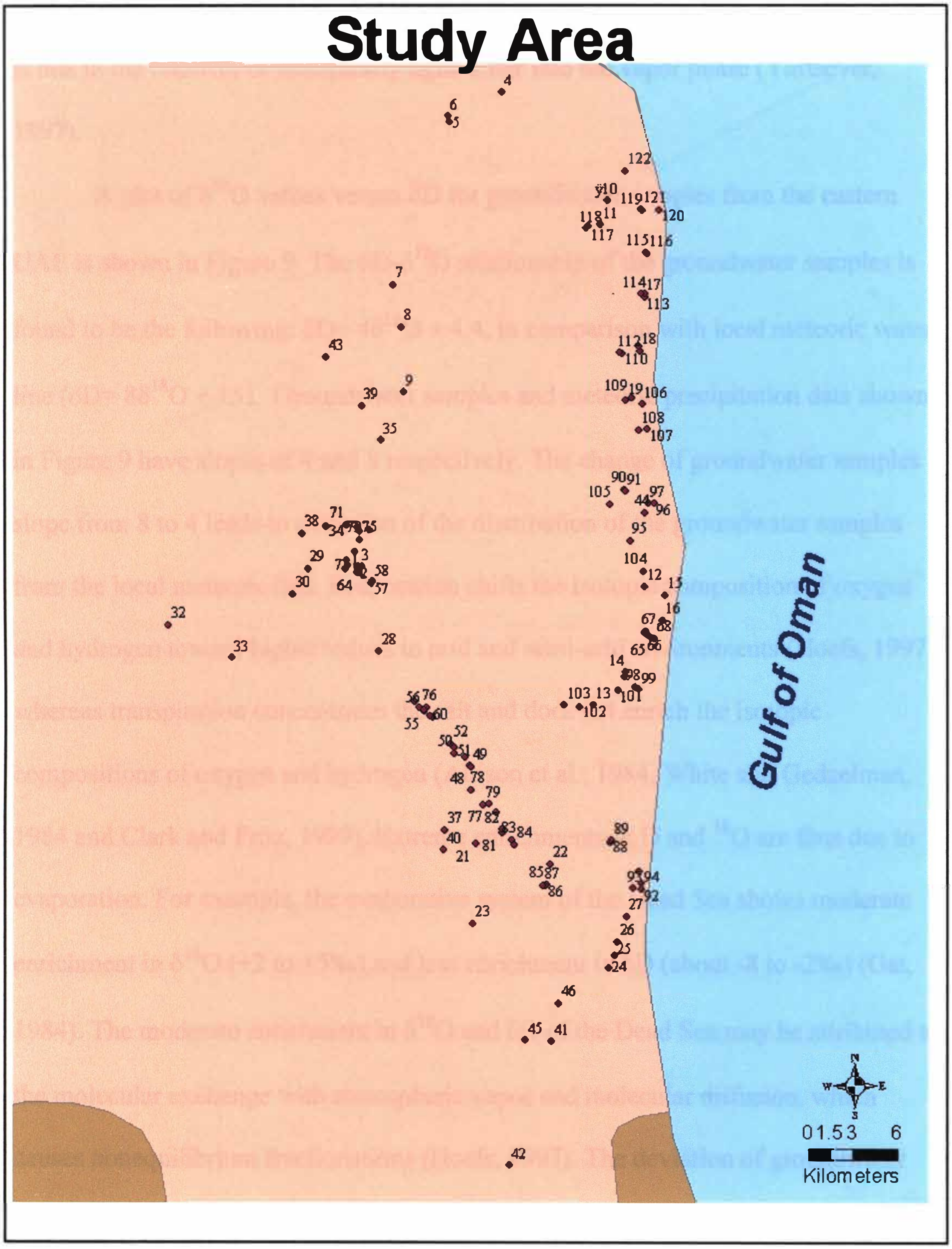

Figure 8. Map Showing the Eastern Part of the UAE and Sample Locations.

respectively. The enrichment of ^{18}O and D in seawater relative to atmospheric water is due to the removal of isotopically light water into the vapor phase (Yurtsever, 1997).

A plot of $\delta^{18}O$ values versus δD for groundwater samples from the eastern UAE is shown in Figure 9. The δD-$\delta^{18}O$ relationship of the groundwater samples is found to be the following: $\delta D = 4\delta^{18}O + 4.4$, in comparison with local meteoric water line ($\delta D = 8\delta^{18}O + 15$). Groundwater samples and meteoric precipitation data shown in Figure 9 have slopes of 4 and 8 respectively. The change of groundwater samples slope from 8 to 4 leads to deviation of the distribution of the groundwater samples from the local meteoric line. Evaporation shifts the isotopic composition of oxygen and hydrogen toward higher values in arid and semi-arid environments (Hoefs, 1997), whereas transpiration concentrates the salt and does not enrich the isotopic compositions of oxygen and hydrogen (Allison et al., 1984, White and Gedzelman, 1984 and Clark and Fritz, 1997). Extreme enrichments in D and ^{18}O are thus due to evaporation. For example, the evaporative system of the Dead Sea shows moderate enrichment in $\delta^{18}O$ (+2 to +5‰) and less enrichment in δD (about -8 to -2‰) (Gat, 1984). The moderate enrichment in $\delta^{18}O$ and δD of the Dead Sea may be attributed to the molecular exchange with atmospheric vapor and molecular diffusion, which causes nonequilibrium fractionations (Hoefs, 1997). The deviation of groundwater samples from the meteoric line and the lower slope of the groundwater distribution relative to the LMWL are due to the isotopic enrichments in both oxygen and hydrogen isotopes. These isotopic enrichments of oxygen and hydrogen isotopes are due to the evaporation of recharging water (meteoric precipitation and irrigation

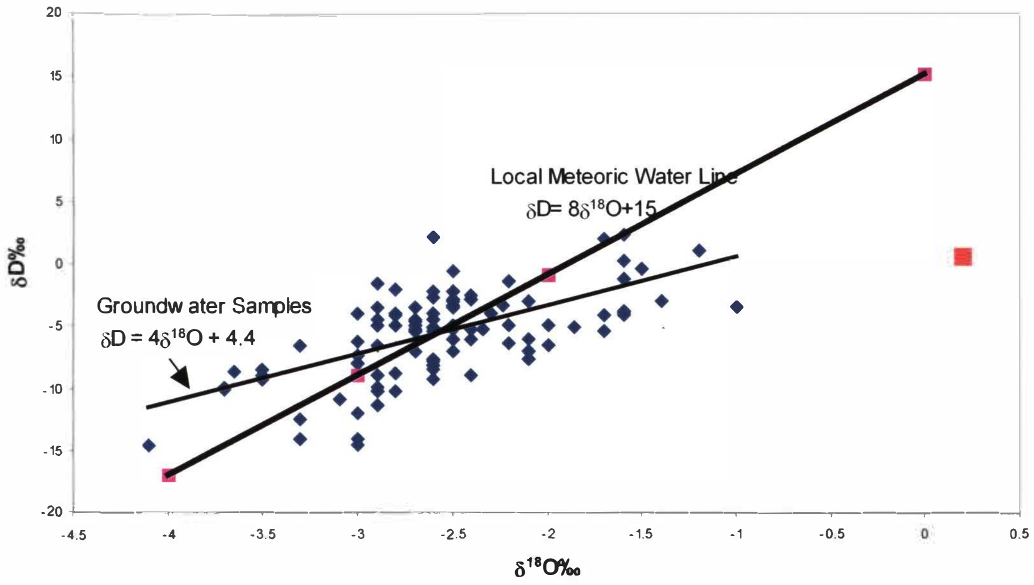

Figure 9. Oxygen-Hydrogen Plot for Groundwater Samples of Eastern UAE. Filled square shows average for Gulf of Oman seawater (LMEL is from IAEA data).

water) prior to infiltration. It has been found that the slope of δ^{18}O -δD for the return flow ranges from 2.5 to 5.5 (Clark and Fritz, 1997). A study conducted on Nile River water in Egypt, which is affected by agriculture drainage, follows a slope of 3.8 (Simpson et al., 1987). Rainfall is very rare, whereas irrigation is heavy in the investigated area. Also, about 90% of extracted groundwater in the study area is used for irrigation purposes. Therefore, the evaporation of irrigation water should be expected to influence the slope of the groundwater samples due to the evaporative enrichments.

The "y-intercept" value of groundwater samples is lower than that for precipitation ("d" = 15) most likely reflecting evaporation of runoff water, including both meteoric precipitation and irrigation water and also evapotranspiration in the unsaturated zone. This is consistent with a study of south Sinai, Egypt, which showed that y-intercept in groundwater is lower than that for precipitation and in some cases reaches 4.17 ‰ (Tantawi et al., 1998), and the study attributed the low y-intercept to evaporation of surface water prior to infiltration. In addition to the evaporation of surface water, evaporation in the vadose zone, could also cause variations in δD -$\delta^{18}O$ and decreasing y-intercept (Criss, 1999).

Groundwater samples have been grouped into samples above and below the local meteoric water line (LMWL) in order to understand the isotopic features of groundwater in eastern UAE. The distributions of collected groundwater samples relative to their location with respect to local meteoric water line are shown in Figure 10. It is clear from the map that most of the samples above the local meteoric water line are located in the north of the Eastern Gravel Plain and Ophiolite aquifers. The δD–$\delta^{18}O$ relationship for samples above the local meteoric water line is found to be: $\delta D = 6.1\ \delta^{18}O + 12.4$ ($r^2=0.8$) (Figure 11). This type of distribution indicates that the source of precipitation is the Mediterranean Sea ($\delta D = 8\ \delta^{18}O + 20$) with primary evaporation during precipitation. This finding is consistent with a previous study conducted by Gonfiantini and Akiti (1985). In addition to that, recharge takes place in the Northern Oman Mountains (Northern Ophiolite aquifer) and quick infiltration of the precipitation does not allow these samples to evaporate much prior to infiltration. Samples above the local meteoric water line from the Eastern Gravel Plain aquifer are irrigated with usage of modern irrigation system (dripping system) with a minimizing effect of evaporation during irrigation.

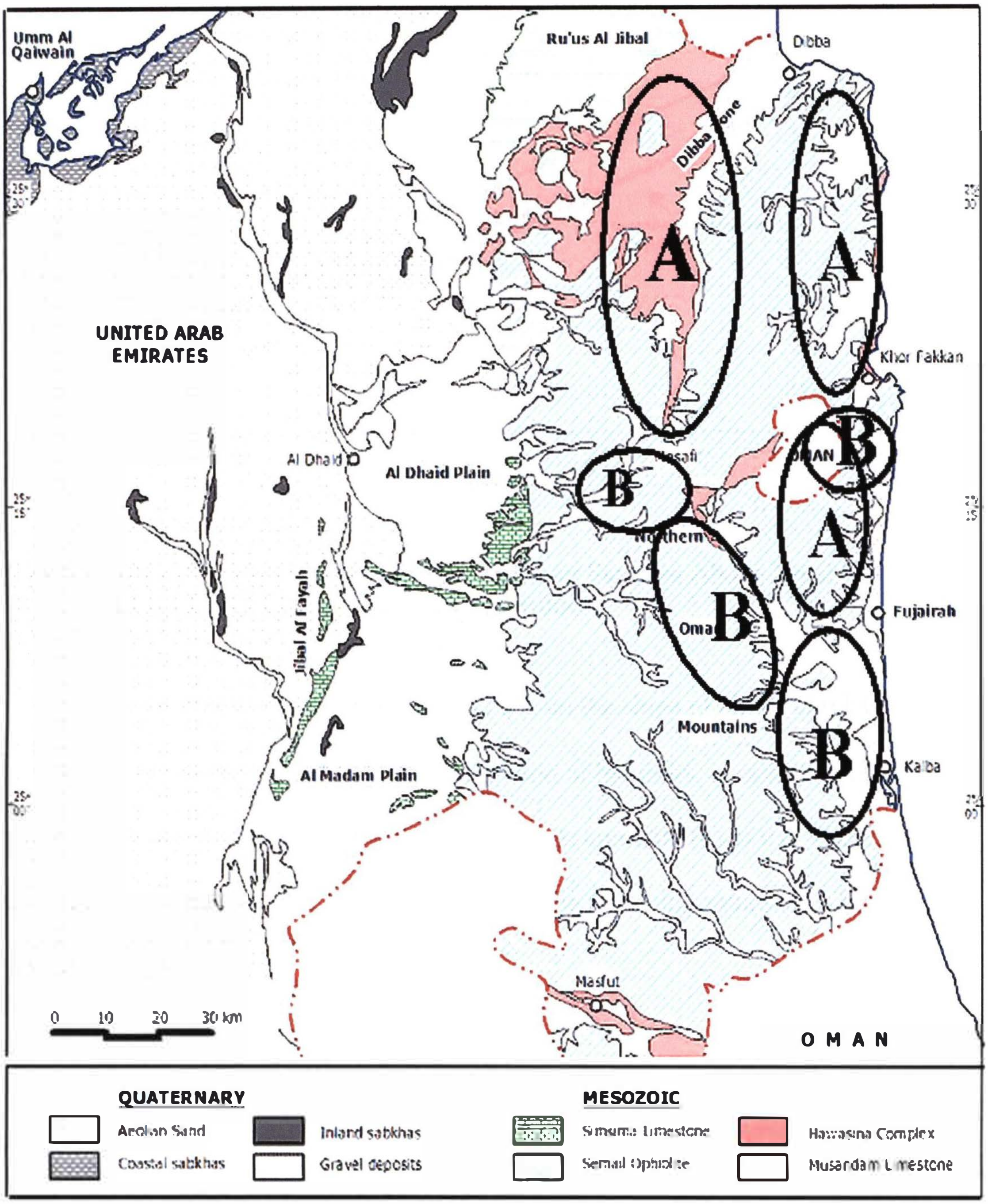

Figure 10. Distributions of Groundwater Samples with Respect to Local Meteoric Water Line. A refers to samples above the local meteoric water line and B refers to samples below the local meteoric water line.

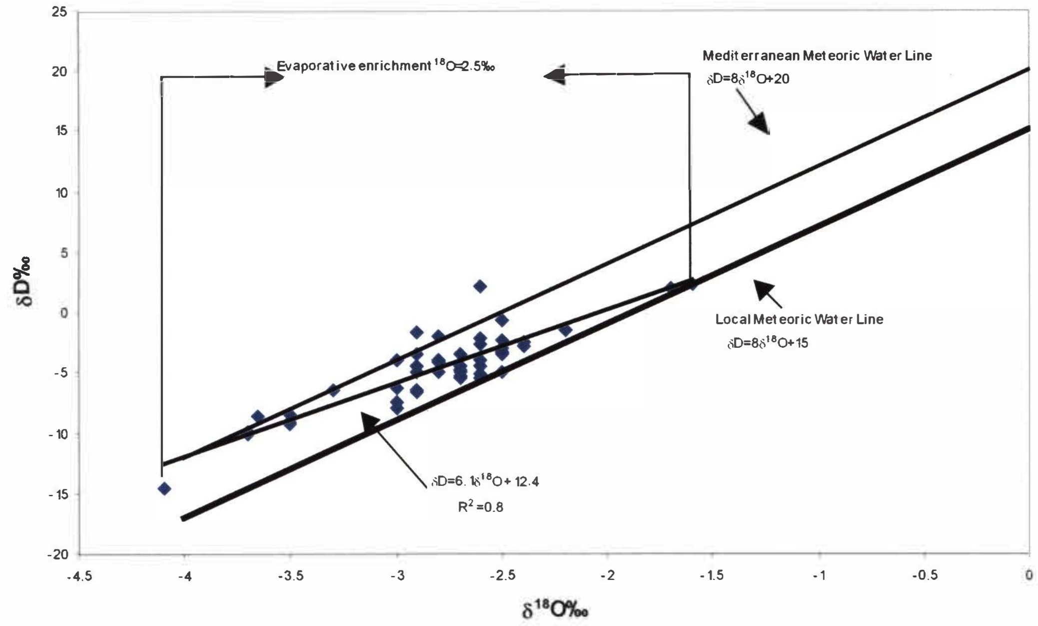

Figure 11. $\delta D - \delta^{18}O$ Relationship for Groundwater Samples Above Local Meteoric Water Line. Square shows seawater value.

Primary evaporation can be calculated from the slope of δD-$\delta^{18}O$ relationship for samples above the LMWL which is a function of humidity, temperature and wind speed (Clark and Fritz, 1997). A slope of 6.1 yields humidity (h) of 0.8. The kinetic fractionation factor can then be calculated using the following equations (Gonfiantini, 1986):

$$\Delta\varepsilon^{18}O_{bl\text{-}v} = 14.2\,(1-h)\ ‰ \qquad (20)$$

$$\Delta\varepsilon^{2}H_{bl\text{-}v} = 12.5\,(1-h)\ ‰ \qquad (21)$$

where $\Delta\varepsilon^{18}O_{bl-v}$ and $\Delta\varepsilon^{2}H_{bl-v}$ are kinetic fractionation factor from boundary layer, which is defined as thick micro atmosphere layer over water interface with 100% saturation, to vapor for $\delta^{18}O$ and δD respectively.

A humidity of 0.8 gives $\Delta\varepsilon^{18}O_{v-bl}$ of –2.84 ‰ and then the overall enrichment should be determined for evaporation under an annual mean temperature of 28℃ in the study area by using the following equation:

$$\varepsilon_{total} = \varepsilon_{v-l} + \Delta\varepsilon_{v-l} \qquad (22)$$

where $\varepsilon_{v-l} = (1-\alpha) * 1000$

$$(23)$$

and α can be calculated using the following equations for 28°C (Majoube, 1971):

$$10^3\ln\alpha^{18}O_{w-v} = 1.137\ (10^6/T^2)-0.4156(10^3/T)-2.0667 \qquad (24)$$

$$10^3\ln\alpha^{2}H_{w-v} = 24.844\ (10^6/T^2)-76.248(103/T)+52.612 \qquad (25)$$

where α = fractionation factor.

The calculated ε_{total} is found to be –11.94 ‰. The residual water fraction *f* can be determined using the Rayleigh distillation model (Clark and Fritz, 1997):

$$\delta^{18}O_{grw}-\delta^{18}O_{prec} = \varepsilon_{total} * \ln f = \Delta^{18}O \qquad (26)$$

whereas $\Delta^{18}O$ (the evaporative enrichment from the precipitation) can be obtained from the δD–$\delta^{18}O$ plot. In this case, $\Delta^{18}O$ is equal to 2.5‰. Thus *f* equals 0.81 which equates to an evaporative loss of about 19%.

The second group of samples is located below the local meteoric water line. These samples are found in the south of the Eastern Gravel Plain and Ophiolite aquifers.

The relationship between δD and $\delta^{18}O$ for the samples that lie below the LMWL is: $5.6\ \delta^{18}O + 6.7$ ($r^2=0.8$) (Figure 12). The slope of 5.6 indicates potential evapotranspiration of irrigation water. Also samples below the local meteoric water line from Eastern Gravel Plain aquifer are characterized by intense agriculture activities with usage of traditional irrigation system (flood system). Whereas evaporated samples from Ophiolite aquifer are concentrated along Wadi Ham where the surface water during the flood period recharges the groundwater. The agriculture activities are located along the Wadi Ham.

Slopes for both samples above and below local meteoric water line are similar and the major difference between two distributions is the y-intercept. The y-intercepts for samples above and below the local meteoric water line are 12.4 ‰ and 6.7 ‰ respectively. The low y-intercept for samples below LMWL may be attributed to the intense agriculture activities in these locations. As a result, evapotranspiration is more pronounced in these locations, which cause to lower y-intercept for these samples.

The evaporative loss for groundwater samples below the local meteoric water line can be calculated in a similar way that the evaporative loss for samples above the local meteoric water line was calculated. The slope of 5.6 would give a humidity of 0.7 and $\Delta\varepsilon^{18}O_{v\text{-}bl}$ equal to –4.26 ‰. The ε_{total} is found to be –13.36 ‰ and f equals 0.84. The evaporative loss for samples below the local meteoric water line is about 16%, which is less than that for sample above the line again suggesting that evapotranspiration is more pronounced in these irrigated areas and particularly due to the transpiration by plants.

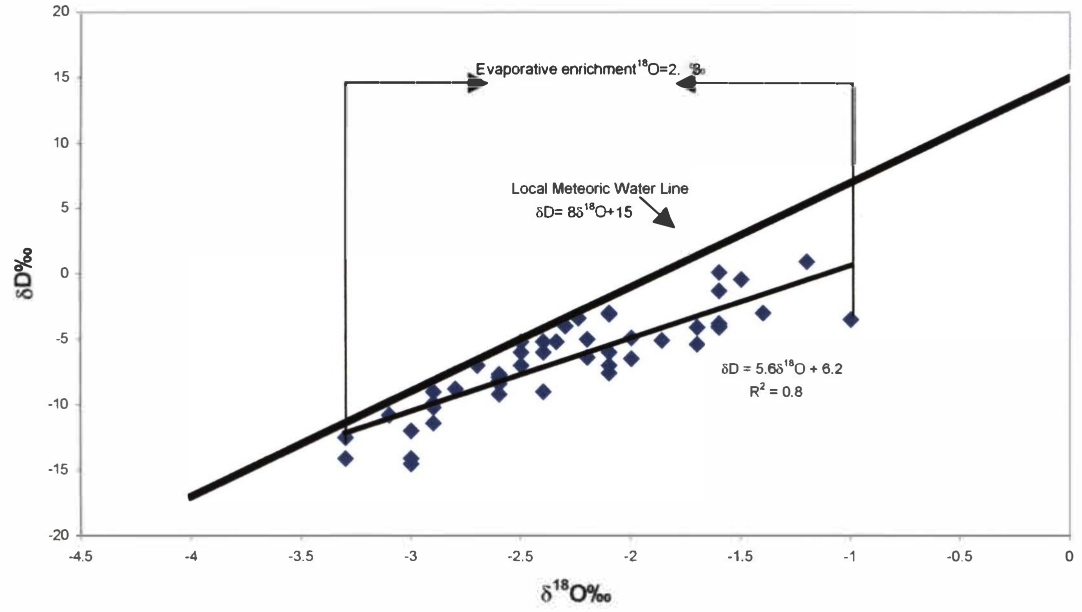

Figure 12. $\delta D - \delta^{18}O$ Relationship for Groundwater Samples Below Local Meteoric Water Line.

Using the isotopic compositions of either oxygen or hydrogen are useful tracers to understand the effect of irrigation water in groundwater quality. In order to quantify the effect of irrigation water, periodic sampling of both groundwater and irrigation water is required. The periodic sampling will help to identify the differences between oxygen or hydrogen isotopes in both groundwater and irrigation water. Most of the time, the differences are enrichments in both oxygen and hydrogen isotopes are due to the evaporation process. The enrichments of oxygen and hydrogen isotopes should be determined per 1% water loss (pan evaporation experiment). Then, the percentage of evaporation of irrigation water can be calculated using the following equation (Simpson et al., 1987):

$$\text{Evaporation \%} = (\delta D_{\text{irrigation water}} - \delta D_{\text{groundwater}}) / (\text{enrichment per 1\% water loss}) \qquad (27)$$

A similar equation can also be used to identify the percentage of evaporation using the isotopic composition of oxygen.

The isotopic tracers D and ^{18}O are often combined with chloride, to identify or eliminate possible sources of groundwater salinization. Figure 13 shows the relationship between chloride concentration (mg/l) and the hydrogen isotopes in groundwater samples from the entire study area. A simple seawater mixing line is drawn by using seawater (19500, 0.5) and freshwater (19.88, -14.6). The freshwater point is well # 39 which was selected because it has the lowest TDS (294 mg/l) compared to others. However a few samples are very close to the mixing line (wells #24, 35, 41 and 42). Nonetheless, the isotopic compositions of these groundwater samples are more depleted than the Gulf of Oman values indicating minimal mixing of seawater. The distribution of groundwater samples relative to the seawater mixing line shows that simple mixing via seawater intrusion is not the main source of groundwater salinization.

If evaporation alone is the cause of increasing groundwater salinity, a positive relationship between the isotopic composition of hydrogen and chloride concentrations should be observed. However, this relationship is absent, indicating that there are other sources of salinity in addition to evaporation of meteoric precipitation and surface water. These possible sources include application of chlorinated pesticides, fertilizers, and animal wastes as fertilizers in the intense by irrigated areas. These sources are explained in detail in the following section (see Impacts from Agricultural Activities).

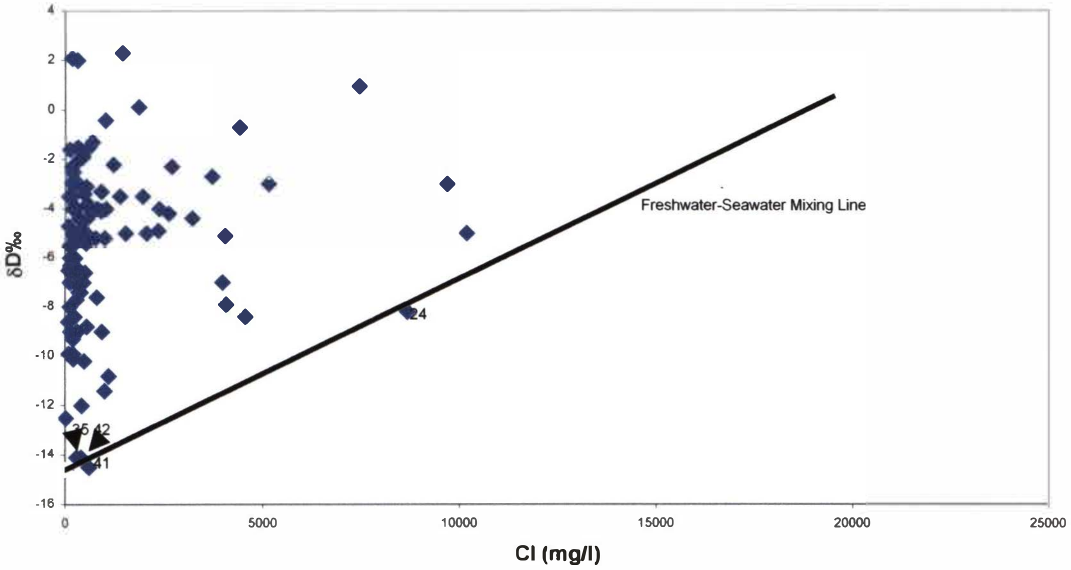

Figure 13. δD‰ Versus Cl (mg/l) Plot for Groundwater Samples from Eastern UAE.

Lack of a correlative relationship also is observed between $\delta^{18}O$‰ and Na^+ (mg/l) (Figure 14) suggesting that evaporation alone cannot account for the high concentration of sodium. One of the sources of high Na^+ is the heavy agricultural activity in the region which could concentrate sodium in the soil and leach to the groundwater. Other potential sources of sodium to the groundwater are seawater intrusion and cation-exchange processes. Seawater intrusion is likely minimal based on $R^{36}Cl$ and oxygen-hydrogen isotopes data (see Figures 9 and 19, and Table 5).

Cation-exchange process is another possible source for increasing sodium in this aquifer. Several factors affect the cation exchange process. These factors include

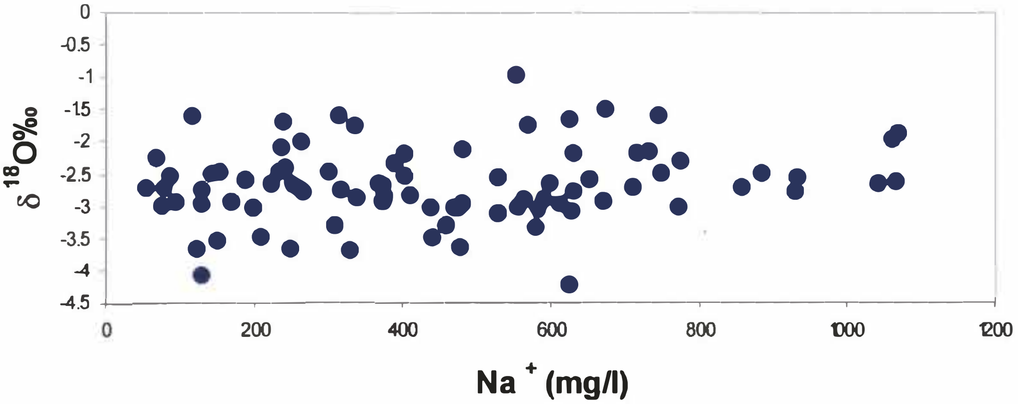

Figure 14. $\delta^{18}O$‰ vs. Na^+ (mg/l) for Groundwater Samples in Eastern UAE.

content of sufficient amount of colloidal-sized particles which have a large electrical charge compared to their surface area, availability of silica, pH of the solution, (with higher pH increasing cation exchange), nature of the ions occupying the exchange sites, presence of carbonate minerals, high partial pressure of carbon dioxide and also the presence of clay with abundant sodium (Freeze and Cherry, 1979; Stumm and Morgan, 1996; Drever, 1997 and Kehew, 2001). In addition, the geology and hydrology properties of the aquifer may have significant influence on the cation exchange process. For example, the mixing of freshwater and water which has a high sodium to calcium ratio leads exchange reversed with sodium in the solution exchanging for calcium from clay minerals. This has been observed, for example in the Black Creek aquifer (Kehew, 2001). In the cation exchange process, divalent cations such calcium (Ca^{+2}) and magnesium (Mg^{+2}) are extracted from the solution and monovalent cations such sodium (Na^+) are released to the solution according to the following equation:

$$NaX + Ca^{+2} \rightarrow Na^+ + CaX \tag{28}$$

Chlorine-36

Twelve groundwater samples were collected during January and February 2002, nine of which were from the Ophiolite aquifer (samples #1,8,12,13,20,32,56,57 and 72) (Figure 7) and three of which were from the Eastern Gravel Plain aquifer (sample nos. 18,25 and 68). Chlorine-36 measurements were made at the Purdue University Rare Isotope Measurement Laboratory (Elmore et al., 1979). ^{36}Cl is presented in both the R (^{36}Cl /Cl) and A (atoms/l) terminologies using conventional notations (Clark and Fritz, 1997). A ^{36}Cl can be calculated using the following equation (Clark and Fritz, 1997):

$$A^{36}Cl = R^{36}Cl * (Cl^- \text{ mg/l} * 10^{-3})/35.5 * 6.022 * 10^{23} \tag{29}$$

All the isotopic and chemical data from the study, as well as the available well-depth information, are listed in Table 4. $A^{36}Cl$ values of groundwater from the Eastern Gravel Plain aquifer (Cl> 1000 mg/l) range from $31x10^7$ to $251x10^7$ atoms/l while those for the Ophiolite aquifer (Cl<517 mg/l) are relatively low, with a maximum of $42.1x10^7$ atoms/l. Groundwater samples taken near each other show distinctively different $A^{36}Cl$ values. For example, sample #72 has an A ^{36}Cl value of $22x10^7$ atoms/l, whereas sample #57 has a value of $6.4x10^7$ atoms/l. The distance between these two wells is approximately 1 km. East of the study area, samples #68 and 12 have $A^{36}Cl$ values of 90.1×10^7 atoms/l, and 25.4×10^7 atoms/l, respectively. The distance between these two wells is approximately 3 km. This type of distribution may be attributed to either the absence of lateral flow or to the intermixing of groundwater at these locations. Mazor (1992) provides such an explanation for varying $A^{36}Cl$ values between closely placed samples in the Murray-Malle region, South Australia.

One of the primary uses of ^{36}Cl is its application in groundwater dating (Bentley et al., 1986a,b; Phillips et al., 1986; Andrews and Fontes, 1992). In determining the age of groundwater using ^{36}Cl, a local intake line is established for each study site. The local intake line, produced by plotting $A^{36}Cl$ vs. Cl, can trace the origin when data points are connected (Mazor, 1997). The slope of this line indicates the $^{36}Cl/Cl$ ratio in precipitation (Mazor, 1992). Samples representing local intake line should not be too old or contain bomb-produced nuclides. The representative samples should have >50 pmc (percent modern carbon) and contain <1 TU (Tritium Unit) (Mazor, 1997). In this study such a local intake line could not be constructed based on the above criteria. However, our ^{36}Cl data could still provide valuable information regarding groundwater hydrology in the area.

The $R^{36}Cl$ vs. Cl plot is shown in Figure 15. Most of the samples, particularly samples from the Ophiolite aquifer, are characterized by high $R^{36}Cl$ and relatively low Cl concentrations. As pointed out earlier, infiltration takes place in the Ophiolite aquifer region and, by analogy with previous studies, the trend observed in this study is a reflection of bomb- produced ^{36}Cl (Bentley et al., 1982; Mazor, 1992) and mostly

Table 4.Isotopic and Chemical Data of Groundwater Samples from Eastern United Arab Emirates. One sample of animal waste analyzed for chloride and bromide gave concentrations of 11200 mg/kg and 28.5 mg/kg respectively.

Sample No and aquifer type	Well Depth (m)	Depth to water table (m)	$R^{36}Cl$ (10E-15)	$A^{36}Cl$ (10E7)	$\delta^{18}O$ (‰)	δD (‰)	Cl (mg/l)	Br (mg/l)	Cl/Br	Na (mg/l)	Cl/Na	K (mg/l)	Ca (mg/l)	Mg (mg/l)	SiO_2 (mg/l)
Eastern Gravel Plain															
18	ND	4.9	17.4	31	-3	-4	1033.8	2.3	449.5	199.5	5.2	12.7	7.3	33.9	19.8
25	ND	ND	14.5	251	-2.7	-5	10188.5	18.2	559.8	858.1	11.9	93.3	557.1	ND	25.5
68	ND	7.6	13.3	90.1	-2.7	-7	3996	10	399.6	ND	ND	122.7	109.2	597.3	29.6
Ophiolite															
1	ND	ND	70	14.2	-3	-8	119.3	0.2	596.5	74.1	1.6	4.4	1.8	47.1	3.8
8	67	42	39	34.2	-2.5	-5	516.9	0.6	861.5	401.3	1.3	20.7	36.7	92.8	14.5
12	58	16.8	52	25.4	-2.9	-5	288.3	0.6	480.5	589.6	0.5	13.6	18	71.8	28
13	41.2	39.5	118	39.8	-2.8	-5	198.8	0.4	497	374.6	0.5	18.9	38.5	38	26.3
20	ND	17.9	68	38	-2.5	-3	328	0.4	820	86.5	3.8	6.2	7.9	32.3	17.2
32	ND	ND	78	42.1	-1.7	2	318.1	0.4	837.1	237.8	1.3	13.4	24.2	77	17.2
56	ND	21.6	86	26.1	-2.5	-3	178.9	0.3	596.3	234.1	0.8	13.6	20	59.1	13.3
57	ND	ND	20	6.4	-2.8	-4	188.9	0.3	629.7	264.7	0.7	13	22.2	18.5	2.3
72	ND	ND	37	22	-2.8	-2	347.9	0.6	579.8	512.8	0.7	8.2	7.6	0.03	71.7

ND = Data Not available.

modern (post -1950) recharge. This observation is consistent with published tritium data (Alsharhan et al., 2001).

Similarly, recently published ^{14}C data suggests that the groundwater age in the study area generally ranges from modern to 7000 years B.P. (Rizk and Alsharhan, 1999). The measured ^{14}C values for total dissolved inorganic carbon (TDIC) vary from 69.6 pmc in Fujairah to 91.3 pmc in Khalbah (Bakhit, 1998). Three samples, #18, 25 and 68 from the Eastern Gravel Plain aquifer, are characterized by low R^{36}Cl values compared to the samples from the Ophiolite aquifer. This can be attributed to lower precipitation there compared to the recharge region for the Ophiolite aquifer. Another likely explanation for lower R^{36}Cl values in the Eastern Gravel Plain aquifer is contribution from chloride- containing materials in the unsaturated zone or mixing with water of lower R^{36}Cl values (Calf et al., 1988). This possibility is discussed below.

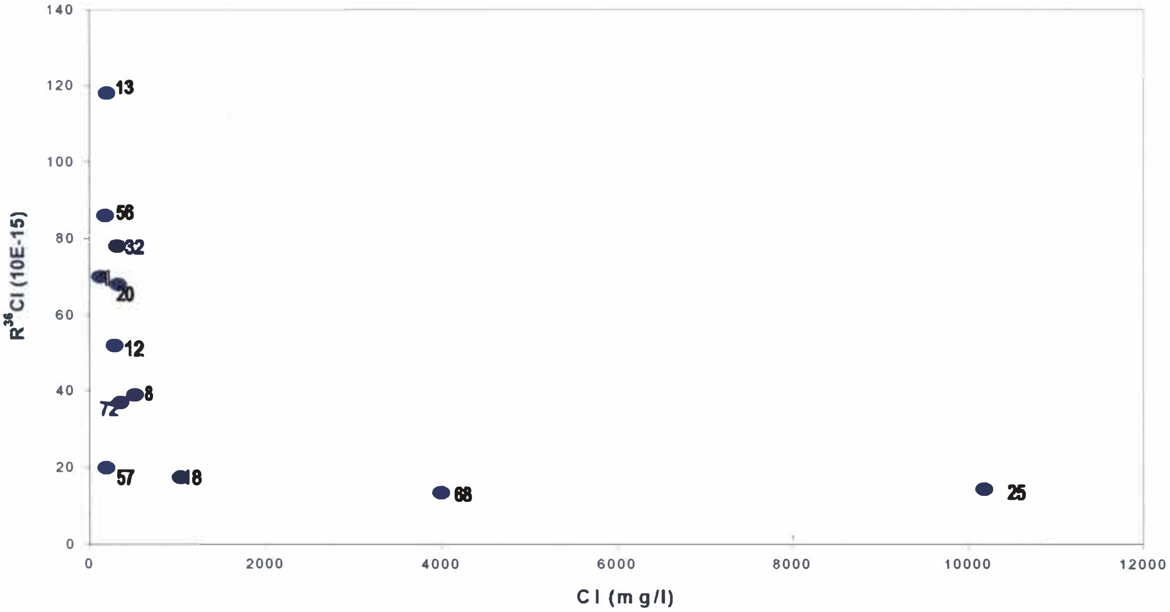

Figure 15. Plot Showing R^{36}Cl vs. Chloride Concentration in Groundwater Samples From Eastern UAE. Sample numbers are also indicated.

In order to further understand the factors that might influence groundwater quality, the δD-$\delta^{18}O$ values of the groundwater samples and Gulf of Oman samples are plotted in Figure 16. The δD- $\delta^{18}O$ relationship is found to be the following: $\delta D = 5.8\ \delta^{18}O + 11$ ($r^2 = 0.7$). When compared to the local meteoric water line ($\delta D = 8\ \delta^{18}O + 15$), the slope of 5.8 clearly suggests evaporation of precipitation prior to infiltration. Evaporation can also be seen in an $A^{36}Cl$-Cl plot (Figure 17) since, unlike $R^{36}Cl$, $A^{36}Cl$ should correlate with Cl enrichment by evaporation. However, this linear relationship is absent if the samples from the Eastern Gravel Plain aquifer (sample nos.18, 25, 68) are omitted. Moreover, when treating chloride as a proxy for salinity, no positive relationship exists between chloride and $\delta^{18}O$ (Figure 18) which

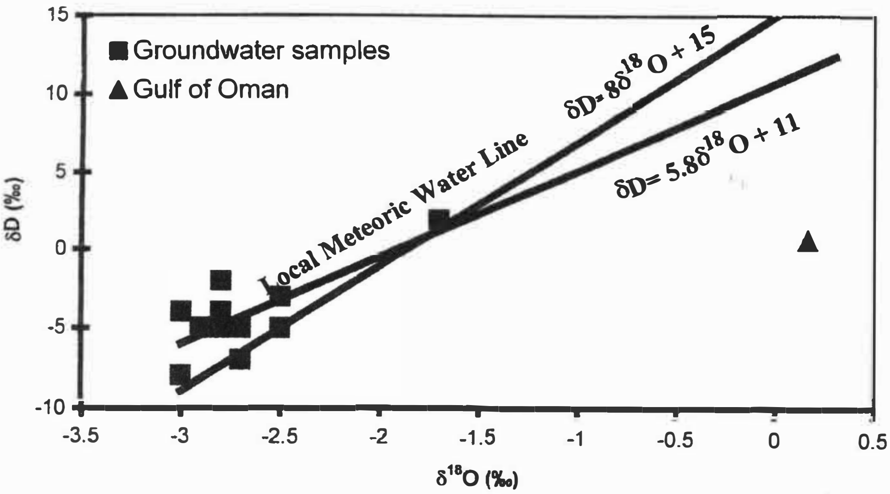

Figure 16. δD- $\delta^{18}O$ relationship from groundwater samples from eastern UAE ($\delta D = 5.8\delta^{18}O + 11$). The Local Meteoric Water Line is also shown for comparison ($\delta D = 8\delta^{18}O + 15$).

suggests that evaporation alone could not be the cause of higher $A^{36}Cl$ values in general and in samples 25 and 68 in particular. We propose additional input of chloride as the most likely process that causes higher $A^{36}Cl$ values. Chemical data, discussed below, are used to test this argument.

One of the sources that can contribute chloride and thus increase the $A^{36}Cl$ is the mixing of brine, seawater, or the addition of sea-spray. Based on the geology of the study area, there is no evidence for the presence of brines. The possibility of seawater as a source is considered by comparing the Cl/Br (Edmonds et al., 1985) and Cl/Na ratios of a water sample from the Gulf of Oman with those from the groundwater. The bromide concentrations were measured, while the Cl/Na ratio for the Gulf of Oman was taken as the average value for seawater (1.81). If seawater is the source of external chloride, the conservative nature of Cl/Br and Cl/Na ratios will

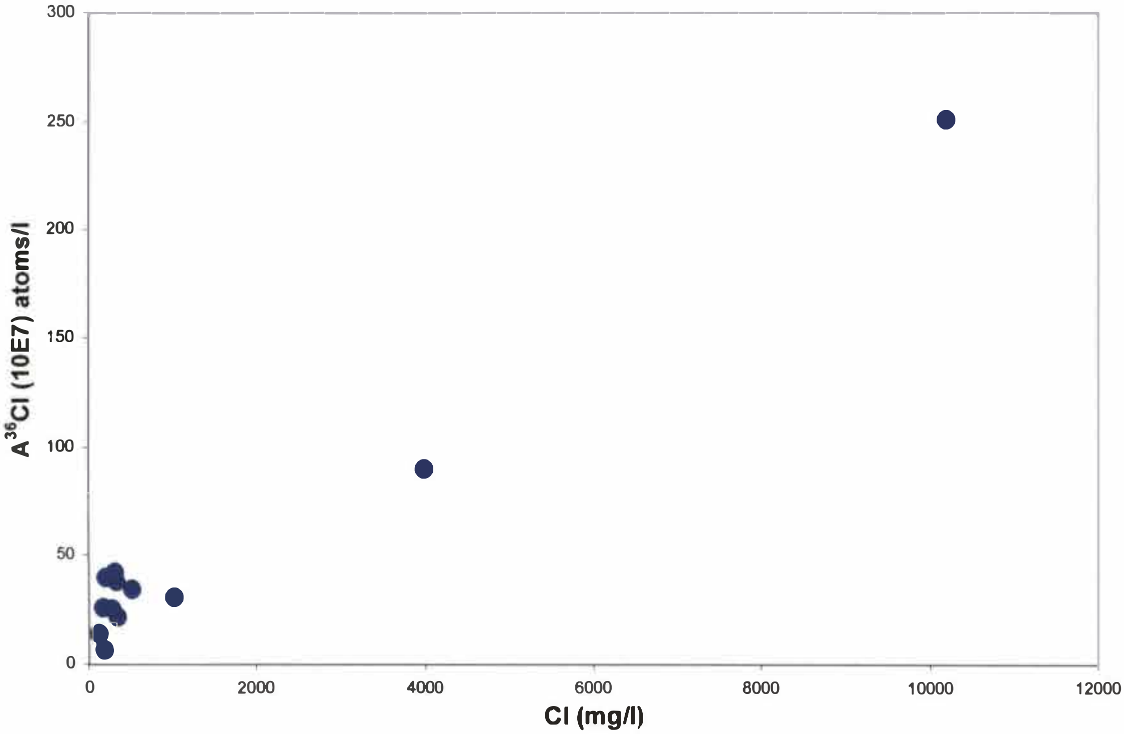

Figure 17. Plot Showing $A^{36}Cl$ vs. Chloride Concentration in Groundwater Samples from Eastern UAE.

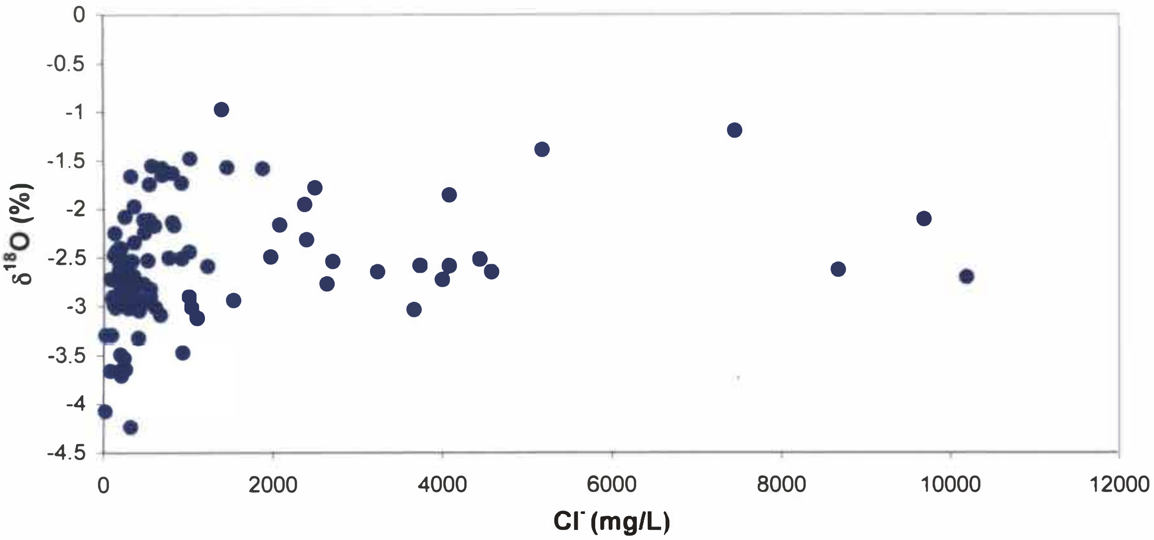

Figure 18. Plot of Cl (mg/l) vs. $\delta^{18}O$ (%).

be expected to be preserved through a simple mixing process. In addition to this, another piece of evidence against seawater being the source of chloride is observed in the distribution of $\delta^{18}O$ values. The $\delta^{18}O$ values define a rather narrow range despite the wide spatial distribution of sample locations and are also quite separated from the value for the Gulf of Oman.

Seawater mixing effects can be calculated by using an $A^{36}Cl$ vs. Cl plot. As seen in Figure17, the distribution of samples indicates that different portions of the study area are affected by different degrees of evaporation. An evaporation line can be drawn as shown in Figure 19. All samples below the line show the effect of mixing with seawater. To find the effect of seawater, lines from the evaporation line can be constructed through samples points to the seawater point ($A^{36}Cl$ = 0*10E7 atoms/l (Lyons et al., 1998), Cl = 19500 mg/l (Hitchon et al., 1999)). The results (Table 5) demonstrate that seawater mixing accounts for only between 0.8 to 4% of the chloride. Therefore, seawater as a primary source for high chloride is minimal. But, with time, this effect will increase and may become significant because of excessive pumping of groundwater. This conclusion is consistent with oxygen-hydrogen isotope ratios and Cl-36 data. The low ^{36}Cl/Cl in Eastern Gravel Plain aquifer is likely due to the presence of very small quantities of seawater (negligible amount as seen in Table 5) and agriculture chemicals as stated by Davis, Cecil, Zreda and Moysey (2001) (see also discussion below).

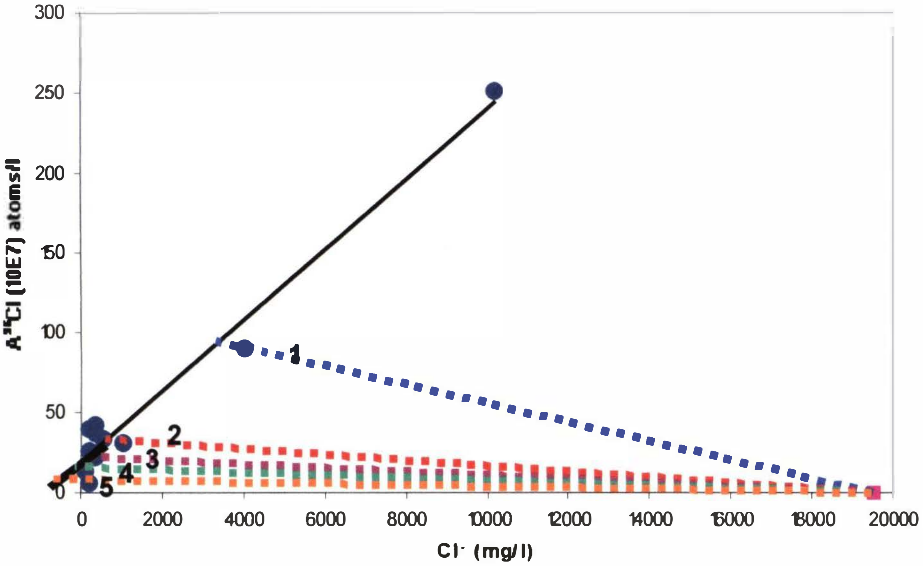

Figure 19. Plot Showing Evaporation Line (black bold) Constructed from A^{36}Cl (atoms/l) vs. Cl (mg/l). Lines 1,2,3,4 and 5 passing through samples #68,18, 72, 1 and 57, respectively, to seawater point.

Impacts from Agriculture Activities

Since seawater mixing as the primary cause for elevated chloride concentrations is ruled out, other likely sources are examined. Traditionally agriculture is one of the most important land uses in eastern UAE. Agriculture

Table 5. Seawater Contribution to Some Samples in the Study Area Based on Cl-36 Data

Sample No.	**Aquifer**	**Percentage of seawater**	**Cl (mg/l)**	**Excess of Cl (mg/l)**
1	Ophiolite	1.5	119.3	117.5
18	Eastern Gravel Plain	2.3	1033.8	1010.0
57	Ophiolite	2.9	188.9	183.4
68	Eastern Gravel Plain	4	3996	3836.2
72	Ophiolite	0.8	347.9	345.1

accounts for about 90% of groundwater use in the eastern region of the UAE and particularly in the Fujairah emirate. Therefore, agriculture practices are likely to be a primary reason for groundwater quality deterioration and are likely to contribute greater salinity to the groundwater and soil compared with other processes such as seawater mixing or intrusion.

The continuous cycling of irrigation is playing a vital role in increasing groundwater salinity. Extracted groundwater is typically placed in a pool and from that pool fed via artificial pathways (falaj) to the cultivated areas. The water in the pool and also the water in the falaj are subject to evaporation with time. Some farmers use the water in the pool to irrigate the area for two or three days (personal communications with 5 farmers). Also, note that the temperature in the area could exceed 35°C which will help to increase the evaporation rates. On the other hand, most farmers use the artificial pathways to irrigate the crops directly from the wells. Based on the length of the pathways, the evaporation rate varies. The density of agriculture varies from one area to another and also it varies from one farm to another. The number of farms has increased dramatically over the years due to encouragement from the government. For example, the cultivated area in Fujairah emirates is approximately 49 Km^2 with about 5300 holdings in 1990 (Bakhit, 1998). Generally, from 1990 to 2003, the cultivated area and number of holdings have increased. The effect of this growth will vary from one location to another. For example, it is observed that the land overlying the Eastern Gravel Plain aquifer is more irrigated than Ophiolite aquifer. Therefore, it should be expected that the Eastern Gravel Plain aquifer will deteriorate more rapidly than the Ophiolite aquifer.

Animal wastes (manure) used intensively in the region for the past 30 years or more, are also likely playing a role in groundwater salinization. Animal waste is a primary fertilizer throughout the whole country: visits to around 80 farms in the eastern region of the UAE revealed that animal waste is the predominant basic fertilizer used. The extracted water, which flows through the artificial falaj, washes the animal wastes into the underlying aquifer. This process could happen two times a day. An analysis of a sample of these animal wastes showed that the concentration of chloride is 11200 mg/kg. The irrigated areas are exposed daily to animal waste through flowing water. The distribution of animal wastes in each farm differs from one location to another depending on the density of agriculture. Typically animal waste stays in the same spot for about one month or more and with continuous irrigation within this period, generally with flushing two times a day, is likely to leach significant quantities of chloride into underlying groundwater. Furthermore, most farmers periodically replace the animal waste with artificial fertilizers to increase crop yields.

The system of agriculture activities is complicated in the region in part because the majority of the farmers are not educated. For example, since old groundwater pumps are considered to be problematic, farmers use diesel pumps to extract groundwater. Diesel fuel contains chloride compounds and other toxic elements. These diesel fuel machines are located close to the well typically, within a distance of 2-3 meters. Leaks of diesel fuel periodically spill into the wells, especially dug wells. Recently (about 10 years ago), the majority of farms changed this type of pump to the electrical pump. However the diesel machines had been used for a long time to extract groundwater. No environmental study has been conducted in the area to check for contamination of soil and groundwater due to use of diesel pumps. Thus, these diesel pumps may have been a significant source of chloride and other compounds to the aquifer. At this time, a few farmers are still using these diesel machines.

As mentioned above, the size of cultivated area and agricultural production in the Fujairah emirate has increased in recent years. For example the cultivated products increased from 1.9 tons/1000 m^3 in 1987 to about 2.4 tons/1000 m^3 in 1990 (Bakhit, 1998). To control an epidemic in unwanted plants, the farmers routinely use different types of pesticides (Table 6) such as, Tattoo-C (Propamocarb hydrochloride and Chlorothalonil) and PIRISP 48 EC (O,O-diethyl O- (3,5,6-trichloro-2-pyridil) phosphorothioat). Hence, another potential source of chloride in groundwater could be pesticides used in the extensive agricultural practices within the study area. Previous research indicates that this factor may be important in agricultural areas (Davis, et al., 2001). In order to evaluate this possibility, one animal waste sample was analyzed for chloride and bromide concentrations (Table 4). The data provide compelling evidence that chloride organically bound to animal waste can indeed be a major source of chloride to the groundwater, particularly for the Eastern Gravel Plain aquifer.

The effect of animal wastes and pesticides on chloride concentrations in the aquifer can not be exactly quantified, but can be estimated. Because of the lack of information regarding the existing amount of groundwater in the region, the reported annual recharge for the Fujirah emirate is used in this estimation. The annual recharge

Table 6. Pesticides, Which Contain Chloride Compounds, Banned in the UAE According to Ministry of Agriculture and Fisheries Since 1984

Common Name of Active Ingredient	**Use**
BHC, HCH (1,2,3,4,5,6-Hexachlorocyclohexane	Insecticide
Camphochlor	Insecticide
Chlordane	Termiticide
Chlordecane	Insecticide
DDT (dichloro-diphentrichloroethane)	Insecticide
Dichlorvos (DDVP)	Insecticide
Heptachlor	Termiticide
Methoxychlor	Insecticide
Chlordimeform	Acaricide
Chlorobenzilate	Acaricide
Chlorothanlonil	Fungicide
Hexachlorobenzene (HCB)	Fungicide (seed dressing)
2,4,5-T (2,4,5-trichlorophenoxy acetic acid)	Herbicide
Chloropicrin	Clean up the soil and place from insects and fungi.
Dibromochloropropane (DBCP)	Soil sterilant
Pentachlorophenol (PCP)	Protective from fungi and insects

in the Fujairah emirate is about 1×10^6 m^3 and the size of the agriculture area is about 50 Km^2. There are about 5300 farms in the emirates according to the statistics of the Ministry of Agriculture and Fisheries in 1990 (Bakhit, 1998). Some assumptions to be considered in these calculations include the number of irrigation years and the amount of animal wastes and pesticides used annually by each farm. Although irrigation has occurred for more than 30 years, a conservative estimate of 15 years is assumed here. The amount of animal wastes and pesticides used in each farm is estimated at 5-8 tons and 0.1 tons respectively. This suggests that about 42% of chloride in the aquifers comes from infiltration of animal wastes, whereas about 11.4% is from different types of pesticides (Table 6). The contribution from evapotranspiration is estimated to be about 46.6%. The exact percentage will vary from one well to another depending on the relative effect of seawater intrusion (estimated to be <4% of Chloride) and amount of infiltrating wastes.

In general, there is also an excess of sodium and calcium in sample #25. This can be attributed to the release of these cations through the weathering of silicate minerals such as plagioclase in the aquifer. In this region, plagioclase minerals represent a mixture of albite ($NaAlSi_3O_8$) and anorthite ($CaAlSi_2O_8$), which can release calcium and sodium through weathering (Hem, 1989, El Bayoumi et al., 1994-1995). Further support for the release of cations by weathering is seen from elevated levels of silica (Table 4).

Stable Isotope of Carbon

All dissolved inorganic carbon (DIC) and isotopic data from the study including carbon, oxygen and hydrogen are shown in Appendix A. Dissolved inorganic carbon (DIC) and $\delta^{13}C$ values of groundwater from the Eastern Gravel Plain aquifer range from 12 to 100 mg C/l and –9.8 to –17‰ respectively, while those for the Ophiolite aquifer range from 19.5 to 113.7 mg C/l and –11 to –16.4‰ respectively. DIC can also be calculated using pH and temperature for each well assuming equilibrium condition. A positive correlation between $DIC_{calculated}$ (mg C/l) and $DIC_{measured}$ (mg C/l) is shown in Figure 20. This suggests that the assumption of equilibrium and that bicarbonate (HCO_3^-) is the dominant species is valid.

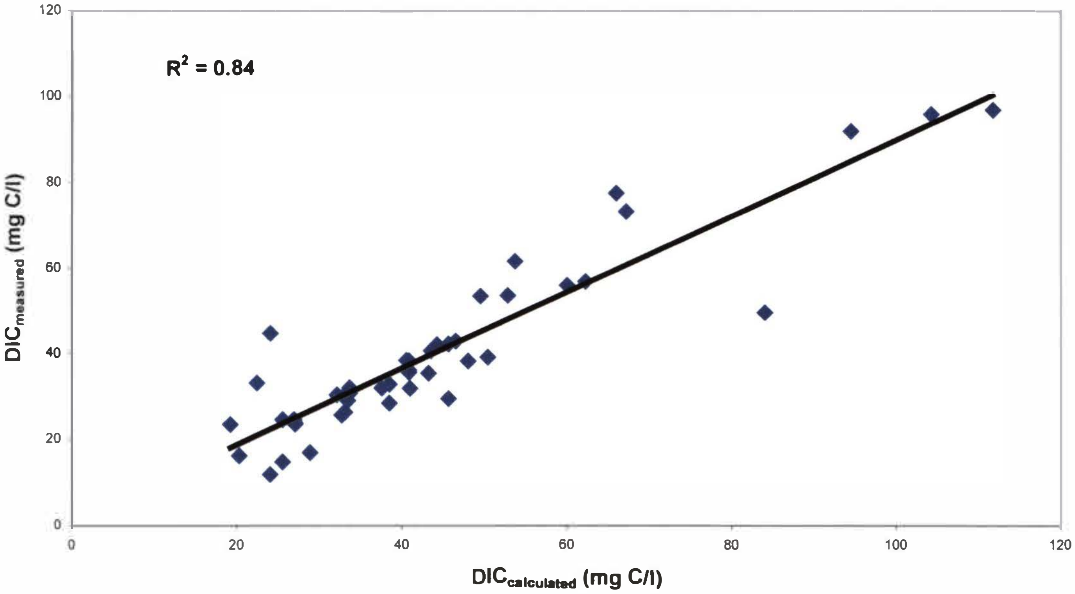

Figure 20. $DIC_{measured}$ (mg C/l) and $DIC_{calculated}$ (mg C/l) for CO_2 for Groundwater Samples in Eastern UAE.

The variation of $\delta^{13}C$ (‰) in the study area is –17 to –10 ‰, whereas DIC values have large variations (Figure 21), which are attributed to the openness or closeness of DIC evolution. Infiltrated water, either meteoric precipitation or irrigation water, gains DIC in the soil zone and then reaches the water table quickly in a closed system with little carbonate (calcite). The fractures and faults of Ophiolite aquifer and soil and gravel would help infiltrated water to reach the water table quickly and isolate produced DIC in the soil zone from the atmosphere. The residence time in the vadose zone is small.

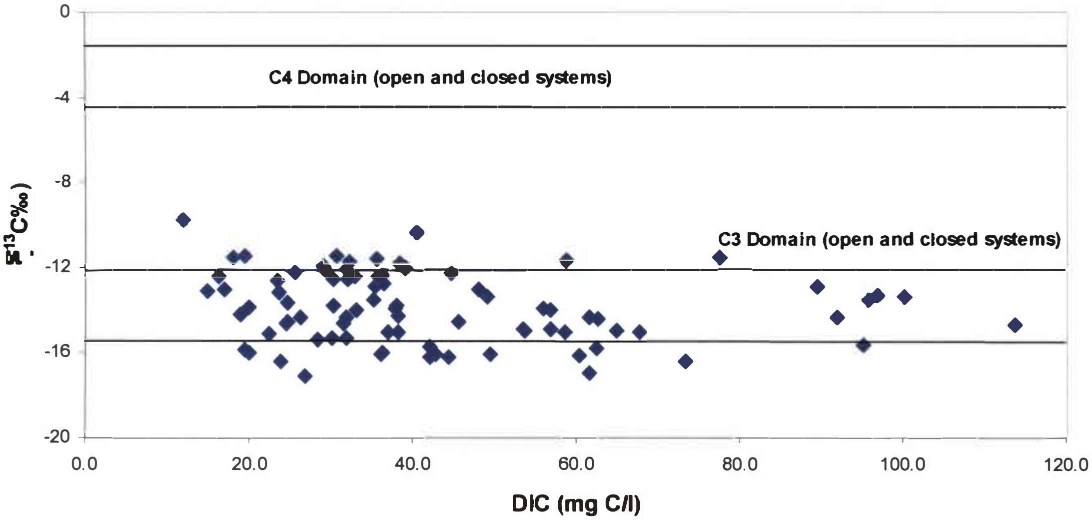

Figure 21. The Relationship Between DIC (mg C/l) and Measured $\delta^{13}C$‰ for Groundwater in Eastern UAE.

$\delta^{13}C$ of the original sources of CO_2 can be calculated using the isotopic mass balance given in equation 15. Assuming that the dominant carbonate species in the study area is bicarbonate (HCO_3^-), this will reduce equation no. 15 to the following simplified isotopic mass balance equation:

$$\delta^{13}C_{DIC} = x\,(\delta^{13}C_{co2(g)} + \varepsilon\ ^{13}C_{CO2(aq)\text{-}CO2(g)}) + (1\text{-}x)(\delta^{13}C_{co2(g)} + \varepsilon\ ^{13}C_{HCO3\text{-}\text{-}\ \text{-}CO2(g)}) \tag{30}$$

where x = mole fraction of $CO_{2(g)}$

and 1-x = mole fraction of HCO_3^- .

The calculated $\delta^{13}C$ of CO_2 source is found to range from –16.6 to –24.3‰ and –18.4 to –23.2‰, with an average of -20.5 and –20.8‰ for the Eastern Gravel Plain and Ophiolite aquifers, respectively. When plotting DIC (mg C/l) vs. calculated $\delta^{13}C$ for CO_2 source, the distribution of samples suggests a mixture between C-3 and C-4 plant species contributing to the DIC in the region under open and closed systems (Figure 22). In an open system, there is a continuous exchange between groundwater and soil CO_2, whereas in a closed system, the supply of soil CO_2 is limited.

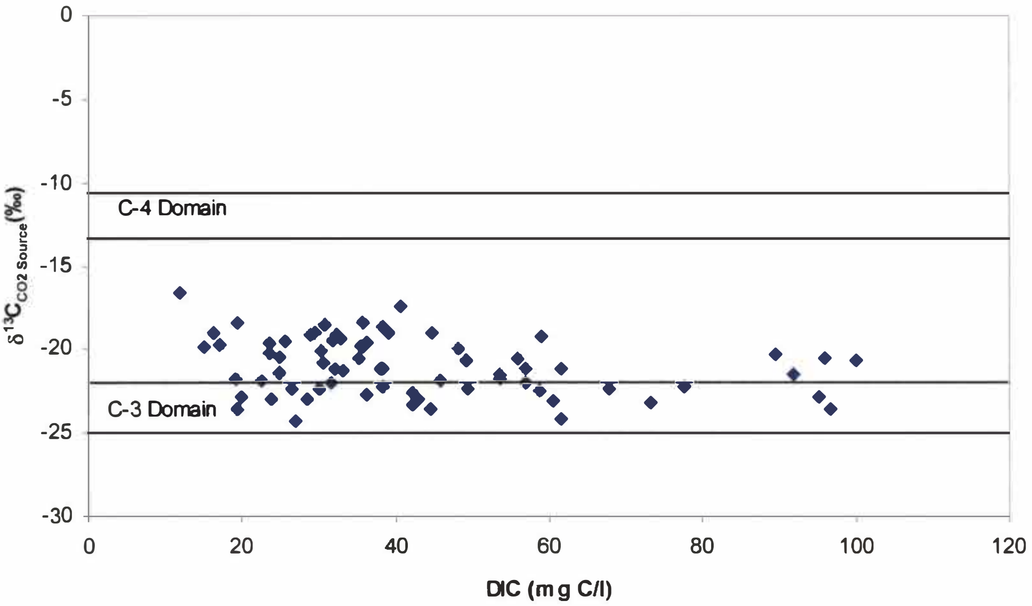

Figure 22. The Relationship Between DIC (mg C/l) and Calculated $\delta^{13}C$‰ for CO_2 Source for Groundwater in Eastern UAE.

Table 7 shows the different types of vegetation which dominate the eastern part of the UAE. This classification is based on the study of Smith (1982) on terrestrial plants (agronomic and forests). As seen from Table 7, the study area is composed of both C-3 and C-4 plant species. The study of Clark (1989) in the Oman area, which is south of the study area, showed that the isotopic composition of soil CO_2 reflects the flora types in the area and is preserved in the groundwater in the region. For example, groundwater samples in Sharqiyah district in Oman have a range of $\delta^{13}C$ from –14 to –10 ‰. In addition to that 40% of flora in Oman is C-4 plant species. Oman and UAE have a similar environment and vegetation types. The DIC of groundwater in eastern UAE is also controlled by the isotopic composition of soil CO_2 which is a reflection of vegetation type.

Table 7. Representative Agronomic Plants by Photosynthetic Type in Eastern UAE

C-3 plants:

- Grains
  - Sunflower
- Root Crops
  - Carrot
- Solanaccae
  - Potato
  - Tomato
  - Pepper
- Tree Fruits
  - Mango
- Forb Fruits
  - Watermelon
  - Cantelope
  - Strawberry (some areas in Ophiolite aquifer)

C-4 plants:

- Crops
  - Sugarcane

CAM plants:

  - Cactus (especially in the mountainous area near the coast).

Ten samples (Table 8) were sampled during the spring of 2002, and the analyses of DIC and $\delta^{13}C$ for collected groundwater samples repeated during the summer of 2002. The results (Figure 23) suggest that the seasonal variation is not significant in the study area. This is likely because of similarity of photosynthetic activity and agricultural activity during summer and spring in the study area. Temperature effect in DIC variations is absent here because the annual temperature variations are minimal.

Table 8. Results of DIC and $\delta^{13}C$‰ for Groundwater Samples in Eastern UAE for Summer and Spring of 2002

Sample ID	**DIC (Spring)**	**$\delta^{13}C$‰ (Spring)**	**DIC (Summer)**	**$\delta^{13}C$‰ (Summer)**
Safad-013	56	-13.9	66.1	-14.4
Murbeh-016	67.7	-15	74	-16.1
Bidyah-018	49.2	-13.4	63.6	-13
Fujairah-036	89.4	-12.9	85.3	-13.3
Khorfakkan-044	100.2	-13.4	106.4	-13.8
Fujairah-092	91.9	-14.4	89.3	-14.8
Khorfakkan-095	95.9	-13.5	96.6	-13.6
Khorfakkan-097	56.9	-14	61	-14.5
Aqah-116	62.7	-14.4	70	-15.1
Zikt-117	62.5	-15.8	55	-16.1

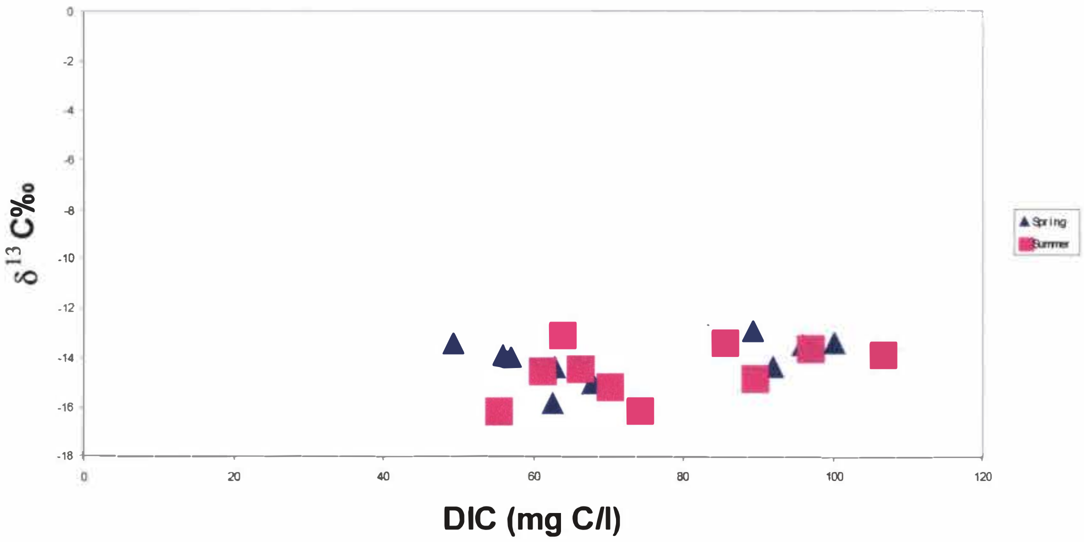

Figure 23. DIC vs. $\delta^{13}C$‰ for Groundwater Samples in Eastern UAE Collected During Spring and Summer of 2002.

CHAPTER V

HYDROGEOCHEMISTRY

Chemical analyses for groundwater samples were conducted at Central Laboratories Unit (CLU) at UAE University to supplement the isotope data and help to provide greater understanding of the groundwater system in the eastern part of the UAE. As discussed in previous chapters, a variety of different factors can affect groundwater quality. Geomorphology and geology both play a vital role in controlling the quality of groundwater. Anthropogenic sources of chemicals from agriculture activities are likely to be a main source of groundwater quality deterioration. The UAE's hot, dry climate also affects the groundwater quality by increasing the salinity possibly though evaporation. Intrusion of seawater appears to be minimal (see chapter IV).

Field Measurements

Temperature, pH and total dissolved solids (calculated from electrical conductivity) are measured in the field because these parameters change quickly after sample withdrawal. All chemical data are listed in Appendix B.

Temperature

The temperature of the groundwater samples from the Eastern Gravel Plain aquifer varied between 26°C and 35.8°C with an average of 30.9°C. The groundwater temperature in the Ophiolite aquifer varied from 25°C to 37°C with an average of

31°C. High groundwater temperature due to deep groundwater circulation indicates that the well depth in this aquifer is deeper than the coastal area.

pH

The pH of the groundwater in the study area varied between 7.6 and 8.5 in the Eastern Gravel Plain aquifer with an average of 8.1. Values are higher, ranging between 7.5 and 11.7 with an average of 9.6 in the Ophiolite aquifer. The groundwater samples are consistently alkaline. This alkalinity may be due to calcite and aragonite buffering, as carbonates are a main constituent in the matrix of the aquifer.

Total Dissolved Solids (TDS) and Electrical Conductivity (EC)

Total dissolved solid (TDS) can be estimated from measurements of electrical conductivity (EC). TDS is an important groundwater quality parameter (Langenegger, 1990). These two parameters affect the quality of groundwater for drinking purposes. The electrical conductivity of the groundwater samples from Ophiolite aquifer ranged from 0.488 to 7.95 mS/cm, whereas for Eastern Gravel Plain aquifer ranged from 0.457 to 24 mS/cm. This EC is equivalent to a total dissolved solids (TDS) in the groundwater of between 294 to 4750 mg/l for the Ophiolite aquifer, whereas the TDS contents in the Eastern Gravel Plain aquifer ranged from 275 to 14,330 mg/l.

TDS values are highest in samples from the Eastern Gravel Plain aquifer, which is adjacent to the Gulf of Oman. This is likely due to the heavy use of groundwater for irrigation purpose causing seawater intrusion. Evidence of heavy agriculture activities in this aquifer is also observed from nitrate (NO_3-) concentrations (see major anions section).

According to Todd (1980), groundwater can be classified as fresh, brackish or saline based on its TDS level. Fresh water ranges from 0 to 1000 mg/l, brackish water varies from 1000 to 10,000 mg/l and saline water ranges from 10,000 to 100,000 mg/l. In this study, 50% of the 122 wells are considered to be brackish, and the other 50% are considered to be fresh. Of the brackish wells, about 59% are from the Eastern Gravel Plain aquifer. As noted earlier (chapter IV), different sources could contribute to groundwater salinity. These factors include evaporation of meteoric precipitation, evaporation of return flow (especially irrigation water), use of animal wastes and pesticides, and excessive groundwater pumping for irrigation, leading to invasion of seawater into wells along the coast. Seawater intrusion is likely minimal based on Cl-36 evidence (wells # 1, 18, 57, 68 and 72), but it might be significant in other wells.

Anions and Cations

Groundwater samples collected from the field were analyzed in the lab for major cations, anions and trace elements to characterize the study area hydrogeochemically. The following is a brief discussion of these parameters.

Major Cations

Major cations (Na^+, K^+, Mg^{+2}, and Ca^{+2}) were analyzed in groundwater collected from the study area. The cation concentrations in the groundwater of the eastern UAE were observed to have the following order: $Na^+ > Mg^{+2} > Ca^{+2} > K^+$. The concentration of sodium in groundwater of the Eastern Gravel Plain aquifer ranges from 54 mg/l in the North to 1066 mg/l in the West. The sodium concentration in the Ophiolite aquifer typically varies less with concentrations ranging from 74 mg/l to the 804 mg/l, except well #61 which has a concentration of 1059 mg/l. The Eastern Gravel Plain aquifer has more sodium than the the Ophiolite aquifer. Multiple sources likely contribute sodium to both aquifers. Sodium sources include evaporation, agriculture activities (irrigation, application of fertilizers and pesticides), cation-exchange with calcium and magnesium and weathering of silicate minerals, particularly in the Ophiolite aquifer. In addition to that, some wells in Eastern Gravel Plain aquifer have very likely been affected by seawater intrusion, but $R^{36}Cl$ data suggests that the amount of mixing is minimal.

The Eastern Gravel Plain aquifer is characterized by higher concentrations of dissolved Mg^{+2} than the Opiolite aquifer. Dissolved Mg^{+2} concentrations range from 18 mg/l to 653 mg/l in the Eastern Gravel Plain aquifer, whereas the dissolved magnesium concentrations in the Ophiolite aquifer are from 0.015 to about 146 mg/l (except well #33, which has a concentration of 211 mg/l). Most wells in the Eastern Gravel Plain aquifer that have particularly high Mg^{+2} concentrations are located near Fujairah (wells # 36, 88, 89, 90, 91. 92 and 93), Khalbah (wells #24, 26 and 27) and near Khorfakkan (wells #15, 16, 96, 98, 99, 100, 107, 108, 111, 113, 115, 116 and 120) (Appendix B). The high concentrations of magnesium in the Eastern Gravel Plain aquifer may be partially attributed to the effects of seawater intrusion. However, other sources of Mg^{+2} are probably more significant. Another potential source of magnesium to this aquifer is agriculture activity in the study area. Fertilizers, which are common in both aquifers, could also account for increasing magnesium concentrations in the groundwater system (Kelly, 1997). In addition the study area is dominated by Mg-bearing olivine, pyroxene and serpentine in the underlying igneous and metamorphic rocks (Hem, 1989). The Ophiolite aquifer in particular and in the areas of Dibba, Khorfakkan and Fujairah beneath the Eastern Gravel Plain aquifer, these primary Mg-bearing minerals are abundant.

Dissolved calcium concentrations in the groundwater of the Ophiolite aquifer vary between 1.7 mg/l to 309 mg/l, whereas in the Eastern Gravel Plain aquifer, the calcium varies between 0.9 and 557 mg/l (except well #24, located in the coastal area, which has a concentration of 1003 mg/l). The most likely source of calcium in the Ophiolite aquifer is weathering of anorthite ($CaAl_2Si_2O_8$) as well as calcic pyroxene and amphibole, which are abundant in the area. In addition to that, fertilizer and irrigation water could introduce elevated concentrations of calcium in the aquifer because agriculture practices are so intense in this region. Wells #24 and 25 have Ca^{+2} concentrations greater than seawater, which also suggests additional inputs of calcium to this aquifer besides seawater intrusion.

The Ophiolite aquifer has potassium (K^+) concentrations between 4.4 and 69.3 mg/l, whereas the concentration of potassium in the Eastern Gravel Plain aquifer varies between 3.9 and 191 mg/l. The highest concentrations of potassium are found in wells from the Eastern Gravel Plain aquifer, which suggests more agriculture activity in this part of the study area. Potassium (K^+) has been used to trace salinity caused by return irrigation and agriculture practices (Edmonds and Droubi, 1998). As noted earlier, agriculture is intense in the study area; thus, elevated potassium is expected if agriculture is an important source of TDS to the aquifers. In addition, groundwater that has high concentrations of potassium in the Eastern Gravel Plain aquifer also have high concentrations of nitrate (NO_3^-), another expected result of agriculturally-induced groundwater salinization. The positive correlation (r^2=0.6) between K^+ and NO_3^- for Eastern Gravel Plain aquifer (Figure 24) strongly suggests that most of the salinity of this aquifer originates from irrigation water. However, a similar correlation is absent in Ophiolite aquifer. This likely reflects a reduction of nitrate to nitrogen (N_2) through denitrification process in Ophiolite aquifer. Additional sources of potassium, for example resulting from dissolution of K-feldspar minerals that are dominant in the Ophiolite rocks.

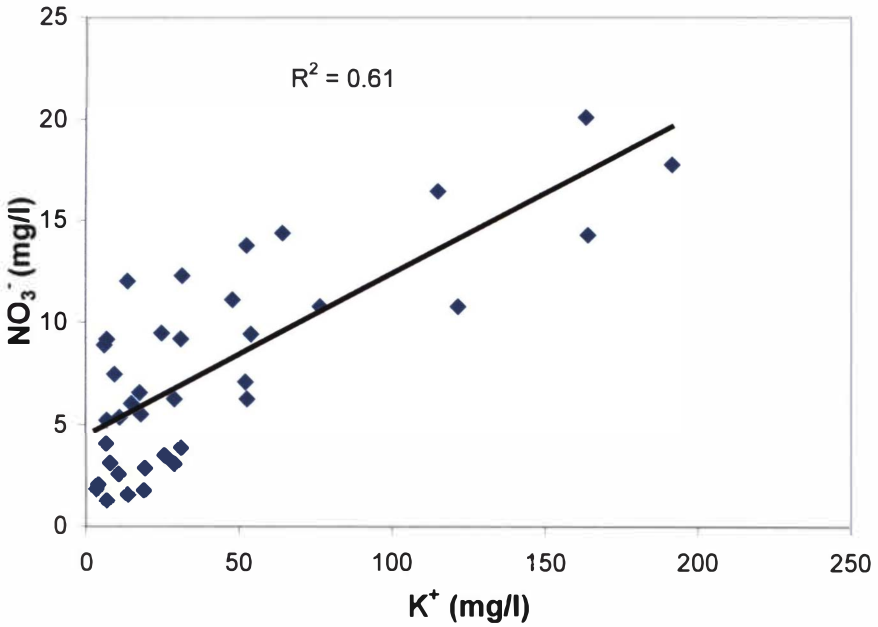

Figure 24. Plot Showing the Correlation Between K^+ (mg/l) and NO_3^- (mg/l) for Eastern Gravel Plain Aquifer.

Major Anions

The study area is characterized by the following order for major anions: $Cl^- > HCO_3^- > SO_4^{-2} > CO_3^{-2}$. However, this order changes to $HCO_3^- > Cl^- > SO_4^{-2} > CO_3^{-2}$ in the north of the Eastern Gravel Plain aquifer near Dibba and also near the Masafi area in the Ophiolite aquifer. Chloride is the dominant anion in the region and its concentration in the Eastern Gravel Plain aquifer ranges from 79.52 to 4622 mg/l, except wells # 24, 25, 36, 92 and 94 have concentrations of 8677.6, 10188.5, 5168.8, 7455 and 9691.5 mg/l respectively. In the Ophiolite aquifer, the chloride concentrations range from 19.9 to 2365.7 mg/l. The dominant anion in the majority of samples from both aquifers is chloride which is typical of groundwater with increasing salinity with time. The possible sources of chloride include evaporation, return flow evaporation, agriculture activity and small quantities of invading seawater (see chapter IV). That agriculture activity has a significant influence on groundwater in the study is also supported by plotting Cl/Br vs. Cl (mg/l) (Figure 25). The distribution of samples shows that the Cl/Br is high and about that expected from seawater mixing alone. A sample of the animal wastes, which are used extensively as fertilizer in the region, has a Cl/Br of 392. Agriculture practices can lead to increase Cl/Br ratio as shown by Davis, Whittemore, and Fabryka-Martin (1998). The irrigation cycle plays a vital role in increasing chloride concentrations in the groundwater. Increasing chloride accordingly increases the Cl/Br ratio in the region. The residual salts left from the previous irrigation period are leached into the groundwater reservoir in the following irrigation periods. This process is also

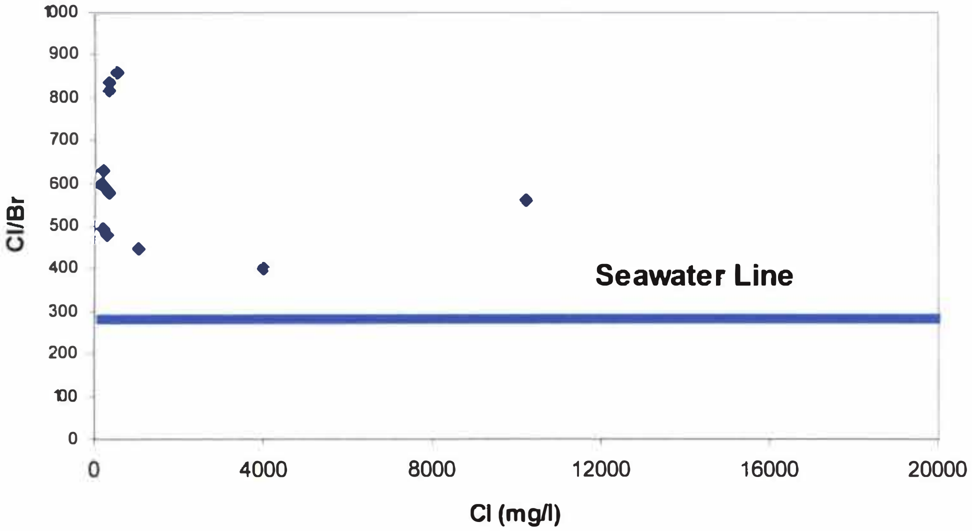

Figure 25. Plot Showing Cl/Br Ratio vs. Cl (mg/l) for Groundwater Samples from the Eastern UAE.

accompanied by evapotranspiration, which concentrates more salts in the vadose zone. The large amount of pumped groundwater circulates and creates a closed basin. The predicted result of this cycle is water too saline for irrigation use (Hem, 1989). In addition to that, as shown in chapter IV, using animal wastes intensively and verities of chlorinated pesticides and fertilizers increases the chloride concentration and Cl/Br ratio in the groundwater. Generally, the agriculture practices are able to increase the Cl/Br ratio in the study area and deteriorate groundwater quality.

The concentration of bicarbonate (HCO_3^-) in the Eastern Gravel Plain aquifer varies from 99 to 568 mg/l, whereas in the Ophiolite aquifer it ranges from 97 to 631 mg/l. Most of the high bicarbonate values are concentrated in the Eastern Gravel Plain aquifer, especially where the agriculture activity is heavy. The major source of bicarbonate in the whole region is soil and plant respiration and also weathering of albite particularly in the Ophiolite aquifer.

The range of sulfate concentration (SO_4^{-2}) in the Eastern Gravel Plain aquifer is from 33 to 289 mg/l except wells #36, 65, 68,98, 115 and 116 have concentrations of 476, 479, 476, 505, 498 and 424, respectively. The concentration of sulfate in the Ophiolite aquifer varies from 0.3 to 368 mg/l, except well #62 has a concentration of 537 mg/l. The major source of elevated sulfate in the region is again likely to be agriculture activity. Using fertilizer in irrigated fields has been shown to elevate the concentration of sulfate in the underlying groundwater (Kelly, 1997). A positive relationship (r^2=0.6) between nitrate (NO_3^-) and sulfate (SO_4^{-2}) is observed for groundwater from the Eastern Gravel Plain aquifer (Figure 26). However as for K^+ and NO_3^-, this relation is absent in the Ophiolite aquifer suggesting irrigation practices have more significant input on groundwater chemistry in the Eastern Gravel Plain aquifer than the Ophiolite aquifer.

The concentration of chloride and sulfate in irrigation water are higher than the recharge due to evapotranspiration. For example in a study conducted in Gila River at the Gillespie Dam, Arizona, irrigation water was shown be elevated the concentration of sulfate to 1000 mg/l (Hem, 1989). In addition to that wells, which have high concentration of sulfate from Eastern Gravel Plain aquifer, have been affected by small seawater intrusion.

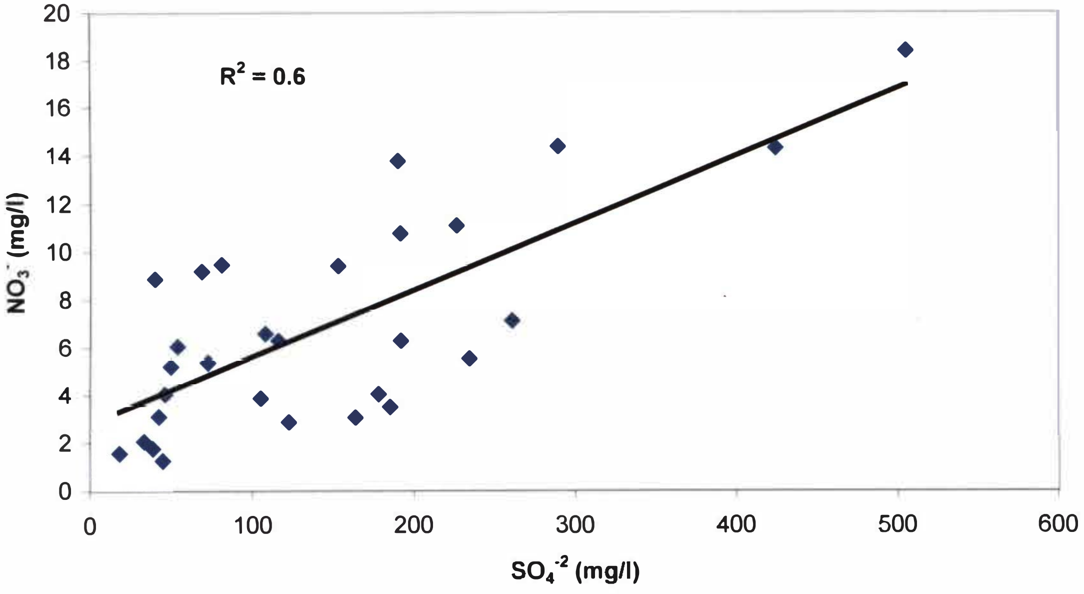

Figure 26. The Relationship Between Sulfate and Nitrate for Groundwater from Eastern Gravel Plain Aquifer.

The content of nitrate (NO_3^-) in the Eastern Gravel Plain varies from 1.1 to 22 mg/l, whereas it ranges from 0.7 to 14.3 mg/l in Ophiolite aquifer. The presence of nitrate in groundwater is certainly due to agriculture activity in region. The highest concentration of nitrate in groundwater found in Eastern Gravel Plain aquifer which suggests the Eastern Gravel Plain is more irrigated than Ophiolite areas.

Trace Elements

Trace elements are very important parameters for determination of groundwater quality and potential sources of contamination. A suite of trace elements (Al, B, Ba, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, P, Pb, Sr, Zn and Hg) were analyzed in collected groundwater samples. The trace elements Cd, Mn, Co, Cr, P, Cu, Pb, and

Hg were all below the detection limits. Strontium (Sr) is a common indicator of seawater invasion. As noted earlier, Cl-36 and oxygen-hydrogen isotopes data suggest that the effect of seawater mixing is minimal. Sr could come from other sources beside seawater such as agriculture activity and in particular using fertilizer in the study area. A positive correlation (r^2=0.64) between Sr and NO_3^- in the Eastern Gravel Plain aquifer exists (samples #105, 106, and 114 have high nitrate and low Sr concentrations are excluded) (Figure 27) which suggests that agriculture practices and use of different types of fertilizers and pesticides are a main source for Sr in this aquifer. Similar conclusions have been drawn from study of a sand aquifer beneath an irrigated field on the property of the Mason State Tree Nursery in Mason County, Illinois, USA (Kelly, 1997). However, this correlation is absent in the Ophiolite aquifer which again suggests that the Eastern Gravel Plain is more irrigated than Ophiolite areas. Sr in the Ophiolite aquifer predominantly comes from igneous rocks in this area. The analyses of different rocks from Ophiolite aquifer by El –Bayoumi, Dardir, and Abdel-Kader (1994-1995) showed that the concentration of Sr is high.

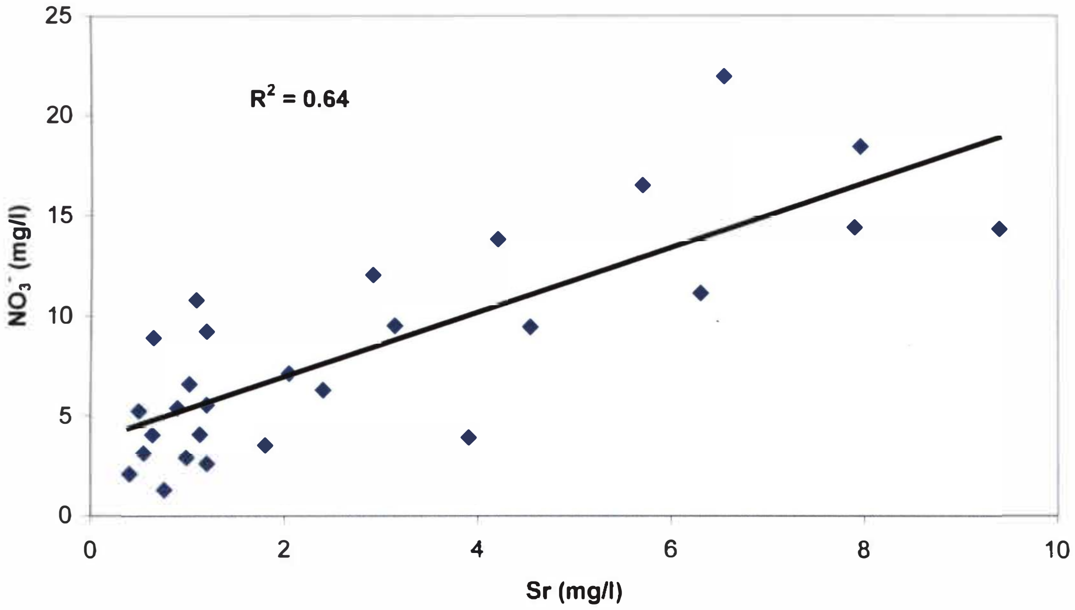

Figure 27. The Relationship Between Sr (mg/l) and NO_3^- (mg/l) for Groundwater Samples of Eastern Gravel Plain Aquifer.

CHAPTER VI

CONCLUSIONS

Two main aquifers occupy the eastern part of the UAE: the Eastern Gravel Plain aquifer in the east and the Ophiolite aquifer in the west. Rainfall, which is the main source of groundwater recharge, is very rare. Recently, the demand for groundwater in this region has led to depletion of the aquifers and reductions in the quality of groundwater. Increasing salinity and depletion of the aquifers are the most crucial problems facing groundwater resources in eastern UAE. Isotopes of oxygen, hydrogen, carbon and chlorine, and chemical analyses were used to investigate this problem in detail.

^{36}Cl data from groundwater in the eastern region of the UAE are consistent with previous studies indicating that the recharge to the aquifers is modern (post-1950). ^{36}Cl concentrations could be related to the amount of precipitation, which is higher in the recharge area and lower in the discharge area. The δD- δ^{18}O relationship points to potential primary and secondary evaporation of the recharging water (rainwater and irrigation water) prior to infiltration. Both Samples from the coastal Eastern Gravel Plain and Ophiolite aquifers have chloride concentrations in excess of what could be ascribed to evaporation or seawater mixing. Seawater intrusion appears to be absent or minimal based on oxygen-hydrogen isotope ratios and bromide concentrations. The high concentrations of chloride, therefore, are attributed to sources such as fertilizers and pesticides in this heavily agricultural area. As shown by Cl-Br data, animal waste appears to be one of the sources. The positive relationship between potassium (K^+) and nitrate (NO_3^-) observed in the Eastern Gravel Plain aquifer indicates that the contribution from irrigation to groundwater salinity is significant in the region. Also, similar relations are observed between nitrate and other ions such Sr and SO_4^{-2} suggesting release of these ions via agriculture activity especially using fertilizer and pesticides.

Samples of groundwater from the Eastern Gravel Plain aquifer have $\delta^{13}C$ and DIC values in the range of –10 to -17‰ and 12 to 100 mg C/l respectively. While samples from the Ophiolite aquifer have $\delta^{13}C$ and DIC values in the range of –11 to –16.4‰ and 16 to 114 mg C/l respectively. The calculated $\delta^{13}C$ of CO_2 source ranges from –16.6 to –24.3‰ and –18.4 to –23.2‰ with an average of -20.5 and –20.8‰ for the Eastern Gravel Plain and the Ophiolite aquifers respectively. This suggests that the control on DIC is via soil cover vegetated by C-3 and C-4 plants.

The complexity of irrigation systems in UAE generally and the eastern part of the country in particular causes several problems related to groundwater quality such as salinity. This problem will be increasing unless irrigation systems are improved. Most of the salinity arises from agriculture activity in the region because about 90% of extracted groundwater is used for irrigation. Possible recommended ways to improve the irrigation system and reduce the risk of salinity are: growing crops that require less usage of water and fertilizer, using modern irrigation system such as a dripping system and also growing crops that adapt to saline water. In addition to that, strict environmental regulations should be established to reduce the risk of agrochemicals and also to prevent loss of groundwater by extensive use. Periodic monitoring is necessary to check if farmers follow the environmental regulations.

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APPENDIX A

ISOTOPE ANALYSES

Appendix A: Isotopic Analyses of Groundwater Samples Collected from Eastern Part of the UAE.

Sample ID	**DIC (mg C/L)**	δ^{13}C(‰)$_{(meas.)}$	δ^{13}C(‰)$_{(calcu.)}$	**δ^{18}O (‰)**	**δD (‰)**
Masafi-001	NS	NS	NS	-3	-8
Masafi-002	33.2	-14	-21.3	-2.8	-8.8
Masafi-003	NS	NS	NS	-2.9	-1.9
Dibba Rafa-004	12	-9.8	-16.6	-3.5	-8.4
Al-Goab No.6-005	30.8	-11.5	-18.5	-3.7	-9.9
Al-Goab No.12-006	35.6	-11.6	-18.4	-3.7	-10.1
Al-Hala No.3-007	29.6	-12.1	-19.0	-3	-7.4
Wadi Al-Abadellah-008	35.4	-12.9	-19.8	-3	-5
Goanah-009	39.2	-12	-19	-3	-7.4
New Dadnah No.5-010	NS	NS	NS	-2.7	-4.7
Zikt No.1-011	42.2	-16.2	-23.3	-2.9	-9.9
Qidfa No.3-012	38.3	-14.3	-21.2	-2.9	-5
Safad No.1-013	56	-13.9	-20.5	-2.8	-5
Theyab No.1-14	36.1	-16	-22.7	-3.5	-9
Qidfa-015	19	-14	-21.8	-2.2	-5
Murbeh-016	67.7	-15	-22.4	-2.3	-4
Sharam-017	NS	NS	NS	-3	-6.3
Bidyah-018	49.2	-13.4	-20.7	-3	-4
Bidyah-019	19.5	-11.4	-18.4	-3.3	-6.5
Bithnah No.3-020	32.9	-12.4	-19.4	-2.5	-3
Kidnah No.3-021	32.1	-12.5	-19.4	-1.6	-1.3
Sarrah No.5-022	17.1	-13	-19.7	-2.9	-10.2
Al-Hayel-023	53.6	-14.9	-21.8	-2.5	-7
Kalbah-024	31.5	-14.6	-22.0	-2.6	-8.2
Kalbah-025	36.3	-16	ND	-2.7	-5
Kalbah-026	24.5	-14.6	ND	-2.6	-7.9
Kalbah-027	37	-15	ND	-2.6	-8.4
Wadi Ham-028	30.3	-12.6	-20.1	-2.1	-6
Murbad-029	35.8	-12.4	-19.9	-1.97	-6.5
Masafi-030	36.3	-12.4	-19.6	-1.7	-5.4
Blydah-031	44.4	-16.2	-23.6	-3.3	-12.5
Siji-032	32.3	-11.8	-19.1	-1.7	2
Wadi Siji-033	45.7	-14.5	-21.9	-0.97	-3.5
Wadi Falakh-034	19.9	-13.8	ND	-2.2	-6.4
Al-Klibyah-035	58.6	-15.003	-22.5	-3	-14.1
Fujairah-036	89.4	-12.9	-20.3	-1.4	-3
Ferfar-037	19.5	-15.8	-23.5	-2.9	-11.4
Maidaq-038	NS	NS	NS	-1.7	-4.1
Tayyibah-039	38	-14	-21	-4.1	-14.6
Wadi Sehem-040	58.9	-11.6	-19.3	-2.6	-5.5
Wadi Mai-041	19.9	-15.9	-22.8	-3	-14.5

Wadi Madiaq-042	60.4	-16.1	-23.1	-3.3	-14.1
Wadi Seider-043	95.1	-15.6	-22.8	-4.2	-1.5
Khorfakkan-044	100.2	-13.4	-20.7	-2.9	-9
Wadi Mai-045	73.3	-16.4	-23.2	NS	NS
Ahfrah No.1-046	49.5	-16	-22.3	-3	-12
Murbeh-047	28.5	-15.4	-22.9	-3	-10.8
Bithnah-048	NS	NS	NS	-2.4	-9
Bithnah-049	16.3	-12.4	-19.0	-2.4	-6
Bithnah-050	23.5	-12.6	-19.6	-2.6	-9.2
Bithnah-051	25.7	-12.3	-19.5	-2.4	-2.5
Bithnah-052	NS	NS	NS	-2.4	-2.5
Blydah-053	29.1	-11.9	-19.1	-2.6	-5.1
Blydah-054	NS	NS	NS	-2.5	-6
Blydah-055	NS	NS	NS	-2.5	-2.3
Blydah-056	31.9	-12.097	-19.5	-2.5	-3
Qamrah-057	NS	NS	NS	-2.8	-4
Qamrah-058	NS	NS	NS	-2.9	-4.4
Masafi-059	ND	NS	NS	-2.9	-6.6
Blydah-060	NS	NS	NS	-2.5	-2.9
Masafi-061	NS	NS	NS	-1.95	-4.9
Masafi-062	NS	NS	NS	-1.60	-4.1
Masafi-063	31.95	-15.3	ND	-2.6	-7.7
Masafi-064	NS	NS	NS	-2.3	-5.2
Qirat-066	38.2	-15	-22.2	-3.5	-9.3
Qirat-067	30.4	-13.8	-20.8	-3.7	-8.6
Murbeh-068	NS	NS	NS	-2.7	-7
Masafi-069	26.4	-14.4	-22.3	-2.9	-6.5
Masafi-070	NS	NS	NS	-2.7	-7
Masafi-071	113.7	-14.7	ND	-2.1	-7.6
Masafi-072	NS	NS	NS	-2.8	-2
Masafi-073	NS	NS	NS	-2.7	-4.4
Masafi-074	NS	NS	NS	-2.9	-1.6
Masafi-075	NS	NS	NS	-2.9	-6.6
Bithnah-077	NS	NS	NS	-1.5	-0.41
Bithnah-078	56.9	-14.9	-22.0	-2.2	-1.5
Bithanah-079	NS	NS	NS	-1.6	-3.8
Ferfar-080	NS	NS	NS	-1.6	-4
Ferfar-081	35.2	-13.5	-20.6	-2.1	-3.1
Ferfar-082	NS	NS	NS	-2.1	-7
Fujairah-084	NS	NS	NS	-2.2	-3.4
Al-Hayel-085	22.4	-15.1	-21.9	-2.5	-5.2
Al-Hayel-086	48	-13	-20	-2.8	-4.9
Al-Hayel-087	NS	NS	NS	-2.4	-5.2
Fujairah-088	26.8	-17	-24.3	-1.9	-5.1
Khorfakkan-090	61.7	-16.9	-24.2	-2.5	-2.3
Khorfakkan-091	NS	NS	NS	-2.5	-3.3
Fujairah-092	91.9	-14.4	-21.5	-1.2	0.95
Fujairah-093	38	-13.8	ND	-1.6	0.122

Fujairah-094	NS	NS	NS	-2.1	-3
Khorfakkan-095	95.9	-13.5	-20.5	-2.7	-5.2
Khorfakkan-096	NS	NS	NS	-2.6	-2.2
Khorfakkan-097	56.9	-14	-21.1	-2.6	2.1
Qurayah-098	53.5	-14.9	-21.5	-2.6	-4.4
Qurayah-099	NS	NS	NS	-2.6	-2.7
Theyab-100	44.7	-12.297	-19	-2.9	-5
Qurayah-101	61.7	-14.4	-21.2	-2.6	-4
Safad-102	77.6	-11.5	-22.2	NS	NS
Safad-103	64.9	-14.9	ND	NS	NS
Qidfa-104	42.8	-16	-23	-2.7	-5.5
Wadishi-105	38.4	-11.801	-18.7	-1.6	2.3
Zubarah-106	40.6	-10.4	-17.5	-2.7	-3.5
Lulayah-107	42	-15.7	-22.6	-2.8	-4.2
Lulayah-108	32	-14.3	-21.2	NS	NS
Zubarah-109	18	-11.6	ND	NS	NS
Bidyah-110	24.7	-14.5	-21.4	NS	NS
Bidyah-111	96.8	-13.3	-20.4	-2.5	-3.5
Bidyah-112	30.1	-15.3	-22.3	NS	NS
Sharam-113	23.9	-16.4	-23.0	NS	NS
Sharam-114	24.7	-13.6	-20.4	NS	NS
Aqah-115	36.5	-12.8	ND	-2.5	-0.7
Aqah-116	62.7	-14.4	ND	NS	NS
Zikt-117	62.5	-15.8	ND	-2.9	-3.5
Dadnah-119	23.6	-13.2	-20.2	-2.7	-3.5
Rual Dadnah-122	14.9	-13.1	-19.8	NS	NS

NS = No sample.
ND means either pH or Temperature is unknown.

APPENDIX B

CHEMICAL ANALYSES

Appendix (B): Chemical Analysis for Groundwater Samples Collected from Eastern Part of the United Arab Emiraes (Eastern Gravel Plain Aquifer and Ophiolite Aquifer).

Samples 1-45

Sample ID	Aquifer	UTM (E)	UTM (N)	pH	T °C
Masafi-001	Ophiolite	416021	2798760	8.6	31.6
Masafi-002	Ophiolite	415846	2799078	8.5	30.3
Masafi-003	Ophiolite	415933	2799130	8.5	31.2
Dibba Rafa-004	E. Gravel Plain	425520	2830746	7.95	34
Al-Goab No.6-005	Ophiolite	422027	2828734	8.05	33
Al-Goab No.12-006	Ophiolite	421901	2829119	8	34
Al-Hala No.3-007	Ophiolite	418277	2817880	8.1	34
Wadi Al-Abadellah-008	Ophiolite	418832	2815079	7.85	33
Goanah-009	E. Gravel Plain	418924	2810718	7.95	32
New Dadnah No.5-010	E. Gravel Plain	432608	2823491	8.25	33
Zikt No.1-011	E. Gravel Plain	432150	2821881	7.9	31.5
Qidfa No.3-012	Ophiolite	435126	2797808	7.85	33
Safad No.1-013	Ophiolite	431655	2789832	7.6	34.5
Theyab No.1-014	Ophiolite	433871	2792046	7.65	34
Qidfa-015	E. Gravel Plain	436527	2797228	8.1	28
Murbeh-016	E. Gravel Plain	436339	2795557	8	30
Sharam-017	E. Gravel Plain	435086	2817082	8	33
Bidyah-018	E. Gravel Plain	434773	2813487	8.2	31
Bidyah-019	E. Gravel Plain	433843	2810152	8	34
Bithnah No.3-020	Ophiolite	423068	2786366	7.95	32
Qidnah NO.3-021	Ophiolite	423777	2780648	7.95	33
Shaarah NO.5-022	Ophiolite	428792	2779299	7.75	34
Al-Hayel-023	Ophiolite	423544	2775293	7.85	33
Kalbah-024	E. Gravel Plain	432702	2772359	8.1	30.4
Kalbah-025	E. Gravel Plain	433082	2773169	N	31.7
Kalbah-026	E. Gravel Plain	433295	2774053	N	26
Kalbah-027	E. Gravel Plain	433897	2775750	N	31.4
Wadi Ham-028	Ophiolite	417263	2793347	8	29
Murbad-029	Ophiolite	412496	2799026	8.1	29
Masafi-030	Ophiolite	411484	2797312	8.35	32
Blydah-031	Ophiolite	419658	2790099	8.3	30
Siji-032	Ophiolite	403140	2795218	8.14	31.6
Wadi Siji-033	Ophiolite	407346	2793025	8.2	30
Wadi Falakh-034	Ophiolite	413726	2801769	N	26.2
Al-Klibyah-035	Ophiolite	417396	2807480	8.26	29.7
Fujairah-036	E. Gravel Plain	434716	2778807	7.85	30.15
Ferfar-037	Ophiolite	421714	2781560	8.15	27
Maidaq-038	Ophiolite	412146	2801318	N	23.3
Tayyibah-039	Ophiolite	416125	2809775	8	33.6
Wadi Sehem-040	Ophiolite	421649	2780231	8.25	27.6
Wadi Mai-041	Ophiolite	428877	2767445	7.9	34.8
Wadi Madiaq-042	Ophiolite	426012	2759158	8.21	34.6

Wadi Seider-043	Ophiolite	413732	2813092	8.15	32
Khorfakkan-044	E. Gravel Plain	435100	2802711	7.8	31
Wadi Mai-045	ophiolite	427073	2767526	7.8	34.5

Sample ID	**Conductivity (mS)**	**TDS (mg/l)**	**Na^+ (mg/l)**	**K^+ (mg/l)**	**Mg^{+2} (mg/l)**	**Ca^{+2} (mg/l)**
Masafi-001	0.5	308	74	4.4	47.1	1.8
Masafi-002	1.8	1065	410.4	16.6	106.2	14.3
Masafi-003	1.6	967	371.7	19.3	37.6	38.8
Dibba Rafa-004	0.8	464	149.9	9.6	48.2	27.7
Al-Goab No.6-005	0.7	441	250.2	11.7	29.5	14.5
Al-Goab No.12-006	0.7	449	328.9	15.5	32.6	19.9
Al-Hala No.3-007	1.2	723	468.1	30.5	8.3	10.8
Wadi Al-Abadellah-008	1.7	1043	401.3	20.7	92.8	36.7
Goanah-009	1.5	911	435.9	19.1	57.8	27.8
New Dadnah No.5-010	0.5	317	54.4	3.9	33	3.5
Zikt No.1-011	0.7	442	94.9	6.7	72.2	11.4
Qidfa No.3-012	1.1	692	589.6	13.6	71.8	18
Safad No.1-013	1.2	703	374.6	18.9	38.0	38.5
Theyab No.1-014	2.5	1504	438.0	28.8	91.4	164.1
Qidfa-015	5	3010	715.1	42.2	324	64.9
Murbeh-016	6	3580	773.8	108.7	393.7	63.1
Sharam-017	0.7	401	771.9	108.8	279.1	63.3
Bidyah-018	2.9	1719	199.5	12.7	33.9	7.3
Bidyah-019	0.5	273	457.4	29	221.8	31.3
Bithnah No.3-020	1.3	764	86.5	6.2	32.3	7.9
Qidnah NO.3-021	2.3	1392	313.7	21.1	68	30.2
Shaarah NO.5-022	2	1202	611.7	4.5	10.7	97.8
Al-Hayel-023	0.8	476	142.8	6	59.5	36.9
Kalbah-024	17	10220	1066.3	66.5	421.9	1003.8
Kalbah-025	18.9	11290	858.1	93.3	N	557.1
Kalbah-026	9.5	5690	651.4	48.6	602.8	300.8
Kalbah-027	9.3	5560	598	63.6	653.6	223.6
Wadi Ham-028	1.1	657	235.5	18.2	68.6	13.5
Murbad-029	1.4	816	263.1	12	86.9	28
Masafi-030	1.7	1032	335.4	21.2	107.8	34.5
Blydah-031	1.1	641	309	15.3	24.6	59.4
Siji-032	1.2	692	237.8	13.4	76.9	24.2
Wadi Siji-033	3.6	2160	552.7	39.2	211.1	82.9
Wadi Falakh-034	0.6	356	65.8	3.7	41.1	15.2
Al-Klibyah-035	1.7	1028	475.4	44.3	25.8	86.7
Fujairah-036	11.0	6580	N	129.9	563.5	111.6
Ferfar-037	2.6	1542	561.5	20.2	31.1	158.9
Maidaq-038	2	1188	568	42	0.1	29.9
Tayyibah-039	0.5	294	128.3	11.7	13.8	33.2
Wadi Sehem-040	1.1	669	187.6	9.8	71.2	61.4

Wadi Mai-041	2.0	1220	554.1	3.4	11.3	55.8
Wadi Madiaq-042	1.9	1139	577.7	11	18.8	51.2
Wadi Seider-043	1.9	1140	625.2	21.2	6.8	34.7
Khorfakkan-044	2.3	1338	670.1	21.8	31.3	18.8
Wadi Mai-045	1.4	866	475.7	6.7	10	53.7

Sample ID	SO_4^{-2} (mg/l)	CO_3^{-2} (mg/l))	HCO_3^- (mg/l)	Cl^- (mg/l)	NO_3^- (mg/l)	Al (mg/l)
Masafi-001	39.2	N	N	119.3	N	<0.001
Masafi-002	91.5	N	N	546.7	N	<0.001
Masafi-003	2.3	N	N	447.3	N	0.002
Dibba Rafa-004	32.4	N	122	238.6	1.1	0.002
Al-Goab No.6-005	59.2	N	170.8	198.8	N	0.001
Al-Goab No.12-006	78.7	N	207.4	208.7	N	<0.001
Al-Hala No.3-007	63.4	N	231.8	347.9	0.7	0.0005
Wadi Al-Abadellah-008	93.6	N	219.6	516.9	4.5	0.002
Goanah-009	122.7	N	256.2	397.6	2.9	0.002
New Dadnah No.5-010	33.2	N	109.8	79.5	2.1	<0.001
Zikt No.1-011	44.6	N	231.8	99.4	1.3	<0.001
Qidfa No.3-012	60.2	N	207.4	288.3	1.6	<0.001
Safad No.1-013	88.3	N	305	198.8	1.8	0.004
Theyab No.1-014	70.2	N	207.4	934.4	3.1	0.004
Qidfa-015	216.4	N	N	2067.5	N	0.005
Murbeh-016	245.9	N	N	2385.6	N	0.008
Sharam-017	44.2	N	N	139.2	N	0.005
Bidyah-018	93.4	N	N	1033.8	N	0.002
Bidyah-019	38.5	N	N	89.5	N	0.004
Bithnah No.3-020	117.3	N	195.2	328	4.1	<0.001
Qidnah NO.3-021	254.7	N	170.8	685.9	5	0.002
Shaarah NO.5-022	144.9	N	146.4	487.1	1.1	0.008
Al-Hayel-023	48.5	N	268.4	119.3	1.7	0.003
Kalbah-024	72	N	N	8677.6	N	0.01
Kalbah-025	60.3	N	N	10188.5	N	0.03
Kalbah-026	226.3	N	N	4075.4	N	0.01
Kalbah-027	255.4	N	N	4572.4	N	0.01
Wadi Ham-028	70.3	N	N	248.5	N	<0.001
Murbad-029	85.2	N	N	357.8	N	<0.001
Masafi-030	104.6	N	N	536.8	N	0.003
Blydah-031	82.3	N	N	19.9	N	0.004
Siji-032	106.9	N	N	318.1	N	0.002
Wadi Siji-033	210.9	N	N	1391.6	N	0.005
Wadi Falakh-034	39.6	N	N	129.2	N	0.003
Al-Klibyah-035	300.3	N	N	288.3	N	0.004
Fujairah-036	476.9	N	N	5168.8	N	0.01
Ferfar-037	197.1	N	N	1003.9	N	0.009
Maidaq-038	34.9	N	N	914.5	N	0.03

Tayyibah-039	13.4	N	N	19.9	N	0.003
Wadi Sehem-040	87.2	N	N	188.9	N	<0.001
Wadi Mai-041	326.9	N	N	606.3	N	0.009
Wadi Madiaq-042	301.8	N	N	407.5	N	0.04
Wadi Seider-043	151.9	N	N	318.1	N	0.004
Khorfakkan-044	213.3	N	N	318.1	N	0.002
Wadi Mai-045	148.4	N	341.6	258.4	4	0.003

Samples 1-45

Sample ID	**B (mg/l)**	**Ba (mg/l)**	**Cd (mg/l)**	**Co (mg/l)**	**Cr (mg/l)**	**Cu (mg/l)**	**Fe (mg/l)**
Masafi-001	0.1	0.007	<0.001	<0.001	0.01	0.003	0.001
Masafi-002	0.1	0.03	<0.001	<0.001	0.01	0.004	0.0004
Masafi-003	0.4	0.02	<0.001	<0.001	0.003	0.007	0.0008
Dibba Rafa-004	0.2	0.06	<0.001	<0.001	0.01	0.004	0.0003
Al-Goab No.6-005	0.2	0.03	<0.001	<0.001	0.008	0.004	0.0007
Al-Goab No.12-006	0.3	0.04	<0.001	<0.001	0.01	0.005	0.0001
Al-Hala No.3-007	0.5	0.09	<0.001	<0.001	0.0004	0.003	0.0007
Wadi Al-Abadellah-008	0.2	0.1	<0.001	<0.001	0.004	0.004	0.001
Goanah-009	0.3	0.04	<0.001	<0.001	0.003	0.004	0.0008
New Dadnah No.5-010	0.1	0.01	<0.001	<0.001	0.003	0.005	0.0006
Zikt No.1-011	0.2	0.02	<0.001	<0.001	0.004	0.006	0.0004
Qidfa No.3-012	0.2	0.01	<0.001	<0.001	0.003	0.01	0.001
Safad No.1-013	0.4	0.02	<0.001	<0.001	0.002	0.04	0.001
Theyab No.1-014	0.3	0.03	<0.001	<0.001	0.004	0.0007	0.0006
Qidfa-015	0.3	0.06	<0.001	<0.001	0.003	0.002	0.002
Murbeh-016	0.3	0.1	<0.001	<0.001	0.002	0.002	0.003
Sharam-017	0.3	0.1	<0.001	<0.001	0.002	0.002	0.003
Bidyah-018	0.2	0.007	<0.001	<0.001	0.008	0.002	0.001
Bidyah-019	0.2	0.07	<0.001	<0.001	0.01	0.002	0.0005
Bithnah No.3-020	0.1	0.004	<0.001	<0.001	0.006	0.003	0.0007
Qidnah NO.3-021	0.3	0.03	<0.001	<0.001	0.02	0.005	0.0002
Shaarah NO.5-022	0.2	0.01	<0.001	<0.001	0.003	0.002	0.04
Al-Hayel-023	0.2	0.01	<0.001	<0.001	0.002	0.001	0.001
Kalbah-024	0.8	0.3	<0.001	<0.001	0.002	<0.001	0.005
Kalbah-025	0.4	0.3	<0.001	<0.001	0.005	<0.001	0.1
Kalbah-026	0.3	0.2	<0.001	<0.001	0.006	<0.001	0.007
Kalbah-027	0.3	0.2	<0.001	<0.001	0.006	<0.001	0.004
Wadi Ham-028	0.2	0.04	<0.001	<0.001	0.04	0.002	0.0003
Murbad-029	0.2	0.04	<0.001	0.0001	0.01	0.002	0.0003
Masafi-030	0.2	0.05	<0.001	<0.001	0.005	0.002	0.002
Blydah-031	0.4	0.007	<0.001	<0.001	0.02	0.002	0.001
Siji-032	0.2	0.04	<0.001	<0.001	0.01	0.002	0.0003
Wadi Siji-033	0.3	0.2	<0.001	<0.001	0.01	0.001	0.0005
Wadi Falakh-034	0.1	0.006	<0.001	<0.001	0.005	0.002	0.0005
Al-Klibyah-035	0.4	0.04	<0.001	<0.001	0.003	0.002	0.0007

Fujairah-036	0.6	0.2	<0.001	<0.001	0.003	0.001	0.001
Ferfar-037	0.2	0.02	<0.001	<0.001	0.0009	<0.001	0.0007
Maidaq-038	0.0	0.02	<0.001	<0.001	0.0004	0.002	0.05
Tayyibah-039	0.1	0.006	<0.001	<0.001	0.001	0.002	0.004
Wadi Sehem-040	0.3	0.02	<0.001	<0.001	0.002	0.002	0.001
Wadi Mai-041	0.6	0.003	<0.001	<0.001	0.0004	0.002	0.03
Wadi Madiaq-042	0.6	0.004	<0.001	0.001	0.001	0.003	0.08
Wadi Seider-043	0.6	0.03	<0.001	<0.001	0.0008	0.002	0.001
Khorfakkan-044	1.2	0.04	<0.001	<0.001	0.003	0.002	0.001
Wadi Mai-045	0.6	0.001	<0.001	<0.001	0.001	0.002	0.001

Sample ID	Mn (mg/l)	Mo (mg/l)	Ni (mg/l)	P (mg/l)	Pb (mg/l)	Sr (mg/l)	Zn(mg/l)
Masafi-001	<0.001	<0.001	0.0007	<0.001	<0.001	0.8	0.01
Masafi-002	<0.001	<0.001	0.001	0.02	<0.001	1.3	0.03
Masafi-003	<0.001	0.0009	0.001	<0.001	<0.001	0.9	0.3
Dibba Rafa-004	<0.001	<0.001	0.0008	<0.001	<0.001	1.6	0.01
Al-Goab No.6-005	0.00001	0.002	0.001	<0.001	<0.001	1.2	0.04
Al-Goab No.12-006	<0.001	0.003	0.0007	<0.001	<0.001	1.4	0.08
Al-Hala No.3-007	0.003	0.01	<0.001	<0.001	<0.001	0.7	0.1
Wadi Al-Abadellah-008	0.0006	<0.001	0.002	<0.001	<0.001	1.5	0.07
Goanah-009	0.003	0.002	0.002	<0.001	<0.001	1.00	0.07
New Dadnah No.5-010	<0.001	<0.001	<0.001	<0.001	<0.001	0.4	0.01
Zikt No.1-011	0.0002	<0.001	0.002	<0.001	<0.001	0.8	0.008
Qidfa No.3-012	0.001	<0.001	0.002	<0.001	<0.001	1.3	0.04
Safad No.1-013	0.0001	0.001	0.002	<0.001	0.003	0.9	0.9
Theyab No.1-014	0.003	<0.001	0.03	<0.001	<0.001	3.6	0.05
Qidfa-015	0.0003	<0.001	0.005	0.02	<0.001	4.7	0.04
Murbeh-016	0.0002	<0.001	0.004	<0.001	<0.001	4.6	0.002
Sharam-017	0.0002	<0.001	0.004	<0.001	<0.001	4.6	0.001
Bidyah-018	0.00003	<0.001	0.001	<0.001	<0.001	0.5	0.009
Bidyah-019	0.001	<0.001	0.003	0.02	<0.001	2.4	0.0003
Bithnah No.3-020	0.0002	<0.001	0.001	<0.001	<0.001	0.6	0.003
Qidnah NO.3-021	<0.001	<0.001	0.002	<0.001	<0.001	1.2	0.03
Shaarah NO.5-022	0.0006	<0.001	0.0005	<0.001	<0.001	1.2	0.1
Al-Hayel-023	0.0003	<0.001	0.001	<0.001	<0.001	0.8	0.2
Kalbah-024	0.0000	<0.001	0.02	<0.001	<0.001	N	0.002
Kalbah-025	0.003	<0.001	0.01	<0.001	<0.001	N	0.004
Kalbah-026	0.0003	<0.001	0.005	<0.001	<0.001	N	0.001
Kalbah-027	<0.001	<0.001	0.006	<0.001	<0.001	8.9	0.004
Wadi Ham-028	0.0004	<0.001	0.002	<0.001	<0.001	0.9	0.001
Murbad-029	0.003	<0.001	0.002	<0.001	<0.001	1.1	0.0003
Masafi-030	0.002	<0.001	0.002	<0.001	<0.001	1.7	0.01
Blydah-031	0.0003	<0.001	0.0008	<0.001	<0.001	1.1	0.03
Siji-032	<0.001	<0.001	0.001	<00.1	<0.001	1.4	0.04
Wadi Siji-033	<0.001	<0.001	0.002	<0.001	<0.001	3.6	0.2
Wadi Falakh-034	0.0003	<0.001	0.002	<0.001	<0.001	0.6	0.004

Al-Klibyah-035	0.00006	0.001	0.0008	<0.001	<0.001	2.2	0.3
Fujairah-036	<0.001	<0.001	0.01	0.009	<0.001	7.1	0.0002
Ferfar-037	0.00008	<0.001	0.001	<0.001	<0.001	1.9	0.0005
Maidaq-038	0.0003	<0.001	<0.001	<0.001	<0.001	1.0	0.004
Tayyibah-039	0.004	0.001	<0.01	<0.001	<0.001	1.0	0.4
Wadi Sehem-040	<0.001	<0.001	0.002	<0.001	<0.001	1.2	0.0003
Wadi Mai-041	0.0006	0.005	0.0007	<0.001	<0.001	0.8	0.003
Wadi Madiaq-042	0.004	0.0008	0.02	<0.001	<0.001	1.1	0.3
Wadi Seider-043	0.0001	0.006	<0.001	<0.001	<0.001	0.7	0.003
Khorfakkan-044	0.00008	0.002	0.002	<0.001	<0.001	1.4	0.01
Wadi Mai-045	<0.001	<0.001	<0.001	<0.001	<0.001	1.0	0.06

Sample ID	**Hg (µg/l)**	**SiO_2 (mg/l)**
Masafi-001	<0.5	3.8
Masafi-002	<0.5	5.7
Masafi-003	<0.5	0.04
Dibba Rafa-004	<0.5	13.8
Al-Goab No.6-005	<0.5	15.3
Al-Goab No.12-006	<0.5	18.6
Al-Hala No.3-007	<0.5	23.1
Wadi Al-Abadellah-008	<0.5	14.5
Goanah-009	<0.5	15.9
New Dadnah No.5-010	<0.5	5.5
Zikt No.1-011	<0.5	24.5
Qidfa No.3-012	<0.5	28.0
Safad No.1-013	<0.5	26.3
Theyab No.1-014	<0.5	32.8
Qidfa-015	<0.5	30.5
Murbeh-016	<0.5	48.2
Sharam-017	<0.5	10.1
Bidyah-018	<0.5	19.8
Bidyah-019	<0.5	7.9
Bithnah No.3-020	<0.5	17.2
Qidnah NO.3-021	<0.5	23.6
Shaarah NO.5-022	<0.5	19.7
Al-Hayel-023	<0.5	24.0
Kalbah-024	<0.5	40.3
Kalbah-025	<0.5	25.5
Kalbah-026	<0.5	24.5
Kalbah-027	<0.5	24.5
Wadi Ham-028	<0.5	9.1
Murbad-029	<0.5	16.9
Masafi-030	<0.5	16.1
Blydah-031	<0.5	45.3
Siji-032	<0.5	17.2

Wadi Siji-033	<0.5	23.0
Wadi Falakh-034	<0.5	16.7
Al-Klibyah-035	<0.5	23.2
Fujairah-036	<0.5	32.5
Ferfar-037	<0.5	14.7
Maidaq-038	<0.5	2.9
Tayyibah-039	<0.5	25.8
Wadi Sehem-040	<0.5	25.0
Wadi Mai-041	<0.5	21.1
Wadi Madiaq-042	<0.5	28.6
Wadi Seider-043	<0.5	19.7
Khorfakkan-044	<0.5	34.6
Wadi Mai-045	<0.5	37.6

Samples 46-96

Sample ID	Aquifer	UTE (E)	UTM (N)	pH	T °C
Ahfrah No.1-046	Ophiolite	429350	2769998	7.6	37
Murbeh-047	E. Gravel Plain	435483	2794522	8.15	28
Bithnah-048	Ophiolite	423403	2785793	8.09	31.5
Bithnah-049	Ophiolite	423449	2785765	7.94	36
Bithnah-050	Ophiolite	422377	2786629	8.16	33.2
Bithnah-051	Ophiolite	422335	2786981	8.12	31
Bithnah-052	Ophiolite	422121	2787257	8.02	31
Blydah-053	Ophiolite	420908	2789043	8.11	31.5
Blydah-054	Ophiolite	420466	2789667	8.01	31.2
Blydah-055	Ophiolite	420318	2789411	8.01	31
Blydah-056	Ophiolite	420356	2789530	8.24	29.1
Qamrah-057	Ophiolite	416853	2798165	10.31	38
Qamrah-058	Ophiolite	416813	2798068	11.749	37
Masafi-059	Ophiolite	416144	2799134	11.49	37.8
Blydah-060	Ophiolite	420717	2789077	8.26	30
Masafi-061	Ophiolite	415001	2799026	7.79	30
Masafi-062	Ophiolite	415176	2799267	8.13	26
Masafi-063	Ophiolite	415096	2799570	7.94	N
Masafi-064	Ophiolite	415794	2798770	11.3	32.5
Murbeh-065	E. Gravel Plain	435561	2794387	7.35	32
Qirat-066	E. Gravel Plain	435156	2794732	7.97	30.2
Qirat-067	E. Gravel Plain	435234	2794845	8.2	33.3
Murbeh-068	E. Gravel Plain	435804	2794325	7.65	N
Masafi-069	Ophiolite	415954	2801469	8.32	25
Masafi-070	Ophiolite	415864	2801758	8.36	N
Masafi-071	Ophiolite	415091	2801911	8.06	N
Masafi-072	Ophiolite	415643	2800087	10.68	35
Masafi-073	Ophiolite	415946	2800930	10.57	33.7
Masafi-074	Ophiolite	416644	2801583	8.5	31

Masafi-075	Ophiolite	416010	2800950	11.13	31.2
Blydah-076	Ophiolite	420003	2789663	8.8	30.1
Bithnah-077	Ophiolite	424635	2783301	9.17	37
Bithnah-078	Ophiolite	423443	2784211	7.8	33
Bithnah-079	Ophiolite	424296	2783243	7.77	35
Ferfar-080	Ophiolite	425140	2782757	9.4	37
Ferfar-081	Ophiolite	425591	2781381	7.73	33
Ferfar-082	Ophiolite	425572	2781586	7.58	35
Fujairah-083	E. Gravel Plain	426219	2780924	7.41	37.4
Fujairah-084 (Qidnah)	E. Gravel Plain	426384	2780615	7.77	32.4
Al-Hayel-085	Ophiolite	428534	2777928	7.43	36.6
Al-Hayel-086	Ophiolite	428456	2777838	7.53	34
Al-Hayel-087	Ophiolite	428266	2777869	7.43	36
Fujairah-088	E. Gravel Plain	432811	2780743	7.53	31.5
Fujairah-089	E. Gravel Plain	432896	2780874	7.5	31.6
Khorfakkan-090	E. Gravel Plain	433744	2804258	7.35	31
Khorfakkan-091	E. Gravel Plain	433824	2804127	7.76	33
Fujairah-092	E. Gravel Plain	434912	2778016	7.51	28
Fujairah-093	E. Gravel Plain	434303	2777646	8.15	N
Fujairah-094	E. Gravel Plain	434891	2777599	7.38	31.8
Khorfakkan-095	E. Gravel Plain	434140	2800883	8.06	33
Khorfakkan-096	E. Gravel Plain	435731	2803314	7.94	31.6

Sample ID	**Conductivity (mS)**	**TDS (mg/l)**	**Na^+ (mg/l)**	**K^+ (mg/l)**
Ahfrah No.1-046	1.9	1133	582.1	4.2
Murbeh-047	3.5	2060	526.9	28.9
Bithnah-048	0.6	389	154.0	13.7
Bithnah-049	0.7	426	299.2	22.2
Bithnah-050	0.9	565	N	N
Bithnah-051	0.95	566	242.2	16.7
Bithnah-052	0.99	594	244.5	16.5
Blydah-053	0.9	521	222.1	12.5
Blydah-054	0.7	393	174.7	11.8
Blydah-055	0.9	515	213.1	12.2
Blydah-056	0.96	570	234.1	13.6
Qamrah-057	0.7	440	264.7	13
Qamrah-058	2.5	1469	504.9	30.5
Masafi-059	2.2	1306	479.2	32.6
Blydah-060	0.9	540	218.0	12.7
Masafi-061	8.0	4750	1059.6	69.3
Masafi-062	3.6	2160	804.5	41.8
Masafi-063	1.5	884	528.9	16.5
Masafi-064	1.6	932	387.5	29.2
Murbeh-065	10.6	6330	1043.0	N
Qirat-066	0.98	588	209.9	11
Qirat-067	0.5	305	123.8	6.8

Murbeh-068	11.4	6770	N	N
Masafi-069	0.8	497	167.9	10.2
Masafi-070	1.3	759	270.1	15
Masafi-071	3.6	2140	732.5	53.8
Masafi-072	1.5	882	512.8	8.2
Masafi-073	1.1	678	371.6	32.5
Masafi-074	0.5	297	68.6	3.7
Masafi-075	1.5	876	337.4	23.4
Blydah-076	2.5	1481	627.9	21
Bithnah-077	3.9	2300	673.5	12.7
Bithnah-078	2.5	1481	401.9	29.9
Bithnah-079	2.5	1471	476.4	6.8
Ferfar-080	2.9	1741	625.0	6.5
Ferfar-081	2.7	1623	478.6	38.5
Ferfar-082	2.1	1258	520.6	13.6
Fujairah-083	2.8	1666	628.1	3.3
Fujairah-084 (Qidnah)	2.4	1435	427.1	31.4
Al-Hayel-085	3.8	2250	746.6	16.7
Al-Hayel-086	2.7	1597	628.7	14.1
Al-Hayel-087	4.4	2640	740.5	17
Fujairah-088	11.3	6710	1070.0	64
Fujairah-089	7.3	4340	894.7	52.3
Khorfakkan-090	7.8	4640	931.0	52.5
Khorfakkan-091	3.1	1826	615.5	24.7
Fujairah-092	21.3	12730	N	191.2
Fujairah-093	6.2	3740	745.6	50.7
Fujairah-094	24	14330	N	121.3
Khorfakkan-095	2.2	1343	710.2	10.6
Khorfakkan-096	4.5	2690	862.6	52.0

Sample ID	**Mg^{+2} (mg/l)**	**Ca^{+2} (mg/l)**	**SO_4^{-2} (mg/l)**	**CO_3^{-2} (mg/l)**	**HCO_3^- (mg/l)**	**Cl^- (mg/l)**
Ahfrah No.1-046	10	53.7	274.8	N	427	417.5
Murbeh-047	235.2	16.7	116.5	6.6	195.2	1103.3
Bithnah-048	45.8	3.1	66.5	10.2	97.6	139.2
Bithnah-049	35.2	18.5	79.8	6	103.09	149.1
Bithnah-050	N	N	82.3	4.2	97.6	208.7
Bithnah-051	54.6	20.7	97.7	6.6	165.9	178.9
Bithnah-052	56.5	23.3	108.7	9	174.5	198.8
Blydah-053	49.6	22.04	72.6	7.8	169.6	208.7
Blydah-054	41.1	11.6	54.8	10.8	155.6	129.2
Blydah-055	52.7	18.98	75.2	6.6	195.2	159.04
Blydah-056	59.1	20.04	78.2	11.4	208.01	178.9
Qamrah-057	18.5	22.2	46.1	22.8	48.2	188.9
Qamrah-058	0.07	88.9	4.7	363	389.2	546.7
Masafi-059	0.02	76.8	0.3	285.6	316.6	506.9
Blydah-060	56.1	17.7	73.1	8.4	213.5	169.0

Masafi-061	337.2	108.8	81.9	15.6	500.2	2365.7
Masafi-062	87.8	67.5	537.2	25.8	631.4	685.9
Masafi-063	5.1	25.1	233.2	25.2	218.4	288.3
Masafi-064	0.97	72.7	10.1	195	233.02	357.8
Murbeh-065	675.9	89.7	479.8	1.8	428.2	3657.9
Qirat-066	73.3	11.1	73.03	7.8	244	198.8
Qirat-067	39.2	3.1	50.2	13.2	162.9	79.5
Murbeh-068	597.3	109.2	476.2	19.2	457.5	3995.9
Masafi-069	61.3	14.03	68.4	19.2	167.75	198.8
Masafi-070	103	16.5	108.9	N	N	248.5
Masafi-071	89.5	104.6	313.9	N	N	805.1
Masafi-072	0.03	7.6	133.5	N	N	347.9
Masafi-073	5.6	24.4	43.5	N	N	347.9
Masafi-074	36.2	6.9	53.7	N	N	109.3
Masafi-075	0.6	51.8	22.3	N	N	357.8
Blydah-076	8.7	128.5	338.04	N	N	665.98
Bithnah-077	42.7	309.3	60.9	N	N	1013.9
Bithnah-078	149.07	88.4	252.6	N	N	596.4
Bithnah-079	28.1	89.9	340.8	N	N	566.6
Ferfar-080	4.9	259.1	362.08	N	N	805.1
Ferfar-081	199.3	103.8	67.7	N	N	536.8
Ferfar-082	62.8	105.2	339.6	N	N	467.2
Fujairah-083	7.6	216.7	541.5	N	N	825.02
Fujairah-084 (Qidnah)	177.4	87.7	52.8	N	N	477.1
Al-Hayel-085	33.4	264.9	87.9	N	N	765.4
Al-Hayel-086	53.03	138.8	58.8	N	N	467.2
Al-Hayel-087	16.7	402.95	107.03	N	N	1003.9
Fujairah-088	344.3	357.4	289.4	N	N	4075.4
Fujairah-089	211.4	158.2	190.1	N	N	2485
Khorfakkan-090	374.8	184.3	192.2	N	N	2703.7
Khorfakkan-091	144.7	59.4	81.4	N	N	914.5
Fujairah-092	1050.6	233.95	82.03	0	480.4	7455
Fujairah-093	395.5	154.5	168.8	11.3	217.3	1868.7
Fujairah-094	N	351.2	88.4	0	533.8	9691.5
Khorfakkan-095	18.2	35.2	240.8	3.8	529.9	338
Khorfakkan-096	140.8	64.6	260.9	7.5	488	1222.6

Sample ID	**NO_3^- (mg/l)**	**Al (mg/l)**	**B (mg/l)**	**Ba (mg/l)**	**Cd(mg/l)**	**Co (mg/l)**	**Cr (mg/l)**
Ahfrah No.1-046	2.5	0.003	0.7	<0.001	<0.001	<0.001	0.0005
Murbeh-047	6.3	0.002	0.1	0.04	<0.001	0.0002	0.004
Bithnah-048	5.4	<0.001	0.2	0.008	<0.001	<0.001	0.01
Bithnah-049	5.7	<0.001	0.3	0.02	<0.001	<0.001	0.01
Bithnah-050	7.2	N	N	N	N	N	N
Bithnah-051	N	<0.001	0.2	0.02	<0.001	<0.001	0.02
Bithnah-052	9.9	0.001	0.2	0.02	<0.001	<0.001	0.02
Blydah-053	8.05	<0.001	0.2	0.02	<0.001	<0.001	0.01

Blydah-054	4.6	0.002	0.2	0.01	<0.001	<0.001	0.01
Blydah-055	8.9	0.0009	0.2	0.02	<0.001	<0.001	0.02
Blydah-056	8.9	<0.001	0.2	0.02	<0.001	<0.001	0.02
Qamrah-057	2.4	0.006	0.088	0.007	<0.001	<0.001	0.001
Qamrah-058	1	0.002	0.086	0.03	<0.001	<0.001	0.0002
Masafi-059	1.05	<0.001	0.090	0.02	<0.001	<0.001	0.0004
Blydah-060	8.3	<0.001	0.2	0.02	<0.001	<0.001	0.01
Masafi-061	8.9	0.007	0.9	0.2	<0.001	<0.001	0.007
Masafi-062	4.5	0.005	1.5	0.1	<0.001	<0.001	0.004
Masafi-063	1.1	<0.001	1.1	0.03	<0.001	<0..01	0.0002
Masafi-064	0.8	<0.001	0.06	0.02	<0.001	<0.001	0.004
Murbeh-065	3.2	0.004	0.3	0.1	<0.001	<0.001	0.002
Qirat-066	5.4	<0.001	0.15	0.008	<0.001	<0.001	0.003
Qirat-067	5.3	<0.001	0.13	0.004	<0.001	<0.001	0.004
Murbeh-068	3.7	0.007	0.4	0.06	<0.001	<0.001	0.0007
Masafi-069	8.2	<0.001	0.003	0.02	<0.001	<0.001	0.004
Masafi-070	6.2	0.001	0.1	0.04	<0.001	<0.001	0.01
Masafi-071	0.99	0.002	1.8	0.2	<0.001	<0.001	0.003
Masafi-072	0.8	0.03	0.8	0.01	<0.001	<0.001	0.0002
Masafi-073	2.1	0.002	0.03	0.02	<0.001	<0.001	0.0005
Masafi-074	3.8	<0.001	0.08	0.01	<0.001	0.0002	0.002
Masafi-075	1.1	0.0008	0.04	0.03	<0.001	<0.001	0.0002
Blydah-076	1.3	0.008	1.4	0.03	<0.001	<0.001	0.0005
Bithnah-077	14.3	0.02	0.2	0.005	<0.001	0.0002	0.004
Bithnah-078	13.4	0.005	0.4	0.06	<0.001	<0.001	0.006
Bithnah-079	6.3	0.01	0.3	0.01	<0.001	<0.001	0.001
Ferfar-080	0.7	0.02	0.2	0.0007	<0.001	<0.001	<0.001
Ferfar-081	12.8	0.01	0.3	0.06	<0.001	<0.001	0.005
Ferfar-082	7.7	0.01	0.3	0.01	<0.001	<0.001	0.004
Fujairah-083	1.9	0.01	0.2	0.003	<0.001	<0.001	0.0004
Fujairah-084 (Qidnah)	12.3	0.01	0.3	0.06	<0.001	<0.001	0.008
Al-Hayel-085	19.1	0.004	0.4	0.1	<0.001	<0.001	0.004
Al-Hayel-086	15.6	0.01	0.5	0.01	<0.001	<0.001	0.004
Al-Hayel-087	16.7	0.02	0.3	0.01	<0.001	<0.001	0.002
Fujairah-088	14.4	0.03	0.4	0.3	<0.001	<0.001	0.005
Fujairah-089	13.8	0.007	0.6	0.2	<0.001	<0.001	0.004
Khorfakkan-090	6.3	0.01	0.4	0.1	<0..01	<0.001	0.003
Khorfakkan-091	9.5	0.007	0.3	0.04	<0.001	<0.001	0.005
Fujairah-092	17.8	0.01	0.8	0.2	<0.001	0.0003	0.0007
Fujairah-093	21.97	0.008	0.3	0.2	<0.001	<0.001	0.009
Fujairah-094	10.8	0.02	0.5	0.1	<0.001	<0.001	0.001
Khorfakkan-095	2.6	0.004	1.3	0.02	<0.001	<0.001	0.005
Khorfakkan-096	7.1	0.007	0.6	0.02	<0.001	<0.001	0.004

Sample ID	Cu (mg/l)	Fe (mg/l)	Mn (mg/l)	Mo (ppm)	Ni (mg/l)	P (mg/l)	Pb (mg/l)
Ahfrah No.1-046	0.002	0.002	0.0001	0.008	<0.001	<0.001	<0.001

Murbeh-047	0.002	0.0001	0.003	<0.001	0.003	<0.001	<0.001
Bithnah-048	0.002	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
Bithnah-049	0.002	0.0008	0.0008	<0.001	<0.001	<0.001	<0.001
Bithnah-050	N	N	N	N	N	N	N
Bithnah-051	0.003	0.0008	<0.001	<0.001	0.001	<0.001	<0.001
Bithnah-052	0.002	0.0004	<0.001	<0.001	0.001	<0.001	<0.001
Blydah-053	0.004	0.0009	0.0002	<0.001	0.001	<0.001	<0.001
Blydah-054	0.003	0.02	0.0007	<0.001	0.001	<0.001	<0.001
Blydah-055	0.004	0.01	0.0003	<0.001	0.002	0.01	<0.001
Blydah-056	0.003	0.001	<0.001	<0.001	0.002	<0.001	<0.001
Qamrah-057	0.003	0.1	0.004	<0.001	0.003	<0.001	<0.001
Qamrah-058	0.002	0.0002	<0.001	<0.001	<0.001	<0.001	<0.001
Masafi-059	0.002	0.0008	<0.001	<0.001	<0.001	<0.001	<0.001
Blydah-060	0.002	0.002	0.0001	<0.001	0.002	<0.001	<0.001
Masafi-061	0.001	0.0003	<0.001	<0.001	0.008	<0.001	<0.001
Masafi-062	0.002	0.0005	<0.001	0.001	0.007	<0.001	<0.001
Masafi-063	0.003	0.0003	0.02	0.003	0.0008	<0.001	<0.001
Masafi-064	0.002	0.0002	<0.001	<0.001	<0.001	<0.001	<0.001
Murbeh-065	0.002	0.0004	0.0005	<0.001	0.01	<0.001	0.0008
Qirat-066	0.003	0.0003	<0.001	<0.001	0.001	<0.001	<0.001
Qirat-067	0.003	0.00005	<0.001	<0.001	<0.001	<0.001	<0.001
Murbeh-068	0.0009	0.0004	0.00006	<0.001	0.008	<0.001	<0.001
Masafi-069	0.002	0.003	0.0002	<0.001	0.001	<0.001	<0.001
Masafi-070	0.002	<0.001	<0.001	<0.001	0.003	<0.001	<0.001
Masafi-071	0.003	0.0001	<0.001	0.008	0.002	0.1	<0.001
Masafi-072	0.0001	0.0008	<0.001	0.008	<0.001	<0.001	<0.001
Masafi-073	0.003	0.02	0.001	<0.001	0.0008	<0.001	<0.001
Masafi-074	0.0006	0.003	<0.001	<0.001	0.001	<0.001	<0.001
Masafi-075	0.0003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Blydah-076	<0.001	0.01	0.002	0.0004	0.002	<0.001	<0.001
Bithnah-077	<0.001	0.003	0.007	0.0005	0.005	0.007	<0.001
Bithnah-078	<0.001	0.0005	<0.001	<0.001	0.003	<0.001	<0.001
Bithnah-079	0.002	0.007	0.0006	0.0005	0.002	<0.001	<0.001
Ferfar-080	<0.001	0.0003	0.0004	0.0006	<0.001	<0.001	<0.001
Ferfar-081	<0.001	0.002	0.003	<0.001	0.002	<0.001	<0.001
Ferfar-082	<0.001	0.0002	0.0005	<0.001	0.002	<0.001	<0.001
Fujairah-083	<0.001	0.0003	0.001	<0.001	0.0008	<0.001	<0.001
Fujairah-084 (Qidnah)	<0.001	0.001	<0.001	<0.001	0.002	<0.001	<0.001
Al-Hayel-085	<0.001	0.008	0.001	<0.001	0.001	<0.001	<0.001
Al-Hayel-086	<0.001	0.002	0.0005	<0.001	0.002	<0.001	<0.001
Al-Hayel-087	<0.001	0.007	0.003	<0.001	0.001	<0.001	<0.001
Fujairah-088	<0.001	0.03	0.001	<0.001	0.005	<0.001	<0.001
Fujairah-089	0.0005	0.0008	<0.001	<0.001	0.007	<0.001	<0.001
Khorfakkan-090	<0.001	0.0003	0.0001	<0.001	0.008	<0.001	<0.001
Khorfakkan-091	<0.001	0.0006	0.0003	<0.001	0.002	<0.001	<0.001
Fujairah-092	<0.001	0.00007	0.0007	<0.001	0.02	<0.001	<0.001
Fujairah-093	<0.001	0.0002	<0.001	<0.001	0.004	0.02	<0.001

Fujairah-094	<0.001	0.0003	0.0008	<0.001	0.02	<0.001	0.0009
Khorfakkan-095	<0.001	0.0005	<0.001	0.005	0.001	<0.001	<0.001
Khorfakkan-096	<0.001	<0.001	<0.001	<0.001	0.005	0.02	<0.001

Sample ID	Sr (mg/l)	Zn (mg/l)	Hg (µg/l)	SiO_2 (mg/l)
Ahfrah No.1-046	0.8	0.03	<0.5	32.4
Murbeh-047	2.4	0.002	<0.5	21.2
Bithnah-048	0.8	0.004	<0.5	4.5
Bithnah-049	1.02	0.009	<0.5	5
Bithnah-050	N	N	<0.5	15.9
Bithnah-051	0.9	0.001	<0.5	13.08
Bithnah-052	0.95	0.0006	<0.5	15.1
Blydah-053	0.7	0.002	<0.5	16.4
Blydah-054	0.7	0.001	<0.5	12.6
Blydah-055	0.7	0.001	<0.5	14.3
Blydah-056	0.8	0.0003	<0.5	13.3
Qamrah-057	0.5	0.01	<0.5	2.3
Qamrah-058	0.8	<0.001	<0.5	0.2
Masafi-059	0.7	0.0001	<0.5	0.2
Blydah-060	0.8	0.0004	<0.5	15.4
Masafi-061	6.7	0.001	<0.5	31.5
Masafi-062	2.3	0.006	<0.5	44
Masafi-063	1.06	0.007	<0.5	31.5
Masafi-064	0.7	<0.001	<0.5	0.4
Murbeh-065	5.6	0.006	<0.5	31.2
Qirat-066	0.9	0.0005	<0.5	25.01
Qirat-067	0.5	0.001	<0.5	21.4
Murbeh-068	6.1	0.001	<0.5	29.6
Masafi-069	1.2	0.07	<0.5	8.8
Masafi-070	1.6	0.006	<0.5	11.9
Masafi-071	3.4	0.002	<0.5	46.01
Masafi-072	0.3	<0.001	<0.5	71.7
Masafi-073	1.6	0.04	<0.5	0.1
Masafi-074	0.5	0.007	<0.5	4.6
Masafi-075	1.09	<0.001	<0.5	0.1
Blydah-076	1.5	0.0002	<0.5	44.07
Bithnah-077	1.1	0.2	<0.5	19.7
Bithnah-078	2.1	0.1	<0.5	25
Bithnah-079	0.7	0.07	<0.5	16.5
Ferfar-080	0.3	0.01	<0.5	20.9
Ferfar-081	3.4	0.06	<0.5	20.95
Ferfar-082	1.1	0.6	<0.5	21.8
Fujairah-083	0.5	0.003	<0.5	19.6
Fujairah-084 (Qidnah)	2.5	0.06	<0.5	19.8
Al-Hayel-085	1.8	0.002	<0.5	32.3
Al-Hayel-086	2.3	<0.001	<0.5	35.9

Al-Hayel-087	1.7	0.1	<0.5	27.6
Fujairah-088	7.9	0.01	<0.5	26.8
Fujairah-089	4.2	0.02	<0.5	32.9
Khorfakkan-090	7.5	0.002	<0.5	53.5
Khorfakkan-091	3.1	0.0004	<0.5	42.2
Fujairah-092	N	0.00007	<0.5	32.4
Fujairah-093	6.6	0.002	<0.5	24.7
Fujairah-094	N	0.02	<0.5	36.8
Khorfakkan-095	1.2	0.005	<0.5	28.5
Khorfakkan-096	2.05	0.001	<0.5	43.4

Samples 97-122

Sample ID	**Aquifer**	**UTM (E)**	**UTM (N)**	**pH**	**T ºC**	**Conductivity (mS)**
Khorfakkan-097	E. Gravel Plain	435352	2803314	8.08	32	1.2
Qurayah-098	E. Gravel Plain	434510	2791025	7.67	35	9.6
Qurayah-099	E. Gravel Plain	434762	2790846	7.82	34	10.5
Theyab-100	E. Gravel Plain	433774	2791735	7.5	32	4.4
Qurayah-101	E. Gravel Plain	433337	2790834	8.02	34	1.2
Safad-102	E. Gravel Plain	430808	2789748	7.9	29	1.8
Safad-103	E. Gravel Plain	429734	2789891	7.9	N	1.2
Qidfa-104	E. Gravel Plain	435007	2798829	8.35	33	4.2
Wadishi-105	E. Gravel Plain	432805	2803262	7.86	33	0.6
Zubarah-106	E. Gravel Plain	434942	2809906	8.5	32.6	0.8
Lulayah-107	E. Gravel Plain	435316	2808236	7.87	33.2	6.5
Lulayah-108	E. Gravel Plain	434761	2808202	7.92	32.8	5.6
Zubarah-109	E. Gravel Plain	434264	2810367	7.42	N	0.5
Bidyah-110	E. Gravel Plain	433614	2813297	8.16	34.1	0.98
Bidyah-111	E. Gravel Plain	434746	2813819	7.93	31	5.5
Bidyah-112	E. Gravel Plain	433463	2813356	8.2	33.6	0.8
Sharam-113	E. Gravel Plain	435094	2817353	7.5	33.2	7.6
Sharam-114	E. Gravel Plain	434866	2817312	8.13	35	0.9
Aqah-115	E. Gravel Plain	435204	2820096	7.64	N	10.7
Aqah-116	E. Gravel Plain	435314	2820016	7.57	N	10.3
Zikt-117	E. Gravel Plain	431353	2821807	7.96	N	1.01
Zikt-118	E. Gravel Plain	431217	2821653	8.11	N	0.5
Dadnah-119	E. Gravel Plain	434965	2822854	8.22	33.2	0.5
Dadnah-120	E. Gravel Plain	436087	2822867	7.85	35	3.1
Rual Dadnah-122	E. Gravel Plain	433851	2825459	8.12	35.8	0.5
N means No data.						

Sample ID	**Aquifer**	**TDS (mg/l)**	**Na^+ (mg/l)**	**K^+ (mg/l)**	**Mg^{+2} (mg/l)**
Khorfakkan-097	E. Gravel Plain	695	250.7	14.05	98.4
Qurayah-098	E. Gravel Plain	5680	1041.3	74.3	384.5
Qurayah-099	E. Gravel Plain	6280	N	N	323.7

Theyab-100	E. Gravel Plain	2610	610.5	47.7	170.4
Qurayah-101	E. Gravel Plain	704	366.9	17.5	38.6
Safad-102	E. Gravel Plain	1095	450.3	25.5	76.4
Safad-103	E. Gravel Plain	717	745.5	30.97	0.8
Qidfa-104	E. Gravel Plain	2500	314.8	17.9	55.2
Wadishi-105	E. Gravel Plain	3550	115.3	6.8	44.9
Zubarah-106	E. Gravel Plain	452	127.4	9.3	77.6
Lulayah-107	E. Gravel Plain	3900	928.2	N	319.7
Lulayah-108	E. Gravel Plain	3320	791.9	53.8	289.8
Zubarah-109	E. Gravel Plain	273	81.8	5.9	38.5
Bidyah-110	E. Gravel Plain	585	258.9	15.9	60
Bidyah-111	E. Gravel Plain	3260	883.9	129.2	240.3
Bidyah-112	E. Gravel Plain	504	210.1	13.6	60.96
Sharam-113	E. Gravel Plain	4520	811.5	76.3	469.8
Sharam-114	E. Gravel Plain	508	191.6	14.9	56.2
Aqah-115	E. Gravel Plain	6410	N	163.08	403.3
Aqah-116	E. Gravel Plain	6130	N	163.7	331
Zikt-117	E. Gravel Plain	599	128.01	30.95	97.3
Zikt-118	E. Gravel Plain	274	75.5	7.8	40.9
Dadnah-119	E. Gravel Plain	291	76.5	6.00	46.5
Dadnah-120	E. Gravel Plain	1855	602.7	N	148.9
Rual Dadnah-122	E. Gravel Plain	275	95.2	6.6	35
N means No data.					

Sample ID	**Mg^{+2} (mg/l)**	**Ca^{+2} (mg/l)**	**SO_4^{-2} (mg/l)**	**CO_3^{-2} (mg/l)**	**HCO_3^- (mg/l)**	**Cl^- (mg/l)**
Khorfakkan-097	98.4	20.4	N	11.3	316.4	178.9
Qurayah-098	384.5	286.3	505.8	0	251.6	3230.5
Qurayah-099	323.7	151.9	N	7.5	335.5	3727.5
Theyab-100	170.4	275.2	226.7	0	122	1530.8
Qurayah-101	38.6	44.8	108.3	1.5	272.98	288.3
Safad-102	76.4	77.4	185.3	0	335.5	387.7
Safad-103	0.8	45.7	105.3	11.3	362.2	228.6
Qidfa-104	55.2	54.5	234.3	7.5	236.4	109.3
Wadishi-105	44.9	23.03	N	7.5	205.9	1451.2
Zubarah-106	77.6	1	N	15	221.1	168.98
Lulayah-107	319.7	42	241.3	11.3	224.9	2634.1
Lulayah-108	289.8	68.9	153.6	7.5	190.6	2166.9
Zubarah-109	38.5	3.1	39.6	7.5	99.1	79.5
Bidyah-110	60.02	3.2	52.3	8.3	136.5	278.3
Bidyah-111	240.3	36	178.05	11.3	568.06	1968.1
Bidyah-112	60.96	2.8	53.8	12	166.99	218.7
Sharam-113	469.8	123.2	191.8	0	137.3	3160.9
Sharam-114	56.2	13.009	54.06	7.5	129.6	248.5
Aqah-115	403.3	222.6	498.4	0	221.1	4433.2
Aqah-116	331	191.2	424.5	0	388.9	4622.1

Zikt-117	97.3	N	69	11.3	354.6	139.2
Zikt-118	40.9	6.3	42.2	11.3	141.06	69.6
Dadnah-119	46.5	2.9	40	7.5	137.3	89.5
Dadnah-120	148.9	61.5	N	3.8	232.6	984.06
Rual Dadnah-122	35	3.9	46.2	7.5	129.6	109.3

Last Samples from 97-122

Sample ID	NO_3^- (mg/l)	Al (mg/l)	B (mg/l)	Ba (mg/l)
Khorfakkan-097	17.1	0.001	0.2	0.01
Qurayah-098	18.4	0.01	0.3	0.2
Qurayah-099	16.5	0.009	0.5	0.1
Theyab-100	11.1	0.008	0.5	0.09
Qurayah-101	6.6	0.003	0.4	0.02
Safad-102	3.5	0.006	0.4	0.03
Safad-103	3.9	0.005	0.4	0.05
Qidfa-104	5.6	0.003	0.3	0.01
Wadishi-105	9.2	0.005	0.2	0.01
Zubarah-106	7.5	<0.001	0.1	0.02
Lulayah-107	5.1	0.003	0.2	0.2
Lulayah-108	9.4	0.006	0.3	0.09
Zubarah-109	N	<0.001	0.1	0.01
Bidyah-110	16.3	<0.001	0.2	0.02
Bidyah-111	4.1	0.003	0.6	0.1
Bidyah-112	12	<0.001	0.2	0.02
Sharam-113	10.8	0.01	0.3	0.13
Sharam-114	6.1	0.009	0.2	0.01
Aqah-115	20.1	0.01	0.8	0.1
Aqah-116	14.3	0.01	0.9	0.1
Zikt-117	9.2	<0.001	0.2	0.04
Zikt-118	3.2	<0.001	0.1	0.01
Dadnah-119	8.9	<0.001	0.1	0.01
Dadnah-120	21.9	0.007	0.5	0.06
Rual Dadnah-122	4.1	<0.001	0.1	0.01

Sample ID	Cd (mg/l)	Co (mg/l)	Cr (mg/l)	Cu (mg/l)
Khorfakkan-097	<0.001	<0.001	0.007	<0.001
Qurayah-098	<0.001	<0.001	0.002	<0.001
Qurayah-099	<0.001	<0.001	0.002	<0.001
Theyab-100	<0.001	<0.001	0.003	<0.001
Qurayah-101	<0.001	<0.001	0.003	0.003
Safad-102	<0.001	<0.001	0.003	0.002
Safad-103	<0.001	<0.001	0.005	0.002
Qidfa-104	<0.001	<0.001	0.004	0.002
Wadishi-105	<0.001	<0.001	0.007	0.002

Zubarah-106	<0.001	<0.001	0.01	0.003
Lulayah-107	<0.001	<0.001	0.006	0.003
Lulayah-108	<0.001	<0.001	0.006	0.001
Zubarah-109	<0.001	<0.001	0.006	0.003
Bidyah-110	<0.001	<0.001	0.008	0.002
Bidyah-111	<0.001	<0.001	0.01	0.002
Bidyah-112	<0.001	<0.001	0.008	0.002
Sharam-113	<0.001	<0.001	0.02	0.001
Sharam-114	<0.001	0.0002	0.01	0.002
Aqah-115	<0.001	<0.001	0.03	<0.001
Aqah-116	<0.001	<0.001	0.01	0.0005
Zikt-117	<0.001	<0.001	0.004	0.002
Zikt-118	<0.001	<0.001	0.004	0.002
Dadnah-119	<0.001	<0.001	0.008	0.002
Dadnah-120	<0.001	<0.001	0.02	0.001
Rual Dadnah-122	<0.001	<0.001	0.01	0.003

Sample ID	**Cu (mg/l)**	**Fe(mg/l)**	**Mn (mg/l)**	**Mo (mg/l)**	**Ni (mg/l)**	**P (mg/l)**	**Pb (mg/l)**
Khorfakkan-097	<0.001	0.00005	<0.001	<0.001	0.003	<0.001	<0.001
Qurayah-098	<0.001	0.0006	<0.001	<0.001	0.004	<0.001	<0.001
Qurayah-099	<0.001	0.0005	0.0003	<0.001	0.005	<0.001	<0.001
Theyab-100	<0.001	0.001	<0.001	<0.001	0.003	<0.001	<0.001
Qurayah-101	0.003	0.0009	<0.001	0.0003	0.001	<0.001	<0.001
Safad-102	0.002	0.0002	<0.001	0.0010	0.001	0.008	<0.001
Safad-103	0.002	0.0001	<0.001	<0.001	0.002	<0.001	<0.001
Qidfa-104	0.002	<0.001	<0.001	<0.001	0.004	<0.001	<0.001
Wadishi-105	0.002	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
Zubarah-106	0.003	<0.001	<0.001	<0.001	0.001	<0.001	<0.001
Lulayah-107	0.003	0.0008	<0.001	<0.001	0.004	<0.001	<0.001
Lulayah-108	0.001	0.001	0.0005	<0.001	0.003	<0.001	<0.001
Zubarah-109	0.003	0.002	<0.001	<0.001	0.001	<0.001	<0.001
Bidyah-110	0.002	0.0003	<0.001	<0.001	<0.001	<0.001	<0.001
Bidyah-111	0.002	0.0003	<0.001	<0.001	0.004	<0.001	<0.001
Bidyah-112	0.002	0.0002	<0.001	<0.001	0.001	<0.001	<0.001
Sharam-113	0.001	0.0003	<0.001	<0.001	0.003	<0.001	<0.001
Sharam-114	0.002	0.0001	<0.001	<0.001	0.002	<0.001	<0.001
Aqah-115	<0.001	0.0004	<0.001	<0.001	0.002	<0.001	<0.001
Aqah-116	0.0005	0.0006	<0.001	<0.001	0.004	<0.001	<0.001
Zikt-117	0.002	0.002	0.0001	<0.001	0.001	<0.001	<0.001
Zikt-118	0.002	0.002	<0.001	<0.001	0.001	<0.001	<0.001
Dadnah-119	0.002	0.0008	<0.001	<0.001	0.001	<0.001	<0.001
Dadnah-120	0.001	<0.001	0.0001	<0.001	0.002	<0.001	<0.001
Rual Dadnah-122	0.003	0.0004	<0.001	<0.001	0.001	<0.001	<0.001

Sample ID	Sr (mg/l)	Zn (mg/l)	Hg (µg/l)	SiO_2 (mg/l)
Khorfakkan-097	N	0.001	<05	22.2
Qurayah-098	7.96	0.001	<0.5	27.3
Qurayah-099	5.7	0.0003	<0.5	32.3
Theyab-100	6.3	0.0005	<0.5	33.8
Qurayah-101	1.0	0.007	<0.5	28.5
Safad-102	1.8	0.001	<0.5	29.8
Safad-103	3.9	0.0009	<0.5	26.5
Qidfa-104	1.2	0.001	<0.5	25.7
Wadishi-105	0.6	0.005	<0.5	20.9
Zubarah-106	0.7	0.002	<0.5	4.9
Lulayah-107	3.9	0.003	<0.5	27.1
Lulayah-108	4.5	0.001	<0.5	20.8
Zubarah-109	0.6	0.01	<0.5	8.1
Bidyah-110	1.1	0.001	<0.5	10.9
Bidyah-111	2.9	0.001	<0.5	35.7
Bidyah-112	1.09	0.0004	<0.5	10.1
Sharam-113	7.8	0.0005	<0.5	14.2
Sharam-114	0.8	0.0004	<0.5	7.97
Aqah-115	N	0.002	<0.5	37.7
Aqah-116	9.4	0.005	<0.5	48
Zikt-117	1.2	0.0009	<0.5	33.3
Zikt-118	0.6	0.0004	<0.5	10.6
Dadnah-119	0.7	0.002	<0.5	12.7
Dadnah-120	N	0.002	<0.5	28.5
Rual Dadnah-122	0.6	0.006	<0.5	6.2

N means No data.