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# Investigation of Groundwater Quality of Al Hayer Area, (North of Al Ain City) Using Hydro geochemical Approach

Mohammed Hosny Ibrahim Gadalla

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United Arab Emirates University

College of Engineering

Department of Civil and Environmental Engineering

INVESTIGATION OF GROUNDWATER QUALITY OF AL HAYER  
AREA, (NORTH OF AL AIN CITY) USING HYDROGEOCHEMICAL  
APPROACH

Mohammed Hosny Ibrahim Gadalla

This Thesis is submitted in partial fulfilment of the requirements for the degree of  
Master of Science in Water Resources

Under the Supervision of Dr. Ahmed Murad

December 2015

## Declaration of Original Work

I, Mohammed Hosny Ibrahim Gadalla, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis, entitled “*Investigation of Groundwater Quality of Al Hayer Area, North of Al Ain City, Using Hydrogeochemical Approach*”, hereby, solemnly declare that this thesis is an original research work which has been done and prepared by me under the supervision of Dr Ahmed Murad, in the College of Science at the UAEU. This research has not been previously performed as the basis for the award of any academic degree, diploma or similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation, and/or publication of this dissertation.

Student's signature: \_\_\_\_\_

Date: \_\_\_\_\_

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## Abstract

Al Hayer is located in the northeast of Al Ain area, Eastern region of the United Arab Emirates. Groundwater abstraction for domestic, agricultural and industrial uses has led to major depletion in the aquifer resulting in groundwater quality deterioration. This study aims to identify the factors affecting the groundwater quality in this area, and to determine the recharge mechanism for the study area to understand the behaviour of major ions in regional groundwater by using hydrogeochemical and isotopic approaches. The hydrochemical analysis of 37 collected samples of groundwater revealed that the groundwater is characterized by moderate salinity and high concentrations of cadmium in some of the samples. Therefore, Al Hayer groundwater is not suitable for domestic uses. Groundwater samples were evaluated for agricultural uses by calculation of SAR, TH,  $\text{Na}^+$  percentage and MAR. By using these parameters, Al Hayer groundwater was found to be acceptable for agricultural purposes in 60% of the samples. Three water geneses have been identified; the first one is paleo-marine water, which is originated from magnesium chloride water type, indicating over pumping of deep water. The second is meteoric water, which is originated from sodium sulphate-water type, indicating an occurrence of infiltration of rainfall and ion exchange processes. The third one is meteoric water, which is originated from sodium bicarbonate-water type, found only in few samples. The hydrochemical analyses showed that the dominance of sodium and chloride in the area is due to agricultural effluents and provides indication of moderate-to-high salinity water in the studied area. Isotope analyses of hydrogen and oxygen of twenty-nine groundwater samples suggested that the study area has two different zones. The first one is represented by majority of groundwater samples and located below the LMWL and to the west of the study area, which suggests high rate of evaporation. Meanwhile, the second zone is located above the LMWL and to the east of the study area in close proximity to Northern Oman Mountains, which reveals quick infiltration to rainfall into major aquifer of the study area without evaporation.

**Keywords:** Groundwater quality, hydrogeochemical analysis, water genesis, Al Hayer area, the UAE.

## Title and Abstract (in Arabic)

### تقييم المياه الجوفية في منطقة الهير، شمال شرق مدينة العين

#### الملخص

تقع منطقة الهير في شمال شرق مدينة العين، شرق الإمارات العربية المتحدة. تتصف المنطقة بوجود نوعين رئيسيين من الخزانات الجوفية؛ بينما تتركز المساحات الزراعية بين الكثبان الرملية. تتصف المياه الجوفية في المنطقة بانخفاض معدل التغذية واستخدامها في ري المحاصيل الزراعية. تعاني المياه الجوفية في منطقة الدراسة من النضوب والتلوث نتيجة الإفراط في استخدام الأسمدة العضوية والكيميائية وكذلك الضخ المفرط. تبين من خلال نتائج التحليل الكيميائي لعدد 37 عينة من مياه آبار منطقة الدراسة أن ملوحة المياه الجوفية تتراوح ما بين المتوسطة والعالية (نسبة الأملاح الذائبة والتوصيلية الكهربائية)، وارتفاع تركيز معدن الكاديوم في بعض العينات تقريباً، ولذلك فإن المياه الجوفية في منطقة الدراسة غير صالحة للاستخدام الآدمي. لتقييم المياه الجوفية تم استخدام نتائج فحص كل من MAR, Na%, TH, SAR, لعينات المياه الجوفية والتي أثبتت بانها صالحة للري في ما يعادل 60% من العينات. ومن خلال الدراسة الهيدروجيوكيميائية للمياه، تبين وجود ثلاثة مصادر للمياه الجوفية في منطقة الهير، المصدر الأول هو المياه العميقة المليئة بالأملاح التي تسلت إلى الخزان الجوفي نتيجة الضخ المفرط للمياه الجوفية، والمصدر الثاني هو المياه العذبة التي تدل على وجود عمليات التبادل الأيوني وتسرب مياه الأمطار إلى الخزان الجوفي. والمصدر الثالث من أصل أملاح بيكربونات الصوديوم والموجود بعدد ضئيل من العينات. وأظهر التحليل أن الصوديوم والكلور هما العنصرين السائدين في المياه الجوفية نسبة إلى النفايات الزراعية السائلة مما يعلل زيادة ملوحة المياه الجوفية في المنطقة المدروسة. أما دراسة النظائر المستقرة لعنصري الهيدروجين والأكسجين في 27 عينة من المياه الجوفية بينت أن هناك نوعين مختلفين أحدهما يمثل الجهة الغربية لمنطقة الدراسة ويمثل غالبية العينات ويتميز بمعدلات عالية جداً من التبخر، والآخر يوجد بالقرب من الجهة الشمالية لجبال عمان والذي يتميز بمعدلات تغذية مرتفعة من خلال تسرب مياه المطر السريع عبر الخزانات الجوفية الرئيسية مما يقلل من تعرض مياه المطر لعملية التبخر.

**الكلمات المفتاحية:** جودة المياه الجوفية، التحليل الكيميائي-الجيولوجي، تجمعات المياه الجوفية، منطقة الهير.



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## Dedication

*I dedicate my thesis to my principal, Mr. Abdullah Al Junaibi and vice principal, Mr. Khalifa Al Raesi.*

*A special feeling of gratitude is donated to my loving parents whose words of encouragement and push for tenacity ring in my ears.*

*I also dedicate this thesis to many friends of mine who have supported me throughout the process. I will always appreciate all they have done.*

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## List of Abbreviations and Acronyms

$m^3$	Cubic Meter
ADWEA	Abu Dhabi Water and Electricity Authority
EAD	Environmental Agency – Abu Dhabi
EC	Electrical Conductivity
GW	Groundwater
LM WL	Local Meteoric Line
meq%	Milli-equivalent Percentage
meq/l	Milli-equivalent per Litre
mg	Milligram
mg/l	Milligram per litre
mg/l	Milligram per Litre
mm	Millimetre
Mm <sup>3</sup>	Million Cubic Meters
pH	Hydrogen Ion Concentration
ppm	Parts Per Million
r	Milli-equivalent per Litre (meq/l)
SAR	Sodium Adsorption Ratio
SMOW	Standard Mean Ocean Water
TDS	Total Dissolved Solids
VSMOW	Vienna Standard Mean Ocean Water
WHO	World Health Organization
$\mu\text{g/l}$	Microgram per Litre
$\mu\text{S/cm}$	Micro Siemens per Centimetre

## **Chapter 1: Introduction**

### **1.1. Overview**

Water is an essential bio-resource for all life forms. The freshwater resources are less than 1% and about 0.01% of all water on the Earth (UN WWAP, 2010). The UAE is among those countries in the Middle East and North Africa (MENA) facing serious water shortages. Rapid development in these countries requires additional amount of water to meet the increased demands for different sectors. The UAE's annual water share per capita is less than 200 m<sup>3</sup>(Arman and Murad, 2012), whereas the total water withdrawal per 1,000 m<sup>3</sup> in year 2000 was 2.3 m<sup>3</sup>(AFED, 2010).

High levels of water scarcity are evident throughout the country. Due to water's essential role in supporting all forms of life, the sustainable management of water resources is a major concern for all decision makers, stakeholders and scientists in the UAE. Regional and national governments have implemented water supply techniques to manage the quantity and the quality of water, ensuring an adequate supply of water for each person within the scope of the country's progressive development.

### **1.2. Location and Setting of the UAE**

The United Arab Emirates is located in the south-eastern part of the Arabian Peninsula between latitudes 22° 40' and 26° 00' N and longitudes 51° 00' and 56° 00' E. The Arabian Gulf bounds the country from the north, Sultanate of Oman from the south and Saudi Arabia from the west (Fig. 1.1). The country occupies an area of about 83, 600km<sup>2</sup>. The study area namely Al Hayer is situated within the northern part of the Al Ain area and the north-eastern part of the Abu Dhabi Emirate (Figure 1.2). The area of Al Hayer is 20km<sup>2</sup>.



Figure 1: Map of the Arabian Peninsula showing the location of the UAE

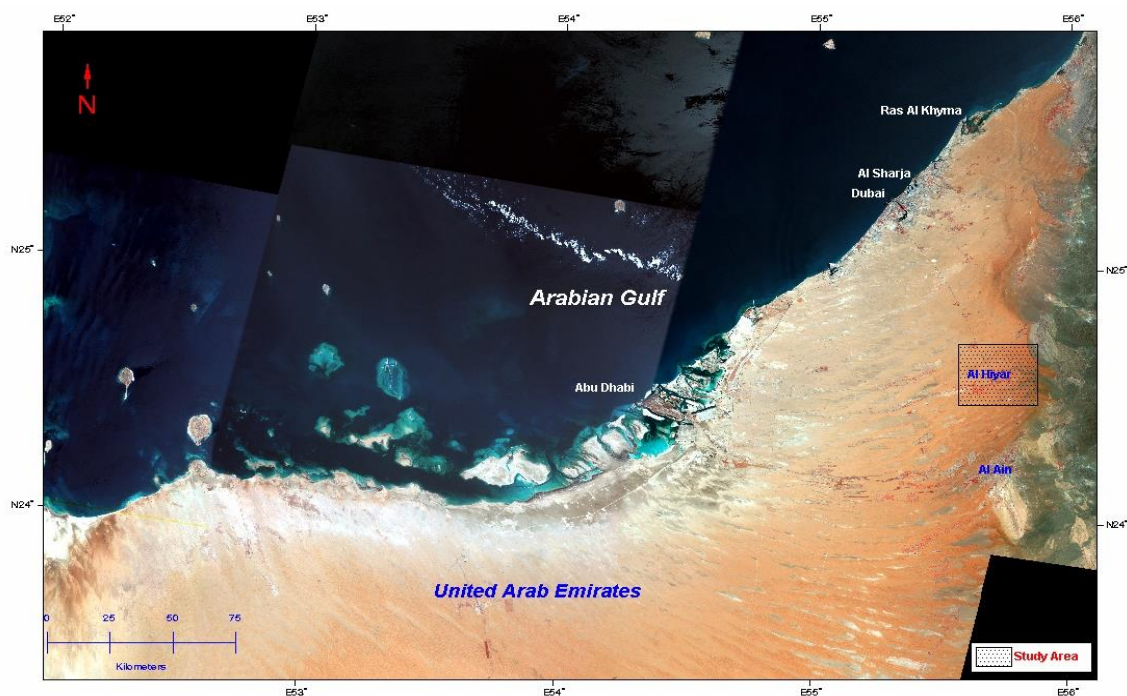


Figure 2: Satellite image of UAE showing the study area

### 1.3. Climate Conditions

The climate of the country is described as an arid that is similar to most countries in the Middle East and North Africa (MENA) region. The arid climate is mainly characterized by low amounts of rainfall or precipitation and heavy rates of evaporation, which is associated with high temperatures. The natural climatic conditions have a negative impact on availability of groundwater in the area. So, the Emirate of Abu Dhabi has a rainfall of less than 100 mm/year (Sherif et al., 2014).

Meteorological data of temperature, rainfall, humidity, and wind speed were obtained from the National Centre of Meteorology and Seismology (NCMS), United Arab Emirates from the period of 2005 to 2014 (table 1.1) The detailed description of the climate data of the study area is shown in Table 1. (UAE National Centre of Meteorology and Seismology, 2015)

<b>Al Faqa</b>				
<b>Year</b>	<b>Temp. [°C]</b>	<b>Relative Humidity (%)</b>	<b>Wind Speed (Km\h)</b>	<b>Rainfall (mm)</b>
	Mean	Mean	Mean	Sum
2005	27.8	49	8.8	22.6
2006	27.9	48	9.0	160.8
2007	28.0	48	9.0	47.6
2008	27.5	48	8.8	222.6
2009	27.9	51	8.8	177.2
2010	28.4	54	8.9	24.4
2011	28.0	57	9.1	108.8
2012	28.1	61	9.2	27.0
2013	27.3	68	9.1	82.4
2014	27.6	53	8.6	121.2

Table 1: Climate data of Al Faqa area in different years

### 1.4. Temperature

The coolest month of the year is January, while July is the hottest month. The annual mean temperature in the study area ranges from 27.3°C to 28.4. The average maximum air temperature of the study area is about 28 as shown in Figure 3.

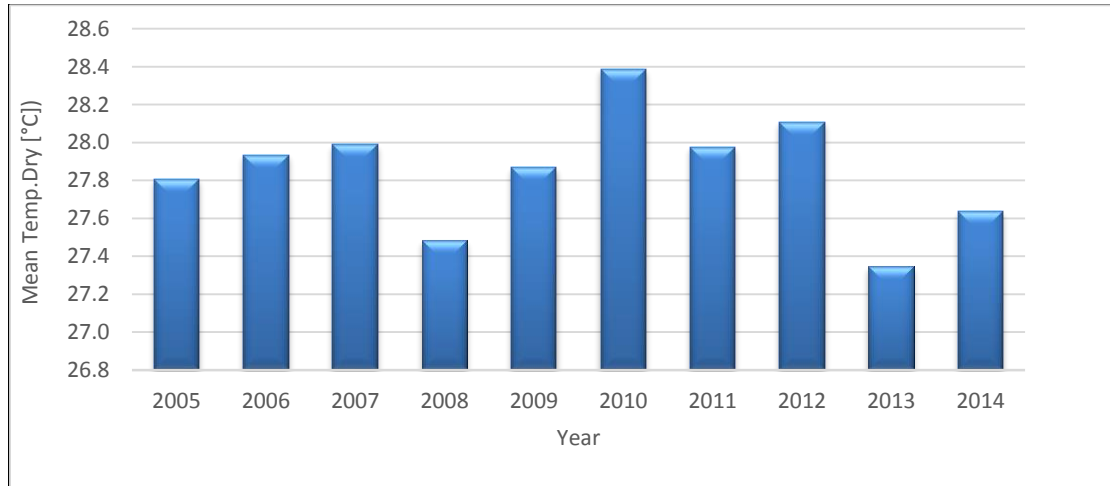


Figure 3: Mean Temperature, [°C] for different years in Al Faqa area (The UAE National Centre of Meteorology and Seismology (NCMS) May 2015)

### 1.5. Humidity

Relative humidity is high in the coastal areas, where the annual average reaches 60%. This value however, declines sharply towards the inland from the coastline where its annual average reaches 39%. Based on the UAE meteorological data, relative humidity was high in the study area ranging between 48 and 68% with an average of 53.7% as shown in Figure 4.

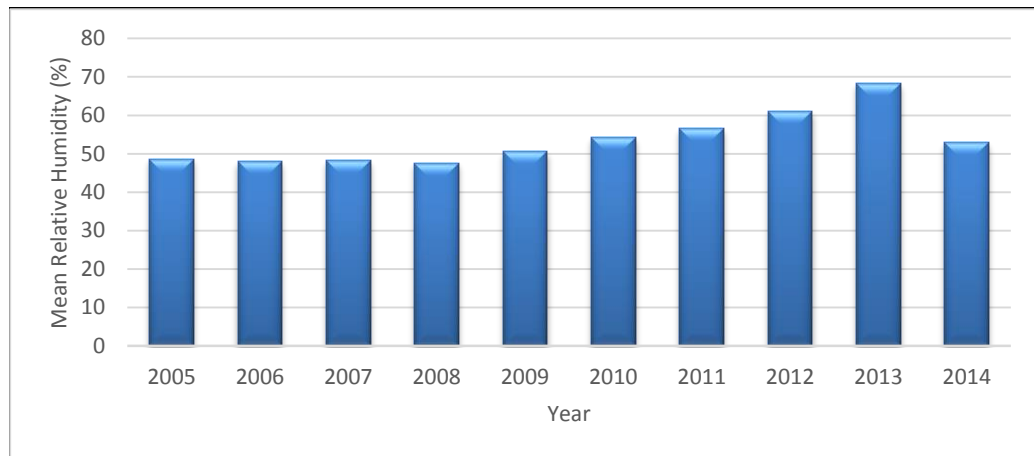


Figure 4: Mean Relative Humidity percentage for different years in Al Faqa (The UAE National Centre of Meteorology and Seismology (NCMS) May 2015)

### 1.6. Wind Speed

Wind speed is generally light to moderate and its annual mean is 9 km/hr (see Table 1).

There is a tendency for winds to be stronger between March and August. The predominant wind directions are from the northwest to the south and southeast. The strongest winds are felt along the Gulf of Oman followed by the mountainous regions. The wind speed ranges from 8 to 9.5 km/hr in the study area as shown in Figure 5.

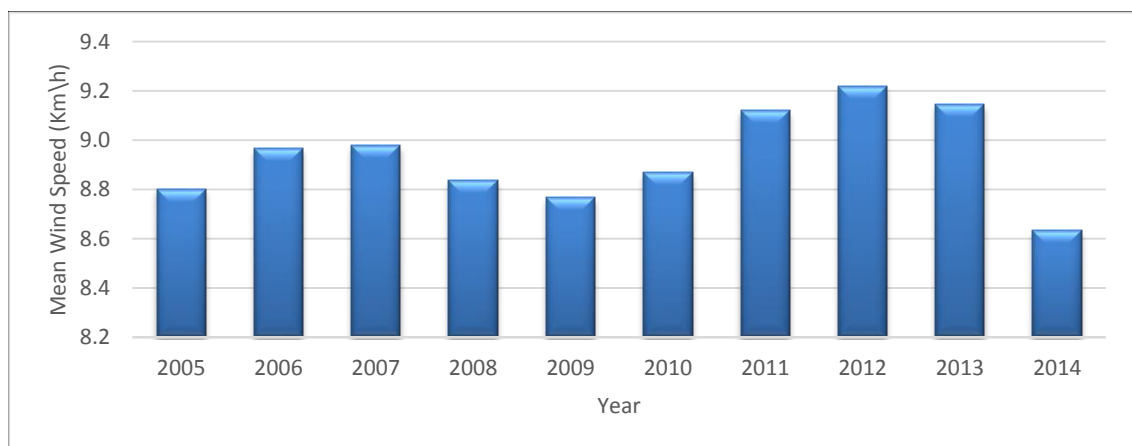


Figure 5: Mean Wind Speed (km/h) for different years in Al Faqa (The UAE National Centre of Meteorology and Seismology (NCMS) May 2015)

### 1.7. Rainfall

Based on rainfall data from 2005 to 2014, the annual rainfall amount in Al Faqa area, which located in about  $15 \text{ km}^2$  from the study area, varied between 22.6 mm in 2005 to 121.2 mm in 2014. The maximum annual average of rainfall in Al Faqa region was 222.6 mm in 2008, whereas the minimum annual average was 22.6 in 2005 as shown in Figure 6. Large amounts of rainfall are lost due to the evaporation process during the accumulation on the surface, while some infiltrate to the ground and contributes to the groundwater.

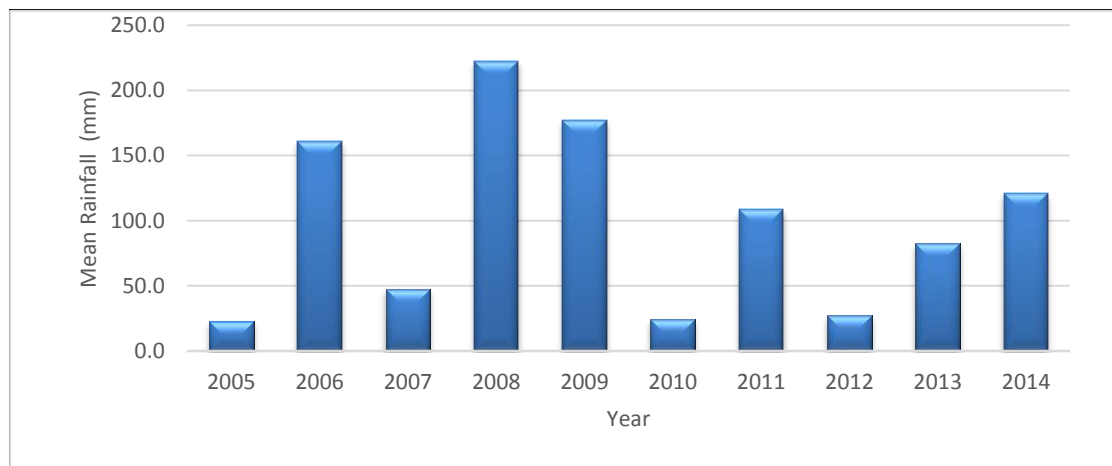


Figure 6: Annual mean rainfall in Al Faqa area  
(The UAE National Centre of Meteorology and Seismology (NCMS) May 2015)

### 1.8. Water Resources in the UAE

Two classifications of water resources in the country are designated as conventional and non-conventional water resources. Seasonal floods, springs, *Afalaj* and groundwater make up the conventional water resources in the UAE. Springs and *Afalaj* went dry due to the harsh climate of the UAE and the heavy use of groundwater; whereas, seasonal floods are

associated with short, heavy periods of rainfall. The new advent of desalinated water and treated wastewater accounts for the non-conventional water resources.

The UAE and other GCC countries have consistently relied upon groundwater as their main water resource. Over time, desalinated water seemed a viable groundwater substitute for practical uses in the UAE and other adjacent countries. However, the UAE's conversion from groundwater dependency to desalinated water dependency has serious implications on the social and economic life of the people.

### **1.9. Statement of Problem**

Groundwater is one of the conventional water resources in the world. Human activities and civilizations were concentrated around the sources of water throughout history. In the UAE, these unplanned human activities and increasing economic developments applied huge stress on groundwater resources. One of the important land uses in Al-Hayer comes from its agricultural practices, which have increased over the last few decades due to the encouragement of the government. Also, agricultural activities were the main sources of food and income of ancient people in this region.

Al Hayer is one of the irrigated areas that witnessed a change in the size of cultivation. Based on assessment of 2004 Landsat imagery of Abu Dhabi Emirate, the growth of irrigated areas in the Emirate had stabilized and had slightly decreased in some areas. This decrease might be attributed to the variability in the measurement techniques and not to the actual decrease in the irrigated areas (Michael and Juanito 2006). Table 2 shows the total irrigated area of vegetable and feed mills in Al Hayer area, and it is clear



that irrigated areas for vegetable and feed mills decreased from 8.26  $km^2$  in 2001/2002 to 1.97  $km^2$  in 2005/2006.

<b>Year</b>	<b>Total irrigated area (<math>km^2</math>)</b>	<b>No. of Farms</b>
2000/2001	7.75	374
2001/2002	8.26	379
2002/2003	6.06	392
2003/2004	2.84	407
2004/2005	2.75	418
2005/2006	1.97	421

Table 2: Total irrigated area and farmsnumber in Al Hayer area

However, the number of farms in Al Hayer has increased from 374 in 2000/2001 to 421 in 2005/2006 (ADC, 2007). The increasing number of farms indicated that the actual irrigated areas increased in the study area over time, which led to a decrease in the planted vegetables and feed mills while increasing other local wild plants. All water requirements for agricultural purposes were extracted heavily from the groundwater. Groundwater abstraction for domestic, agricultural, and industrial uses has led to major depletion in the aquifer, resulting in groundwater quality deterioration.

Most of the wells in the area, which belong to National Drilling Company (NDC-Al Ain) and Abu Dhabi Water and Electricity Authority (ADWEA), went dry due to the severe reduction of water quantity of the aquifer. Because of wells drying, most of these wells were closed. This reduction has led to an increase in salinity, which has progressively become more saline with time, of groundwater in the region. In addition,

increasing the cultivated areas of Al Hayer has introduced groundwater contamination. It is clear that agricultural activities are playing a significant role to the problems related to the groundwater through intense use of agriculture and heavy abstraction of groundwater.

Therefore, reducing the effect of depletion of major aquifers in the area is a major challenge that faces the UAE. Imbalance between the recharge and discharge in the study area has led to reducing the number of supplied wells. According to the Al Ain Distribution Company statistics, the total number of wells in Al Hayer area reduced from 43 in 1999 to 5 in 2005 as shown in Figure 7; whereas, average number of working wells reduced from 35 in 1999 to 2 in 2005 as shown in Figure 8.

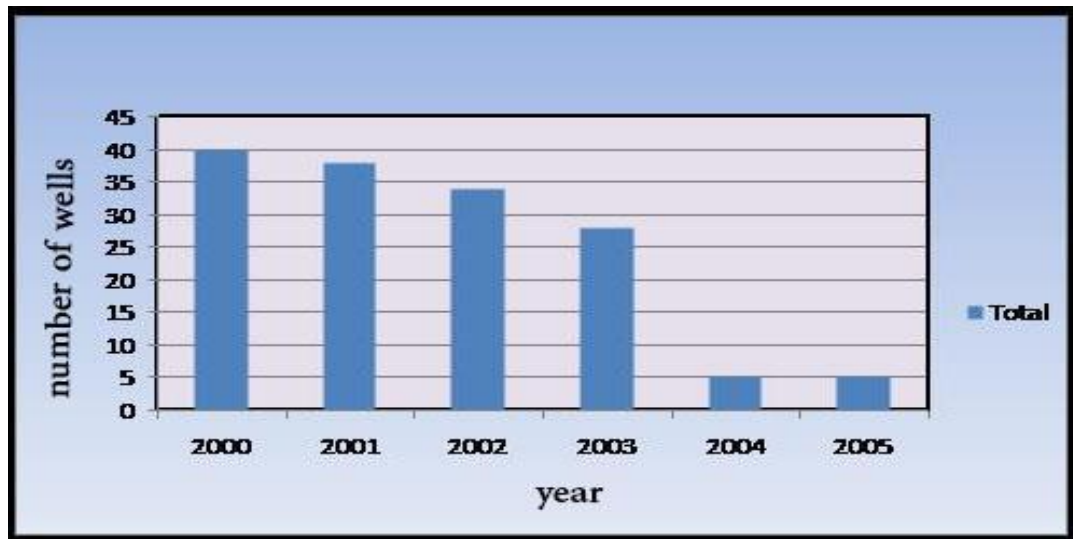


Figure 7: The total number of wells in Al Hayer Area

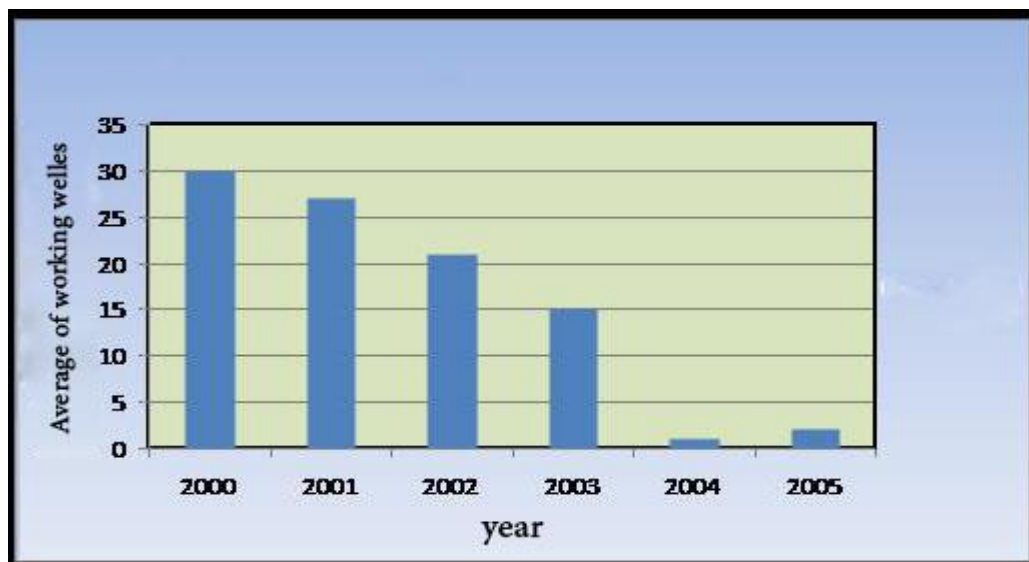


Figure 8: Total average number of working wells in Al Hayer area

The above two Figures related to the number of working wells could indicate that the quantity of groundwater in major aquifers reduced dramatically in the area. Groundwater in the study area has deteriorated over time. The sources of groundwater deterioration need to be investigated in detail. The potential contributions to the deterioration of groundwater quality are the natural climate conditions, which accompanies human activities.

### 1.10. Objectives

It found that the demand of water for domestic and irrigation purposes are growing very fast and is causing over pumping of the water resources in different regions such as Mekelle region in northern Ethiopia (Abreha, 2014). Also, study showed that the results of several isotopic and age dating used tools in to reveal the origin of recharge water in Souss–Massa region of western Morocco (Baouchaou et al., 2007). Moreover, the suitability of water for irrigation is determined based on SAR,  $\text{Na}^+$  percentage and salinity

hazard. In addition to water quality, other factors like soil type, crop type, crop pattern, frequency and recharge (rainfall), climate, etc. have an important role to play in determining the suitability of water (Sadashivaiah, et al. 2008).

The main objective of this study is to characterize the chemical quality of groundwater of Al Hayer area, north of Al Ain area, UAE. Periodic assessment for groundwater resources is essential in arid regions such as United Arab Emirates (UAE). Assessment of groundwater resources will help planners and decision makers to properly measure and take actions towards the deterioration of resources (Buytaert et al., 2012). Chemical analysis accompanied with stable isotopes measurements for oxygen and hydrogen will be used to meet the objectives of this study.

Groundwater characterization can be achieved through the following sub-objectives of the study:

- 1) Identifying the factors affecting groundwater quality using field and chemical analyses for collected groundwater samples. In addition to that, stable isotopes of oxygen and hydrogen will be used as supplemental tools to determine factors affecting the quality of groundwater such as evaporation, seawater intrusion, mixing process ...etc.
- 2) Determining the recharge mechanisms in the study area using stable isotopes of oxygen and hydrogen. Understanding the behaviour of major ions in regional groundwater with the chemical measurements of the collected groundwater samples.

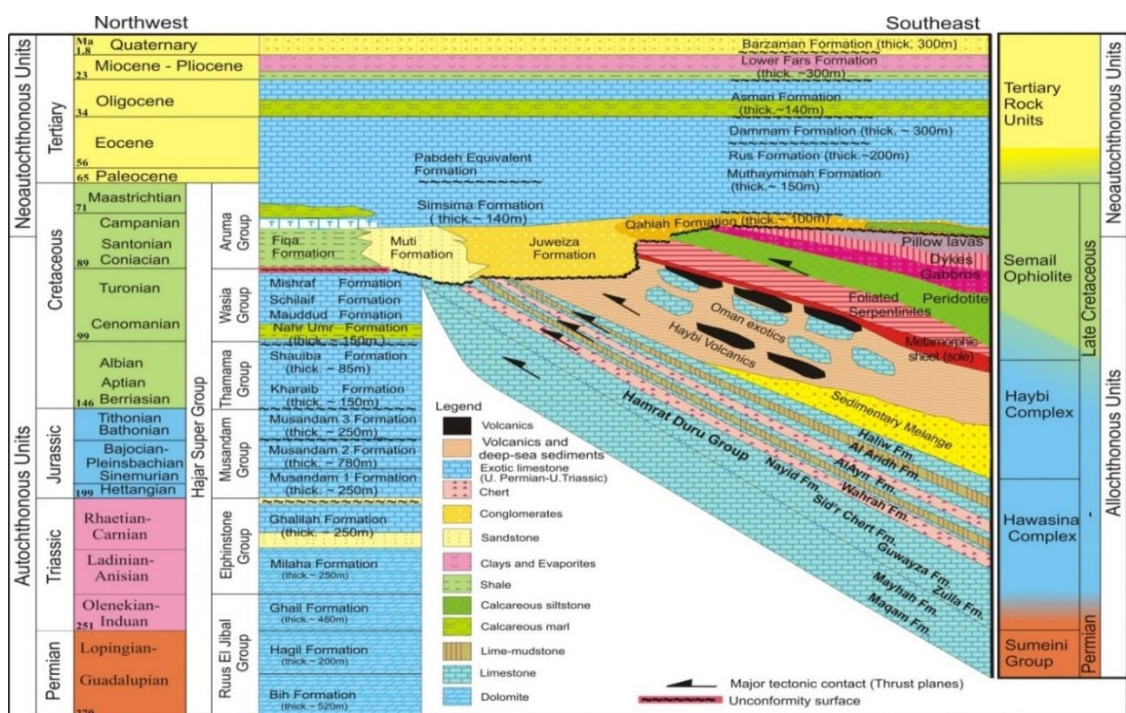
- 3) This objective can be achieved through combinations of chemical analyses for collected groundwater. Chemical ratios between different elements will be also constructed in order to understand the behaviour of groundwater constitutes and how it interacts with aquifer materials and other sources of water.

Groundwater deterioration could be affected by natural and anthropogenic sources of groundwater. One of the major natural sources of deteriorating groundwater quality is evaporation and evapotranspiration. Other natural factors, which might be affecting the quality of groundwater, are the lithological constitutes, such as the presence of salty layers, gypsum, and halite layers.

## Chapter 2: Geology and Hydrogeology

### 2.1. Geology

Large areas of the UAE are covered by Quaternary sediments, while older bedrocks mainly outcrop in the Hajar Mountains and Musandam Peninsula in the eastern UAE. The geology of the UAE comprises six major components (Abdelghany, 2006) as shown in Figure 9, including: i) The Late Cretaceous of Oman-UAE Ophiolite, ii) The Middle Permian to Upper Cretaceous carbonate platform sequence exposed in the northern part of the UAE (Hajar Super Group), iii) A deformed sequence of limestone, and deep-water sediments with minor volcanic rocks of the Dibba and Hatta Zones, iv) Poly-deformed sequence of metamorphic rocks in Masafi-Isma and Bani Hamid areas, v) A younger Late Cretaceous to Paleogene covers sequence in the western edge of the Hajar Mountains, and vi) The Quaternary aeolian, fluvial and marine deposits.



Lithostratigraphic chart of the Northern Emirates (modified from Abdelghany, 2006).

Figure 9: The lithostratigraphic chart of the northern emirates

Al Hayer area is located northeast of Al-Ain city and southwest of Dubai city, along the highway between the two cities. The area of study lies at latitude  $24^{\circ}.35^{\circ}$  N and longitude  $55^{\circ}.45^{\circ}$  E and has an elevation of approximately 50 meter above sea level (see Figure 2). It is a desert area of sand dunes separated by lower lying interdune areas of gravel and sand flats with low dunes. Al Hayer district is a famous of agriculture, mostly private farms with high production rates and are sited between dune ridges. The geology of Al Hayer area is mainly Quaternary sediments. These sediments include aeolian sand, fluvial, alluvial fan and Wadi deposits (Fig. 2.2). The type and pattern of these deposits area vary according to the wind regime, local relief and sand supply (Embabi, 1992).

## **2.2. Aeolian Sand**

The Aeolian sands form dune ridges, which are composed of well-sorted and fine-grained sands. The low dunes are found between main dunes, flat and widespread and the height of these dunes is less than 10m. The alluvial fan deposits were covered most of the study area. The morphology and sedimentology of these deposits were changed as distance from the mountains front increased as illustrated in Figure 10 (Styles et al., 2006).

## **2.3. Alluvial Fan Deposits**

These deposits are dominated by ophiolitic materials and small quantities of limestone material exist which comes from the mountain front of the area. Towards the mountain front, the fan deposits are poorly sorted, very coarse to coarse-grained, cross bedded and imbricated conglomerates. The gravels comprise with fewer amounts of gabbros. Also, the alluvial fan gravel mixed deposits appeared in the interdunes areas (Styles et al., 2006).

The wadi deposits are mainly consist of poorly-sorted, mix of sand and gravel which come from bedrock and older alluvial and terrace deposits as illustrated in Figure 10.

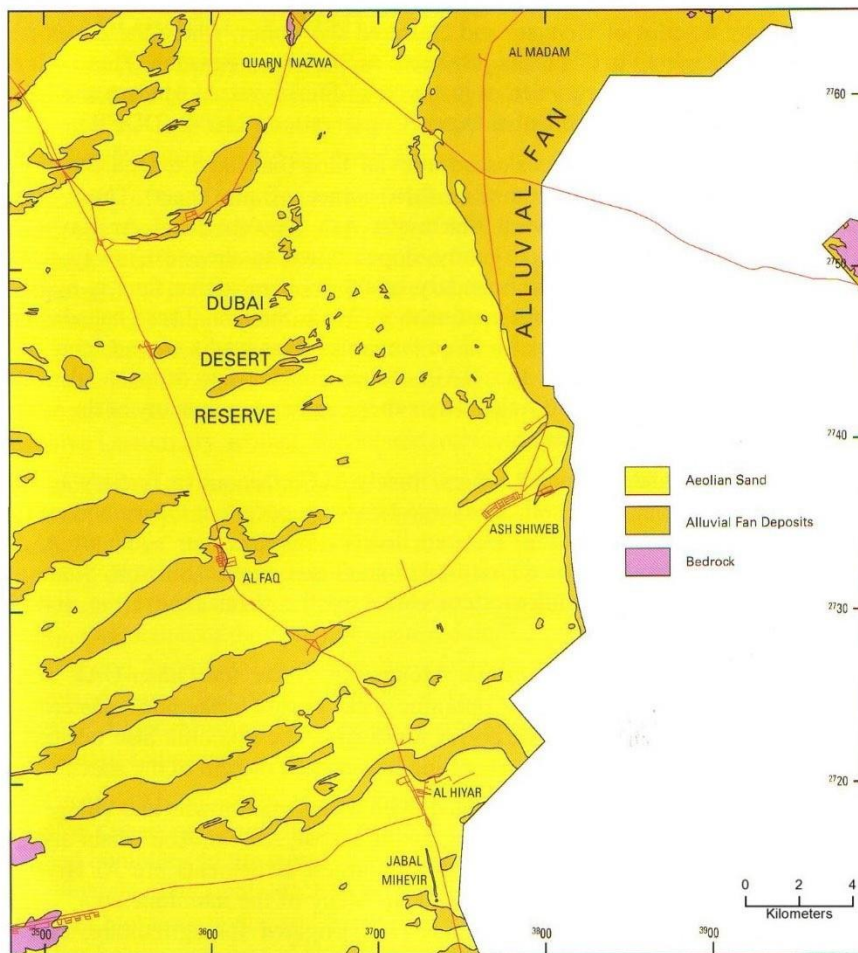


Figure 1. Simplified geological map of the Al Hiyar 1:100 000 sheet, showing the main roads and towns.

Figure 10: Geologic map of the study area

## 2.4. Hydrogeology

The Geology and geomorphology have been impacted the hydrogeology of the study area through the direct interaction between the water holding in the aquifer and the sediments of the aquifer. Al Hayer is characterised by harsh climate, which is introduced in detail in



chapter one, has significant influence on the hydrogeology and this affect is reflected in both the quantity and quality of the groundwater. The lack of sufficient amount of rainfall in the study area limited the surface water to the intense periods of rainfall which might happen every 10 years (Rizk & EI-Etr, 1997).

Agriculture activities are the main contributor to the problems of groundwater quality and quantity. Decreasing the irrigated areas of vegetables and feed mills in Al Hayer area from 826.75 hectares in 2001/2002 to about 197.6 hectares in 2005/2006 (see Table 1) is a clear indication for the reduction of the groundwater quantity. Because of low amount of rainfall, the recharge to major aquifers in the area is reduced with time due to imbalance between the recharge and discharge. The groundwater production in Al Hayer area is reduced from 1033.7 million gallons in year 2000 to 33.3 million gallons in 2005 as shown in Figure 11 (ADC, 2007).

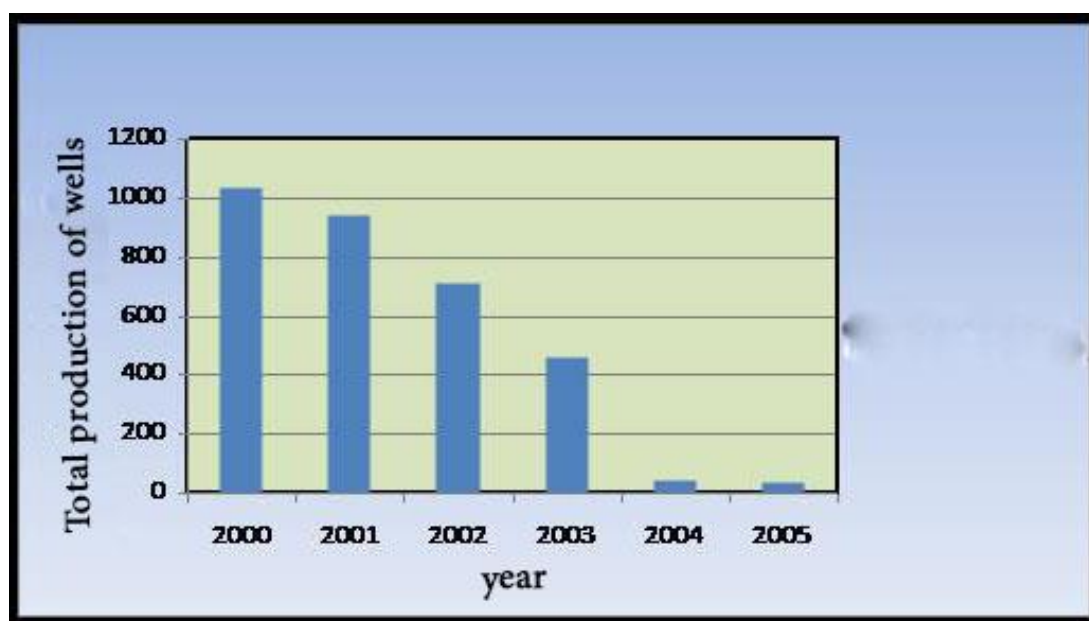


Figure 11: Total production of groundwater in Al Hayer area

As mentioned previously, the study area is located in the arid zone in which rainfall is irregular in space and time. About 80% of groundwater used in Abu Dhabi Emirate is mostly brackish and desalinated (ADWEA, 2005). There are four main aquifers existing in the UAE, including fractured ophiolite aquifer in the east, gravel plain aquifers, which flank the eastern mountain ranges on the east and west, sand dune aquifers in the south and west and limestone aquifer in the north and south east of UAE (Rizk & El-Etr, 1997, Alsharhan et al., 2003). The main aquifers units that exist in Al Hayer area are Quaternary sand and gravel aquifers underlain by mudstone and shale in the east. These aquifers underlain by the Upper Fares Formation as basal unit to the west of the Al Hayer as seen from the hydrogeological map of the study area as shown in Figure 12 (GTZ, 2005a).

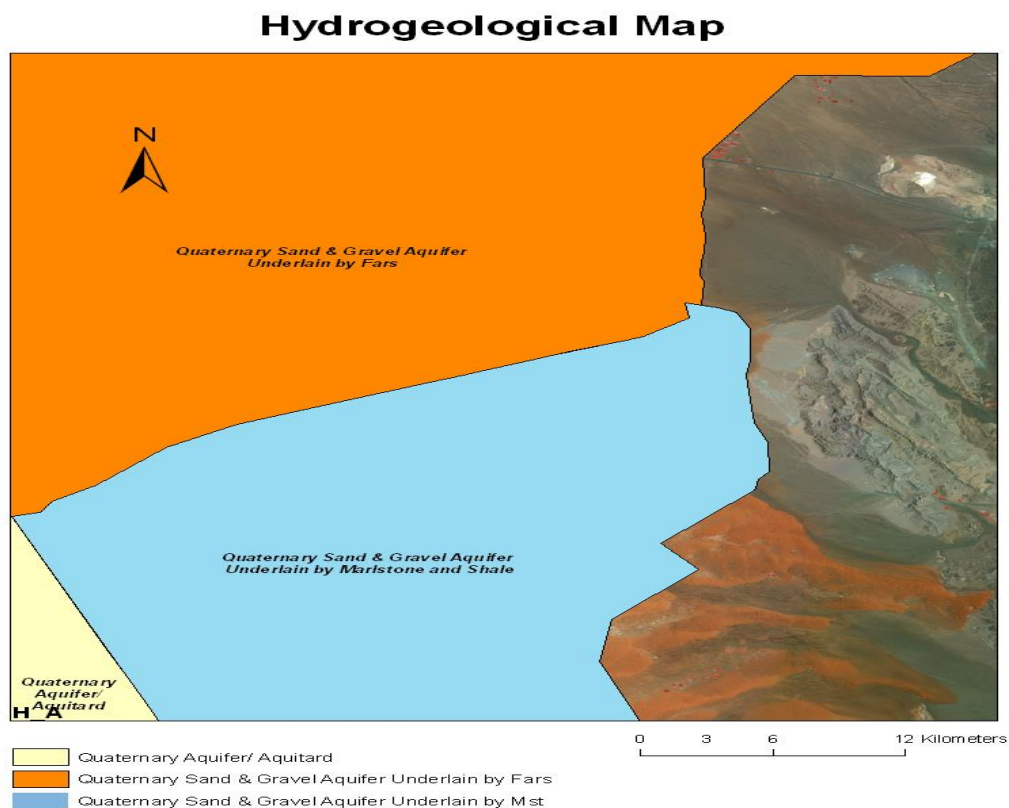


Figure 12: The hydrogeological map of Al Hayer area

Two wells were selected from the study area; one from the east (well #7472), and one from west side (well No. 7548) as designated by EAD (2007). The correlation of the two wells shows that the lithology of the first well is sandstone, gravel, limestone and marlstone. The total depth of this well is 27.43 meters, while the lithology of the second well shows that the lithology of sandstone, siltstone, marlstone, claystone, siltstone, marlstone, claystone and marlstone. The total depth of the second well is 206.2 meters as illustrated in Figure 13, as well as gives a picture of hydrogeological feature of the selected wells.

The water can be found at a depth between 14 and 60 meters below the sea level. The groundwater in Al Hayer area is moving from the east (Oman Mountains) to the west (NDC-USGS, 2005). The hydraulic properties of the aquifer in the study area are varying. The estimated transmissivity for most areas of the Quaternary aquifer of the study area is greater than 500  $m^2/day$ , while some areas to the west of Al Hayer area has a transmissivity in the range of 100 to 500  $m^2/day$ . The specific yield of the aquifer ranges from 140 to 2,349. However, the well specific capacity of the aquifer is varied from 29 to 37 ( $m^2/day$ ) (Bright & Silva, 1998).

Most of the quantities of groundwater abstraction in Al Hayer area are used for agricultural purposes. The estimated water used for agriculture in Al Ghammadh area, west of Al Hayer was 3.3 million  $m^3$  in 1987, and it increased to 4.2 million  $m^3$  in 1991 (NDC-USGS, 1992). The main source of recharge to the study area is the rainfall that occurred in the Oman Mountains, which is located to the east of the study area. In addition,

the infiltration of rainfall in interdunes areas and gravel plains could recharge the Quaternary aquifer of the study area.

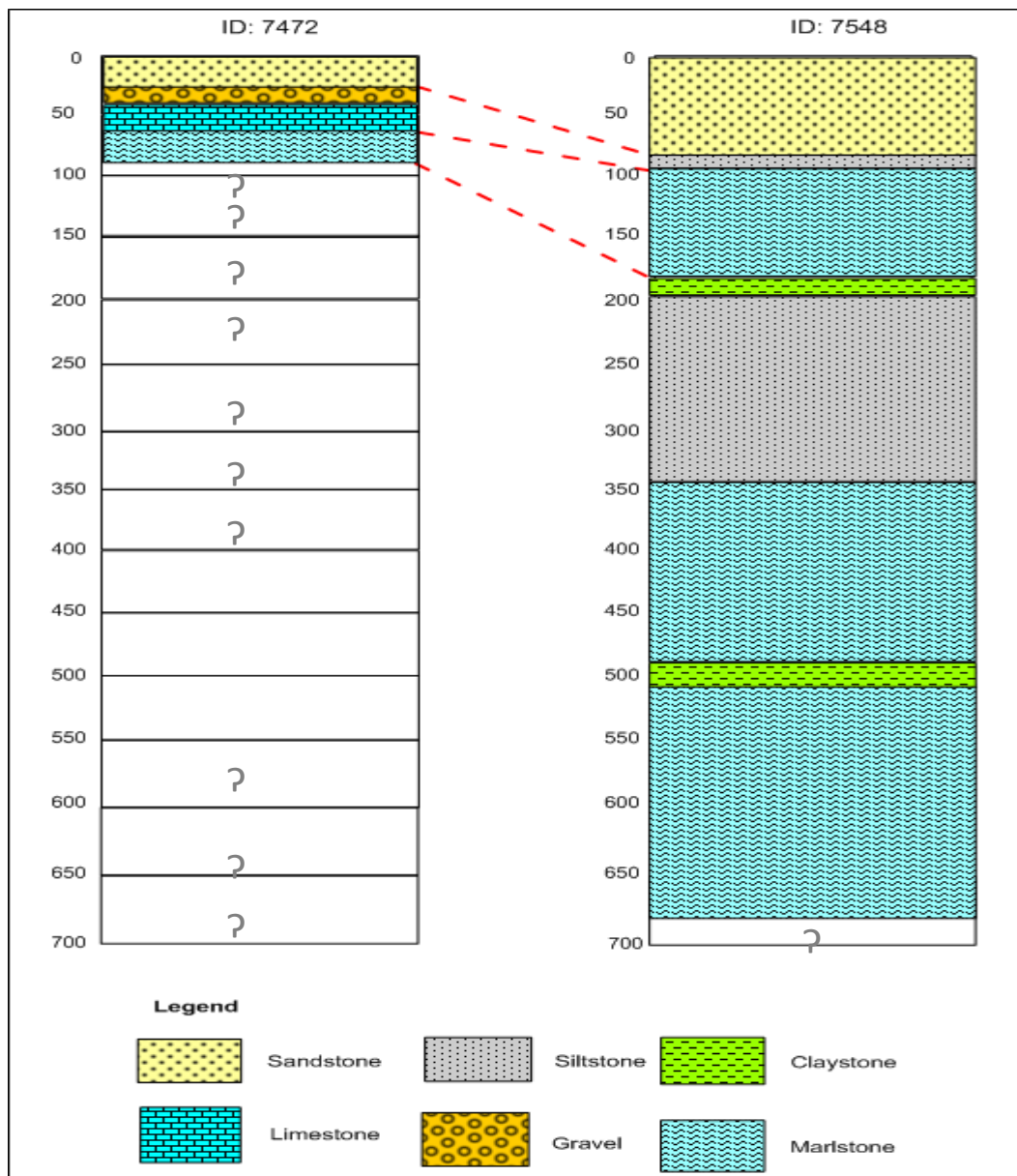


Figure 13: Correlation between well number (7472) and well number (7548) cross section

There are other sources of aquifer recharge in the study area. These sources include return flow, upward from deeper rocks and infiltration of water that lost from water transmission lines (Nuaimi, 2003). Groundwater pumping is considered the main mechanisms for groundwater discharge in the study area. Heavily irrigation practices used the groundwater of Al Hayer. The total depths of the wells in the study area ranged from 130 m to 550 m (ADC, 2007). It was observed that the groundwater pumping in the UAE rose in recent years (Robins et al., 2006). As a result, water levels in the study area were declined dramatically.

The depth to water levels in the study area has been increased from 22.26 m in 1978 to 36.60 in 2000 (ADC, 2007). However, the data obtained by (NDC, 2007) showed that the depth to the water table in Al Hayer area was 208.8 m above sea level in 1995 and it reached 203.1 m above sea level in 2007 as illustrated in Figure 14. The increasing the depth of water level is a clear indication of reducing the groundwater quantity in the aquifer.

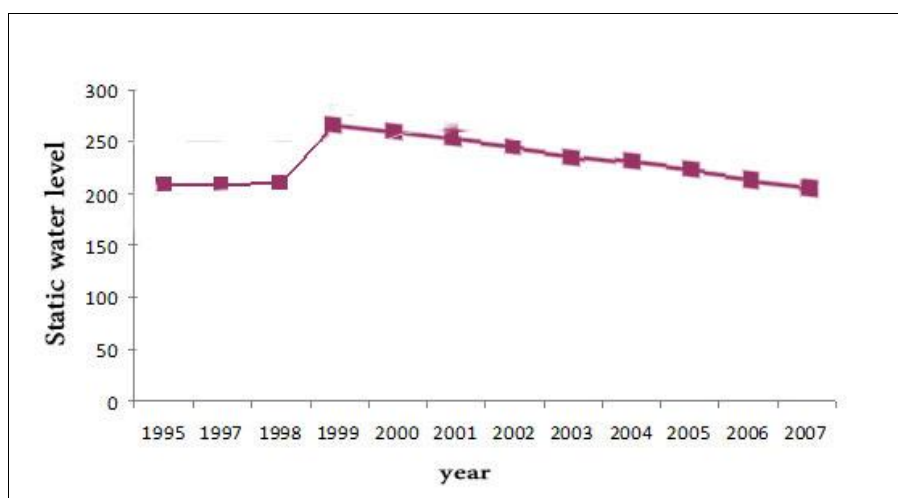


Figure 14: Static water level of Al Hayer area

## Chapter 3: Sampling and Material

### 3.1. Sampling

Thirty-seven groundwater samples were collected from different wells as shown in the study area as shown in Figure 15. As mentioned before, the purpose of the research is to study the chemistry of groundwater using major cations, anions, trace elements, and oxygen and hydrogen isotopes.

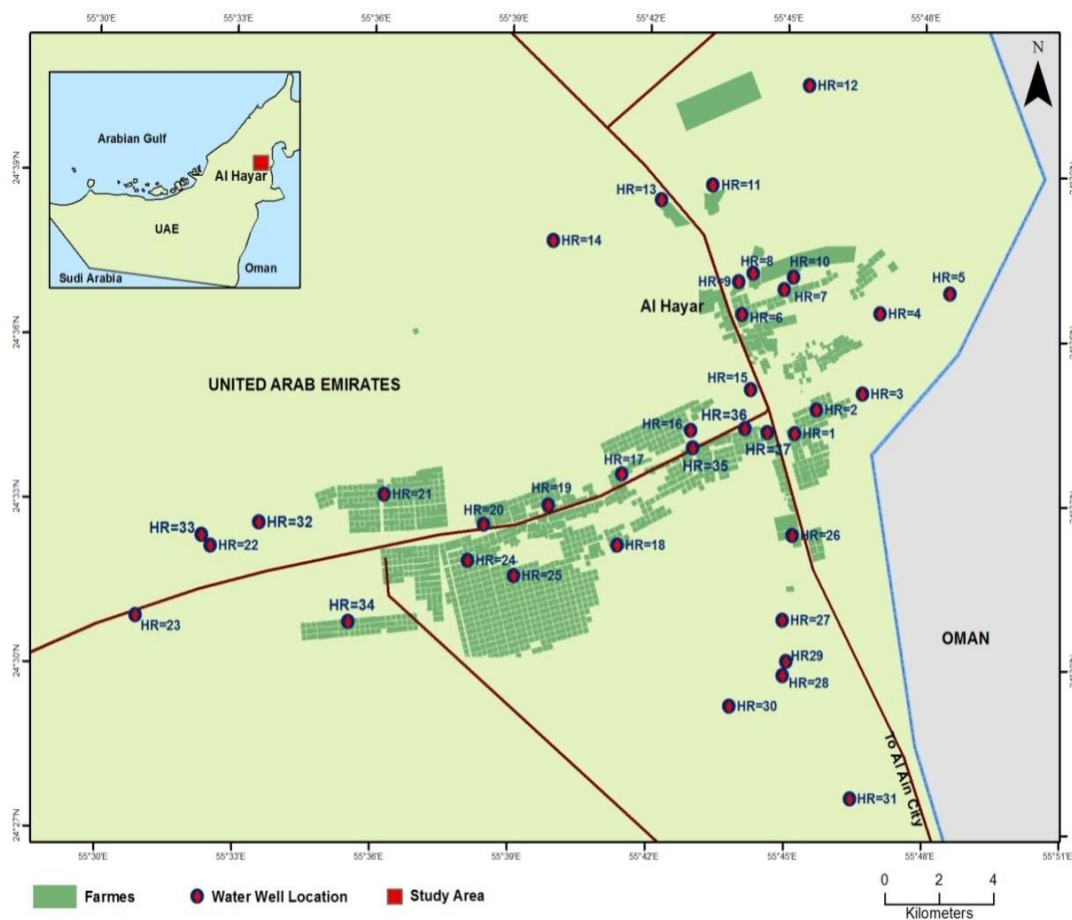


Figure 15: Map illustrates the location of groundwater samples

Three samples from each well were collected to meet the objectives of this study. For cations and anions analyses, one litre was collected from each, in contrast, for hydrogen and oxygen isotopes analysis, 25ml vial bottle of groundwater were collected as illustrated as flow chart in Figure 16. Samples for major cations analysis were acidified with nitric acid (HNO<sub>3</sub> 1%) to block oxidation reaction, stop bacterial growth, and to prevent absorption or precipitation of cations (Bassuony, 2014). Before groundwater sampling, the pump is turned on to improve sampling by removing the stagnant water, which caused because of previous sampling and pumping.

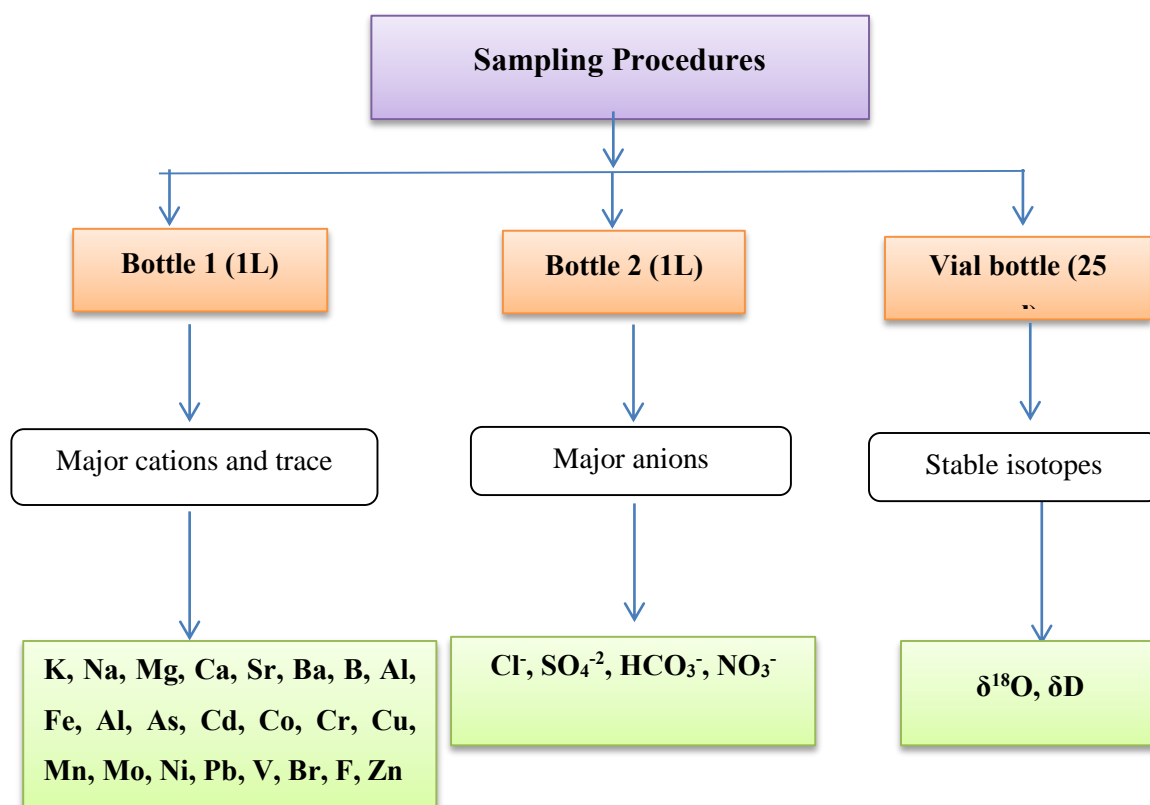


Figure 16: Sketch showing the sampling procedure

### 3.2. Field Measurements of Groundwater Samples

The samples subject to different field measurements, such as salinity, pH, electrical conductivity (EC), temperature and total dissolved solids (TDS), using Hana instrument 9828, which shown in Figure 17. Global positional system (GPS) was used to determine the locations and sampling points.

### 3.3. Laboratory Measurements

Trace elements, anions and cations were found after analysing groundwater samples. Ion chromatography (IC) (Dionex ICS-2000) was used to detect anions including  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ , and  $\text{Cl}^-$ . Anions analysis was performed at the chemistry and geology laboratories at UAE University by using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Trade name: Varian 715-ES) as shown in Figure 17. The interesting cations including  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$ , along with such trace elements as  $\text{Pb}^{3+}$ ,  $\text{Ba}^-$ ,  $\text{Cr}^{3+}$ ,  $\text{Cd}^{2+}$ ,  $\text{Mn}^{2+}$ ,  $\text{F}^-$ ,  $\text{Fe}^{3+}$ ,  $\text{Sr}^{3+}$ ,  $\text{Ni}^{2+}$ ,  $\text{Al}^{3+}$ ,  $\text{Co}^{3+}$ ,  $\text{As}^{3+}$ ,  $\text{Cu}^{2+}$ ,  $\text{Mo}^{3+}$ ,  $\text{V}^{3+}$ ,  $\text{Zn}^{2+}$  and  $\text{Br}^-$ .

All glassware used for measurements were cleaned, rinsed with water, 1% nitric acid and deionized water prior to next use quality control purposes. Samples with high dissolved solids are diluted to ensure correct results. These samples have different viscosities than the standards. Proper care is taken in the preparation and storage to avoid contamination (EMSL, Method 2007).





Hanna Instrument (9828)?



Ion Chromatography (Dionex ICS-2000)?



Figure 17: Instruments used for chemical analysis

### 3.5. Stable Hydrogen and Oxygen Isotopes

Thirty-seven groundwater samples were collected for hydrogen and oxygen isotopes analyses. About 25 ml of water samples were stored in sealed airtight glass bottles. The analysis of stable oxygen and hydrogen isotope was performed by the isotope laboratory at the Water Resources and Hydrology, Hohai University, Nanjing, China.

The Picarro, L2120-i spectrometer was used with analytical precision of 1‰ for  $\delta^2\text{H}$  and 0.1‰ for  $\delta^{18}\text{O}$ . Calibration and elimination of memory effect was made using a standard solution. Laser Evaporation-Based Mass Spectrometry was used to analyze the collected samples. After the analysis of the collected samples, the data was reported in the usual  $\delta$  notation with respect to the Vienna Standard Mean Ocean Water (VSMOW).

## Chapter 4: Results and Discussion

### 4.1. Physical Parameters

The physical parameters, which influence the nature of water and its usage were measured and included:

- a) Hydrogen ion concentration (pH).
- b) Total dissolved solids (TDS).
- c) Electrical conductivity (EC).

These parameters may change with time and therefore straightforwardly measured in the field. Below is detailed description of each parameter.

#### 4.1.1. Temperature

The temperature of the collected groundwater samples in the study area varied between 30°C to 40°C, with an average of 33.7°C. The variations of samples in temperatures, as shown in Figure 18, are relatively relative for most samples among the study zone. The highest temperature was in well No.27, which may be related to low amount of recharge.

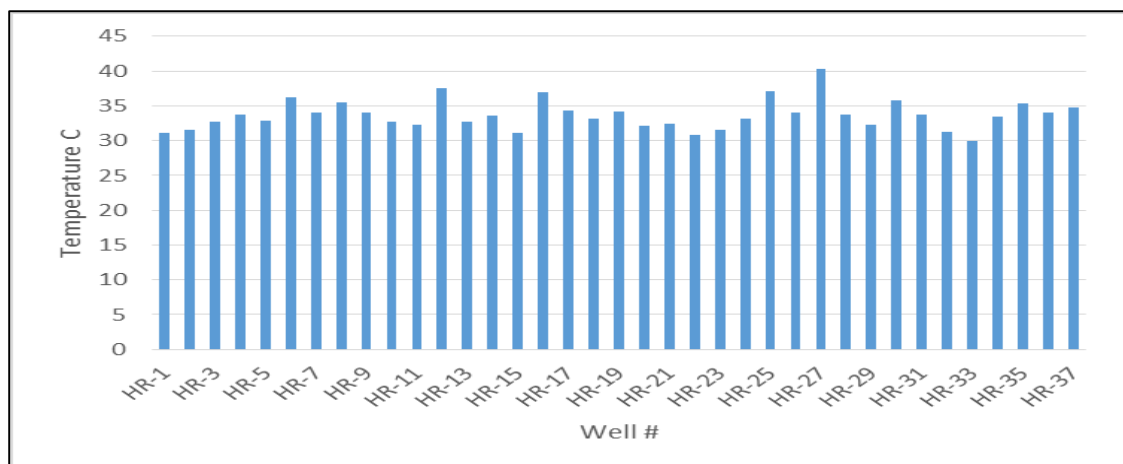


Figure 18: Temperature values of groundwater samples from the study area

#### 4.1.2. Hydrogen ions concentration (pH)

The measurement of the groundwater acidity is used to determine the pH value. The lower the value of pH, the more acidic is the water. The pH is really an estimation of the hydrogen ion ( $H^+$ ) (Galib & Hanna, 2011). The collected groundwater samples were examined to check the pH values in the study zone. The pH values fluctuated from 7.5 to 8.3 with an average of 8. This value meets the WHO pH range from 6.5 to 8.5 (WHO, 2011). The collected groundwater samples of the studied area are mostly alkaline (above 7) as illustrated in Figure 19 and Figure 20.

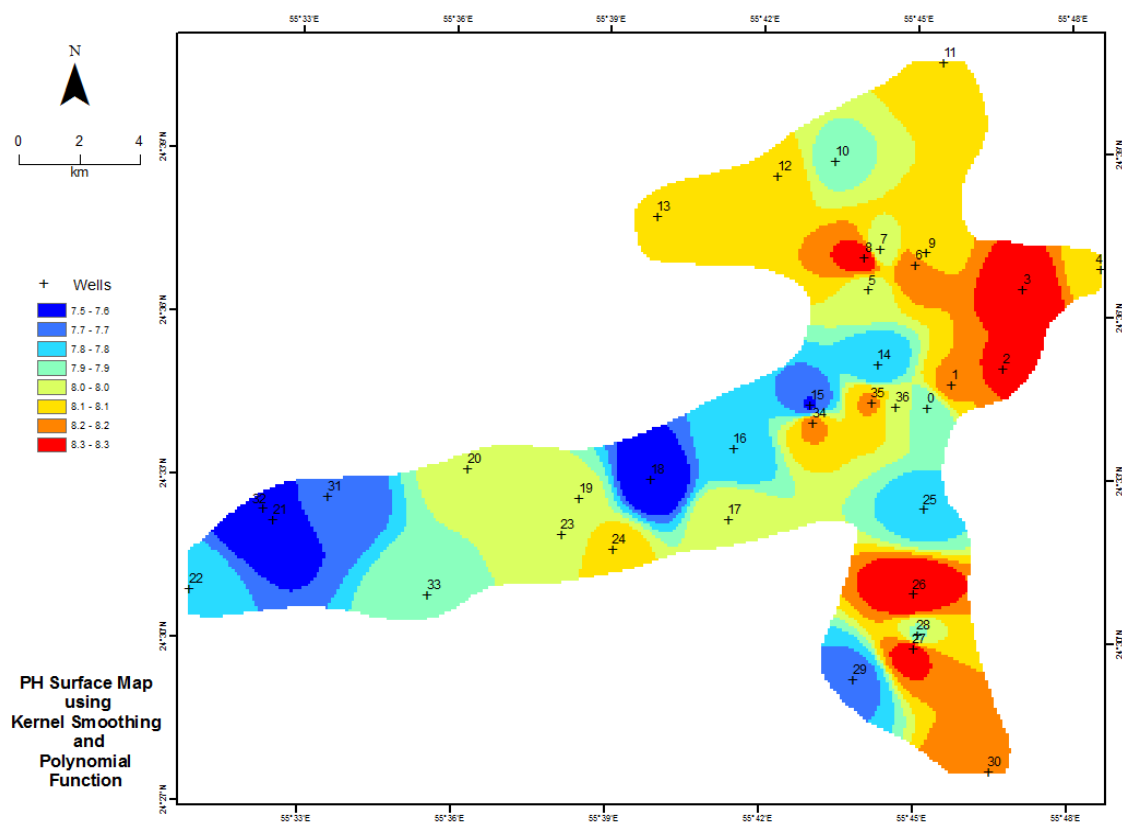


Figure 19: Distribution of pH values in groundwater samples of study area

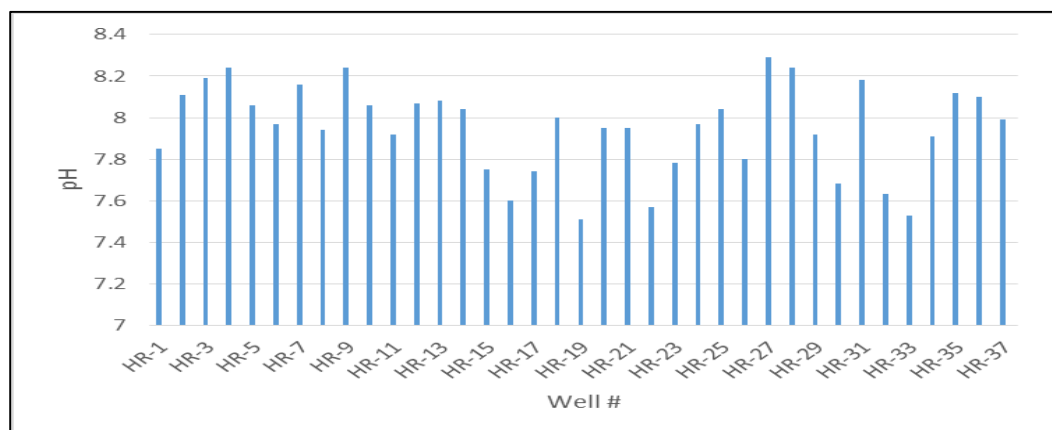


Figure 20: pH values of groundwater samples from the study area

#### 4.1.3. Electrical conductivity (EC)

The Electrical Conductivity (EC) of groundwater is a measure of its saltiness and it is utilized as a parameter for the characterization of drinking. The EC values of the collected groundwater samples extended between 600 $\mu$ S/cm of well No.3, and 13200  $\mu$ S/cm of well No.33. The variations of EC in the study area were critical. In this extraordinary condition, substantial pumping of the aquifer prompts migration of the saline water because of upcoming from the profound aquifer, bringing in high EC. In addition, the higher values were recognized and noted along the western parts of the study area, as shown Figure 21, which might be ascribed to the horticultural exercises and the serious employments of composts. For example, dairy cattle fertilizer and Urea that will prompt increase EC.

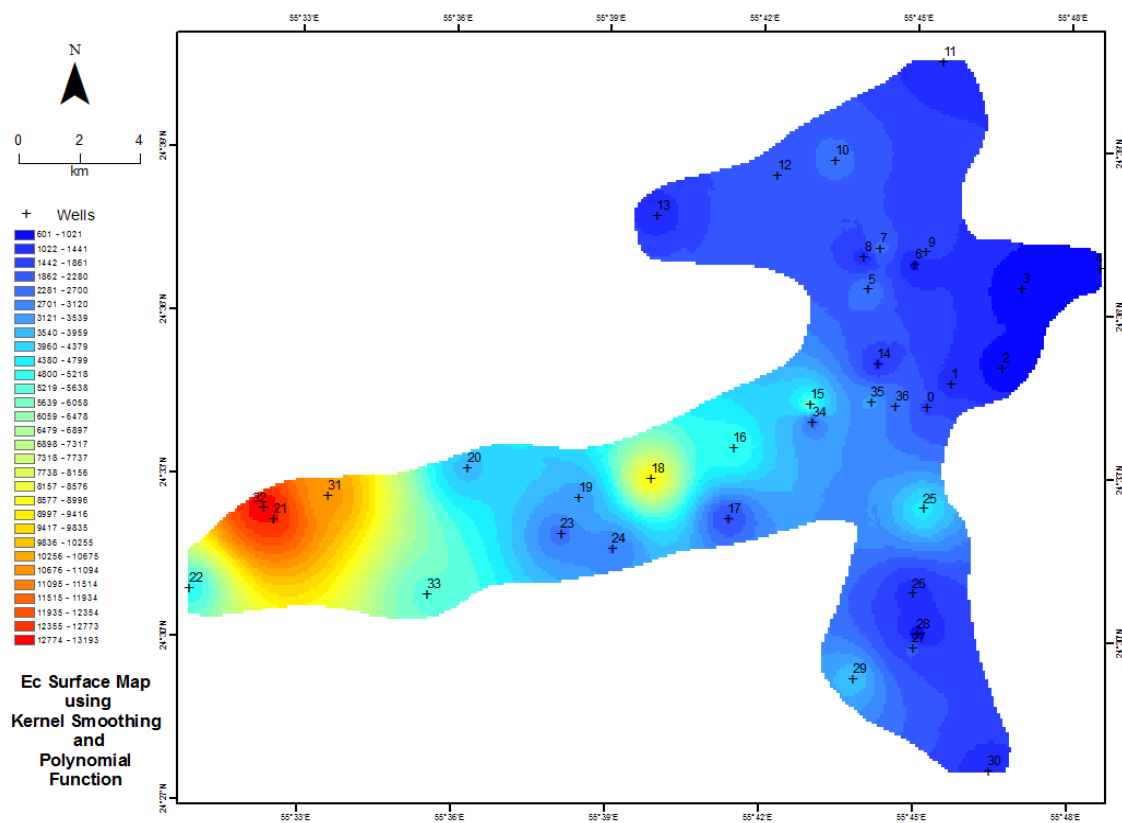


Figure 21: Distribution of EC values in groundwater samples of study area

#### 4.1.4. Total dissolved solids (TDS)

TDS refers to the total concentration of all dissolved solid chemicals in the water. Standards determine a maximum of 500 to 1000 (mg/l) of TDS for drinking water; and up to 2000 (mg/l) of TDS for watering domesticated animals (Kendall et al., 1999). The recorded values of the TDS in the study area were between 317 mg/l to 7544 mg/l as shown in Figure 22. Measurements found that concentrations of TDS increased in the western region of the study area. Under the WHO (2011) standard, about (11%) of the wells are suitable for drinking according to the chemical analysis while more biological tests must be done to make sure that it is acceptable from the biological overview. The

vast majority of them (62%) are slight to moderate for irrigation, while (27%) of the samples are in the "sever degree" category as shown in Table 3.

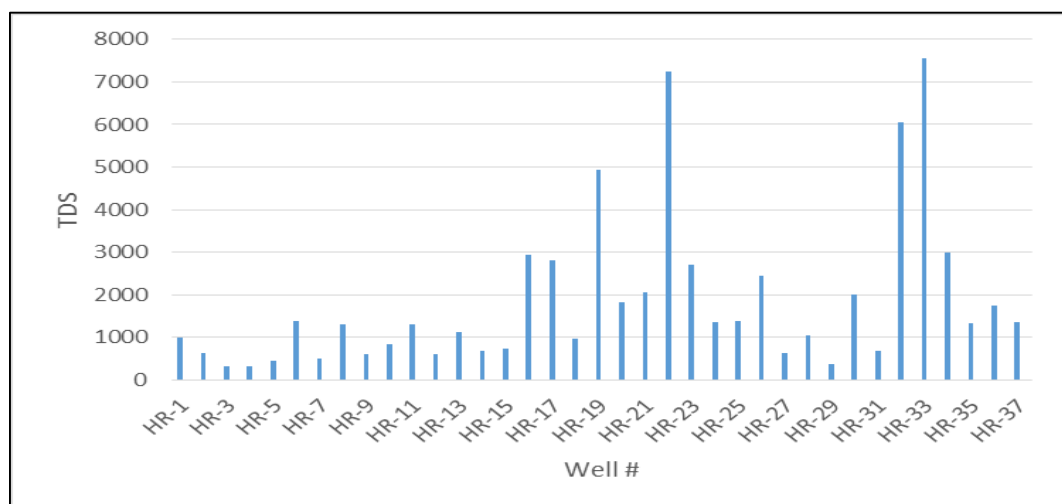


Figure 22: TDS values of Groundwater samples from the study area

WHO standard	Drinking water	Irrigation water		
	500	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
		<450	450- 2000	>2000
# of wells not meeting the WHO standard	4 (11%)	4 (11%)	23 (62%)	10 (27%)

Table 3: TDS in (mg/l) compared to WHO drinking & irrigation standards

Well No. 33 recorded the greatest value of TDS at (13200 mg/l), which may be attributed to its shallow depth (200 m), as the owner of the farm said. Under these circumstances, over-pumping the aquifer prompts movement of saline water that swells

up from the profound aquifer, prompting high level of TDS. Additionally, water interaction with rock and concentrated, dissolving constituents of return-flow may help to increase TDS in groundwater (Zhang et al., 2008).

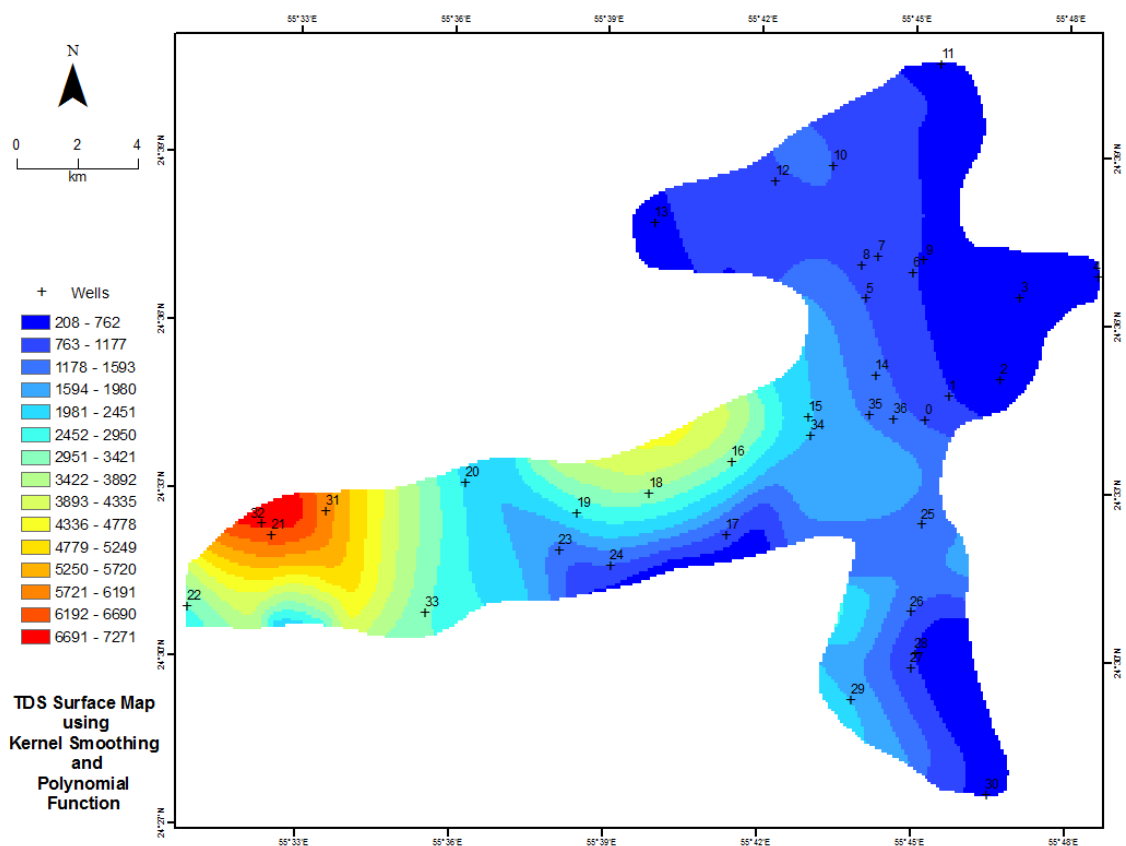


Figure 23: Distribution of TDS values in the study area, in mg/l

## 4.2. Chemical Properties

The chemical composition of groundwater is influenced by the type and the amount of soluble rock weathering and decomposition. The main elements measured in the analysed water quality are cations (including  $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ) and anions (including  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$  and  $\text{NO}_3^-$ ). Other trace elements were measured as well including Pb, Ba, Cr, Cd,



Co, Mn, F, Fe, Sr, Ni, As, Cu, Mo, V, Zn, Br, F and Al. The results of all these chemical elements analysed in the study area for the groundwater samples are presented in the Appendix.

#### 4.2.1. Major cations

The order of most significant to least significant cations found in the study area is  $\text{Na}^+$  (60%) >  $\text{Mg}^{++}$ , (21%) >  $\text{Ca}^{++}$  (17%) >  $\text{K}^+$  (2%), (Figure 4.5). The following discussion shows a complete comparison between groundwater samples with WHO (2011) benchmarks of each component.

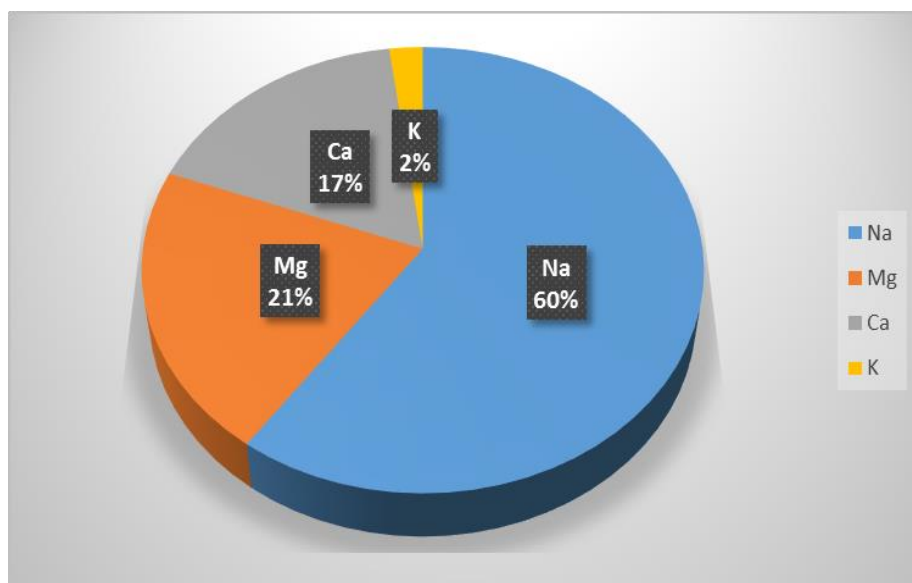


Figure 24: Abundance distribution of major cations (%) in the study area

#### 4.2.2. Sodium ( $\text{Na}^+$ )

Sodium is chemical element, which dissolves easily in water. It is normally found in groundwater, and it has no scent, yet can be tasted by many people at concentrations of

200 (mg/l) or more. High  $\text{Na}^+$  concentrations in groundwater can be observed usually in a few regions. An increase in  $\text{Na}^+$  in groundwater above characteristic levels may indicate the contamination from some source of salt water intrusion (Curriero, 2007). On the other hand, Davis (1966) expressed that the most widely recognized sources of elevated sodium levels in groundwater are from **i)** plagioclase feldspars mineral erosion, **ii)** Argillaceous sediments, **iii)** evaporation of water, **iv)** watering system and draining of precipitation through high soils in sodium, **v)** groundwater contamination by sewage effluent, and **vi)** leaks from landfills or industrial areas.

The  $\text{Na}^+$  ion concentration of groundwater samples extended from 42 mg/l in well No.7 to 2080 mg/l in the well, No.24 with an average of 372.5 mg/l. The distribution of  $\text{Na}^+$  concentrations of groundwater samples in the study zone is shown in both Figure 25 and Figure 26. It was observed that the concentrations of  $\text{Na}^+$  increased toward the west of the study area. The general patterns of the  $\text{Na}^+$  qualities remain practically steady over the distance within the study area. They were within the limit of WHO drinking water standards (WHO 2011 are 200 mg/l). However, wells No. 22, 32, 33, which lie in the west and centre of the study area, have a high concentration. Higher  $\text{Na}^+$  in groundwater correlate with silicate weathering (Singh & Hasnain, 1999), or from disintegration of clay, gravel, (Srinivasamoorthy et al., 2014).

The high concentration values observed within the cultivated areas supports the theory that irrigation water is one of the leading causes of elevated sodium in groundwater. The  $\text{Na}^+$  concentrations of around 30% of water samples is very acceptable may be

accredited to groundwater recharge events from different catchments of Oman's mountains (rainfall/recharge) and to the dilution by infiltrated water (Sherif et al., 2012).

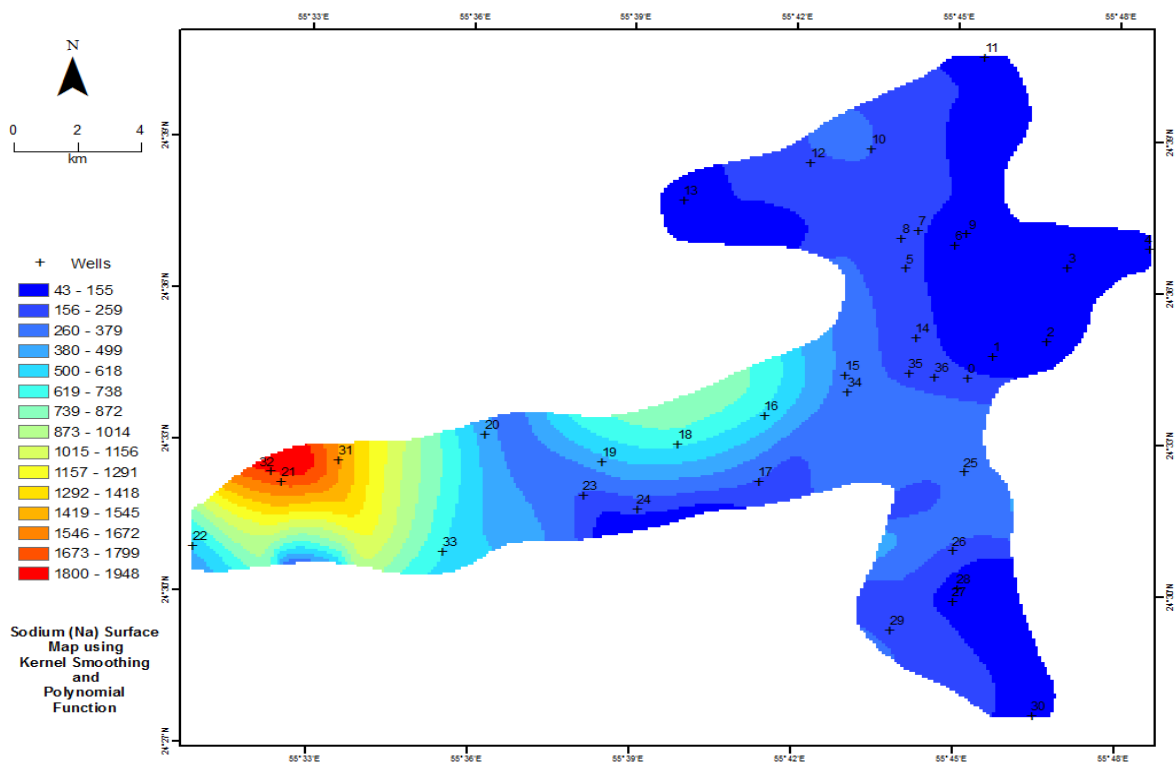


Figure 25: Distribution of Na<sup>+</sup> concentration of groundwater samples in the study area

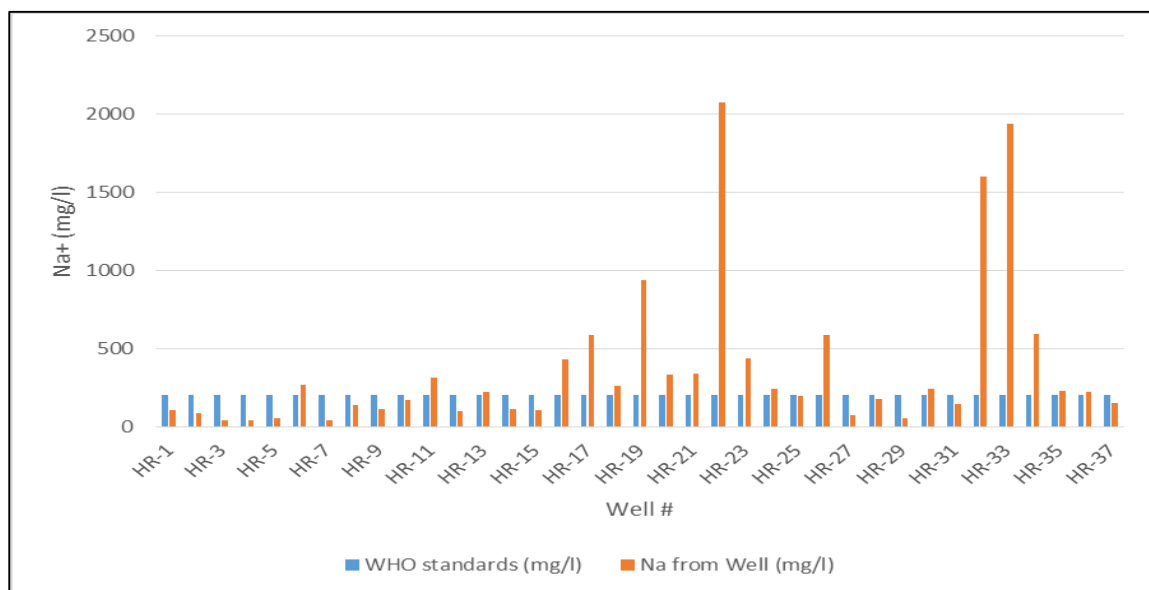


Figure 26: Na<sup>+</sup> Concentration in groundwater samples compared to WHO standard

#### 4.2.3. Magnesium (Mg<sup>2+</sup>)

The common sources of magnesium in the hydrosphere are dolomite in sedimentary rocks, olivine, biotite, hornblende, and augite in igneous rocks, and serpentine, talc, diopside, and tremolite in metamorphic rocks. The Ca<sup>2+</sup> and Mg<sup>2+</sup> ions are more or less comparative condition of balance in most groundwater. In any case, Mg<sup>2+</sup> ion in water influences the soil by making it basic and resulting in diminished the harvest yield (Kumar et al., 2007).

Mg<sup>2+</sup> concentrations in the study area were steady on average with only a few spikes in data. Nonetheless, well No. 19 had the highest concentration of Mg<sup>2+</sup> due to a slight difference in the recharge rate, signifying erosion from the nearby mountainous area. Also, during infiltration or along the stream ways, groundwater may dissolve the CaCO<sub>3</sub>, and CaMg(CO<sub>3</sub>)<sub>2</sub> in the rocks thus increasing calcium and magnesium ions in

groundwater (Srinivasamoorthy et al., 2014) . According to WHO (2011), permissible limit (50 mg/l), around 60% of the water samples fell within the limit; whereas, wells No. 19 and 34 showed the greatest variation as shown in Figure 27.

The maximum acceptable value of magnesium in drinking water is 50 mg/l as set by WHO (2011) permissible limit. The high concentrations of magnesium cause a bad taste, and increases water hardness. The concentrations of  $Mg^{2+}$  were plotted as illustrated in Figure 28. The minimal value recorded in the well No.3 was 26 mg/l and the greatest value recorded in well No.19 was 457 mg/l. The average concentration of ( $Mg^{2+}$ ) was 130 mg/l.

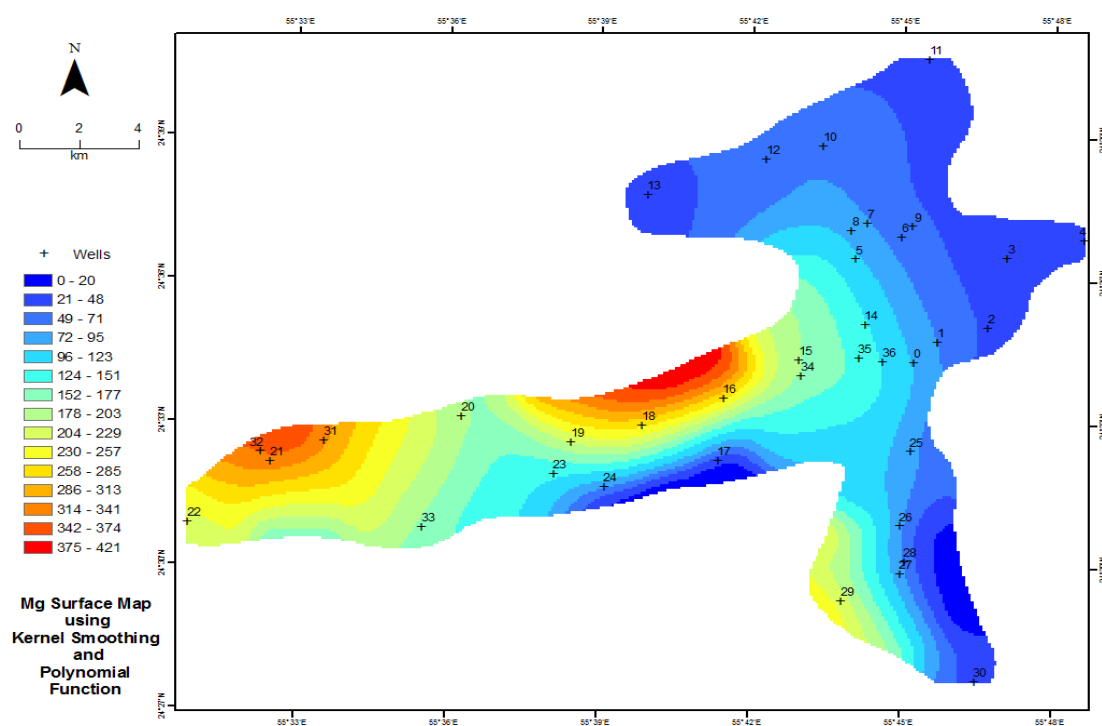


Figure 27:  $Mg^{2+}$  concentration in groundwater samples compared to WHO standard

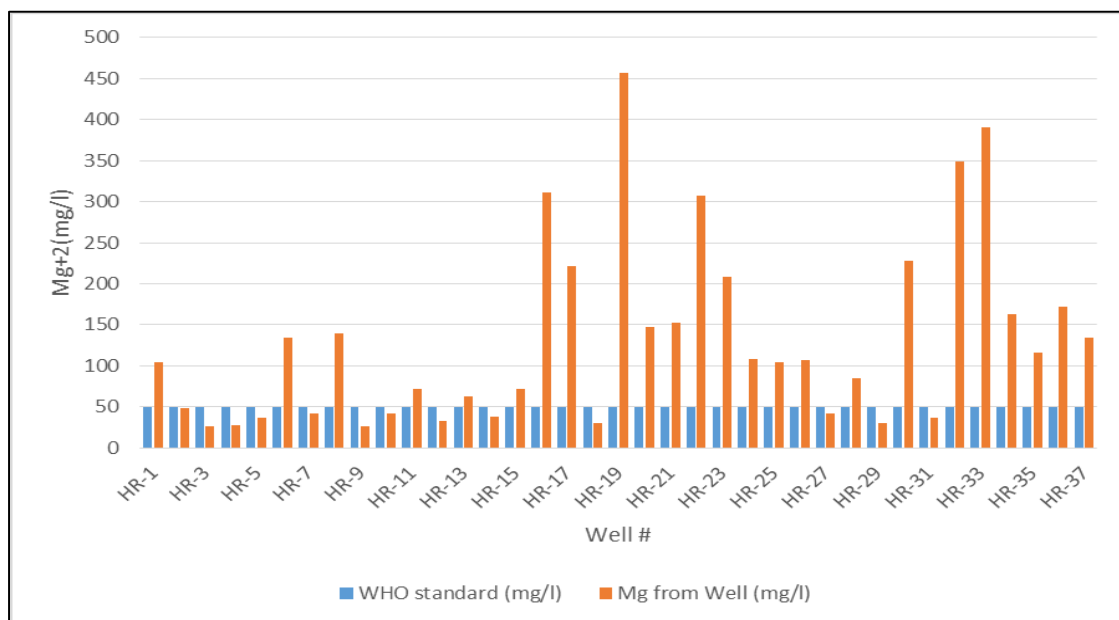


Figure 28: Distribution of Mg<sup>2+</sup> concentration of groundwater samples in the study area

#### 4.2.4. Calcium (Ca<sup>2+</sup>)

Carbonates are the most abundant form of Calcium in sedimentary rock, especially in limestone or dolomite, which dominates the study area. Ca<sup>2+</sup> occurs in the groundwater through carbonate dissolution (Hem & Geological, 1985). Likewise, calcium can be derive from the weathering of silicate minerals (Cartwright et al., 2004). In the study area, the minimum concentration of Ca<sup>2+</sup> was 20 mg/l in sample No. 4, while the highest concentration was 389 mg/l in well No. 19 and the average of Ca<sup>2+</sup> was 107 mg/l. Ca<sup>2+</sup> concentration stayed steady throughout the study region with a small increase to the west of the study area as shown in Figure 29.

This phenomenon may be related to the natural recharge, which dissolves  $\text{CaCO}_3$  and  $\text{CaMg}(\text{CO}_3)_2$ . This appears in limestone rock throughout the study area and increases the  $\text{Ca}^{++}$  in groundwater. Furthermore, intensive farming in this area may also impact  $\text{Ca}^{2+}$  dissolution in groundwater (Böhlke, 2002). Most of the wells in the study region are inside the WHO (2011) permissible limit for drinking water of 200 mg/l, as plotted in Figure 30.

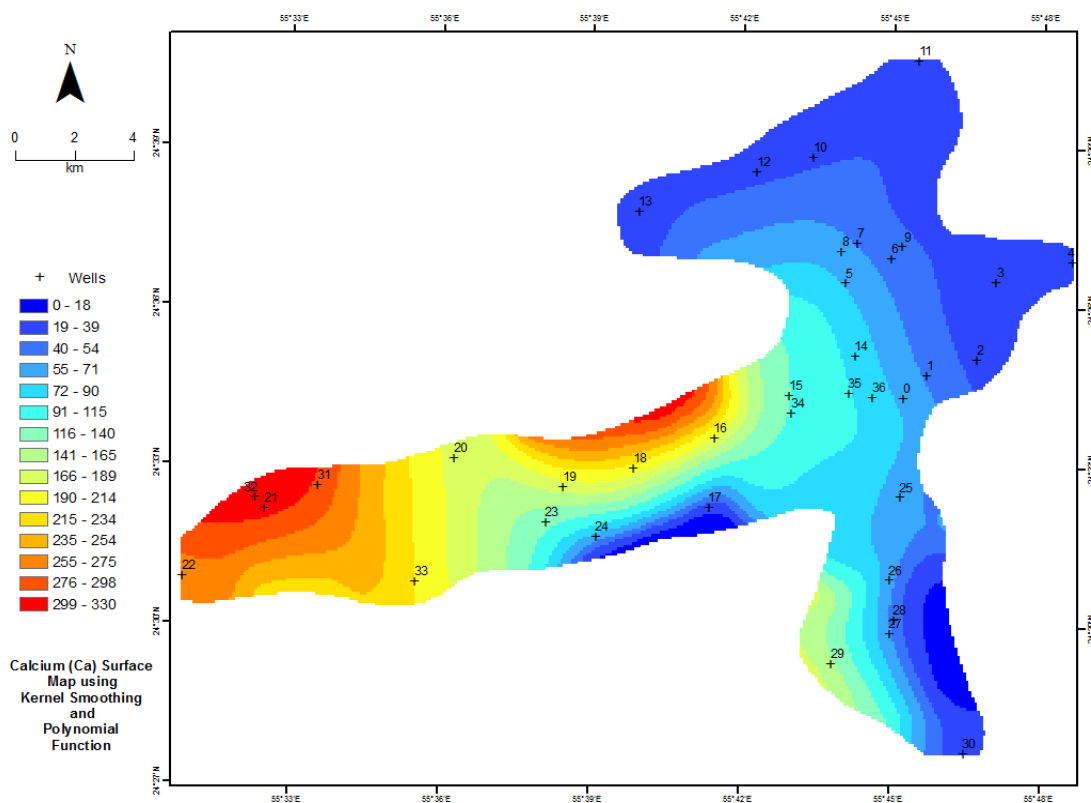


Figure 29: Distribution of  $\text{Ca}^{2+}$  concentrations in ground water of study area

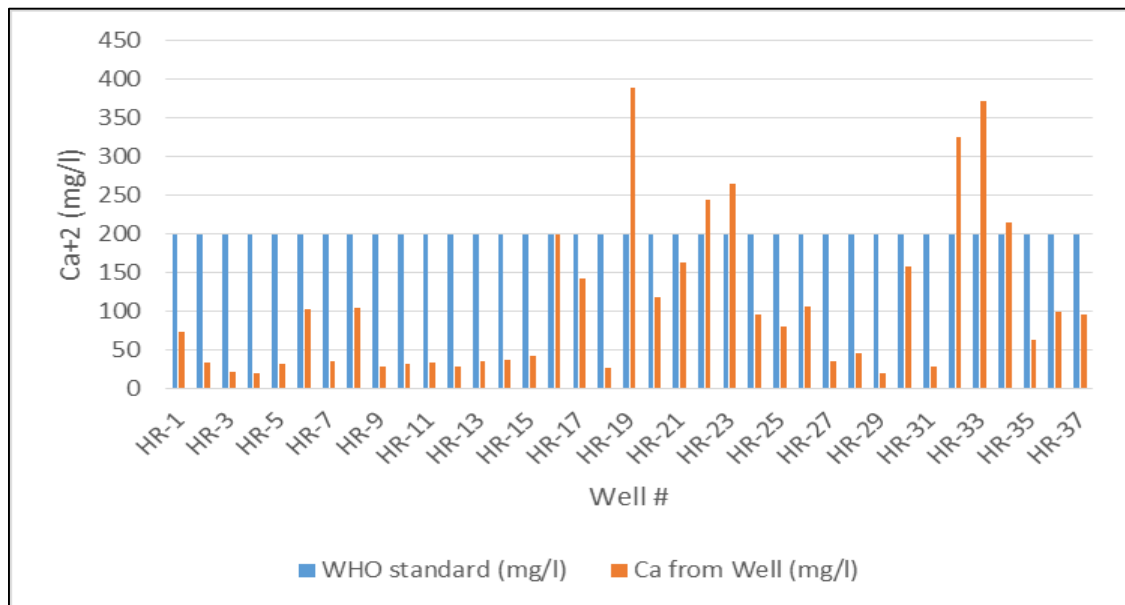


Figure 30:  $\text{Ca}^{2+}$  Concentration in groundwater samples compared to WHO standard

#### 4.2.5. Potassium ( $\text{K}^+$ )

Potassium ions ( $\text{K}^+$ ) often relate to  $\text{Na}^+$  ions in the groundwater; however,  $\text{K}^+$  normally has a much lower concentration compared with  $\text{Na}^+$ . The source of  $\text{K}^+$  ions in groundwater are dissolution of feldspars in igneous rocks, silicate, and clay minerals in sedimentary rocks, manufactured composts (Davis, 1966). The  $\text{K}^+$  concentrations ranged from 3 to 50 mg/l with an average of 13 mg/l. The maximum  $\text{K}^+$  concentrations were recognized in the west (Figure 31). Some sources of  $\text{K}^+$  in groundwater samples were likely from the weathering of feldspar and the utilization of synthetic fertilizers. The  $\text{K}^+$  concentration for the groundwater samples are within WHO (2011) standards (30 mg/l) as displayed in Figure 32. Lower  $\text{K}^+$  in groundwater is due to its greater resistance to weathering and fixation in the form of clay minerals found in the area's aquifers (Kolahchi & Jalali, 2007).



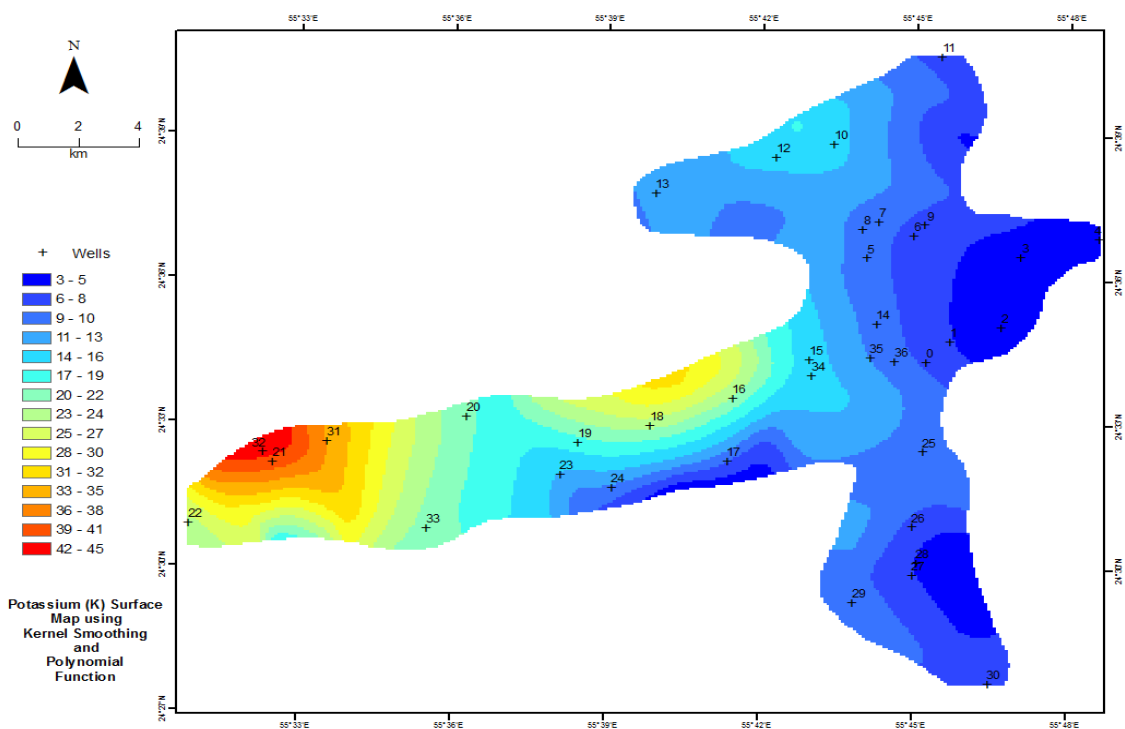


Figure 31: Distribution of K<sup>+</sup> concentration in groundwater samples of the study area

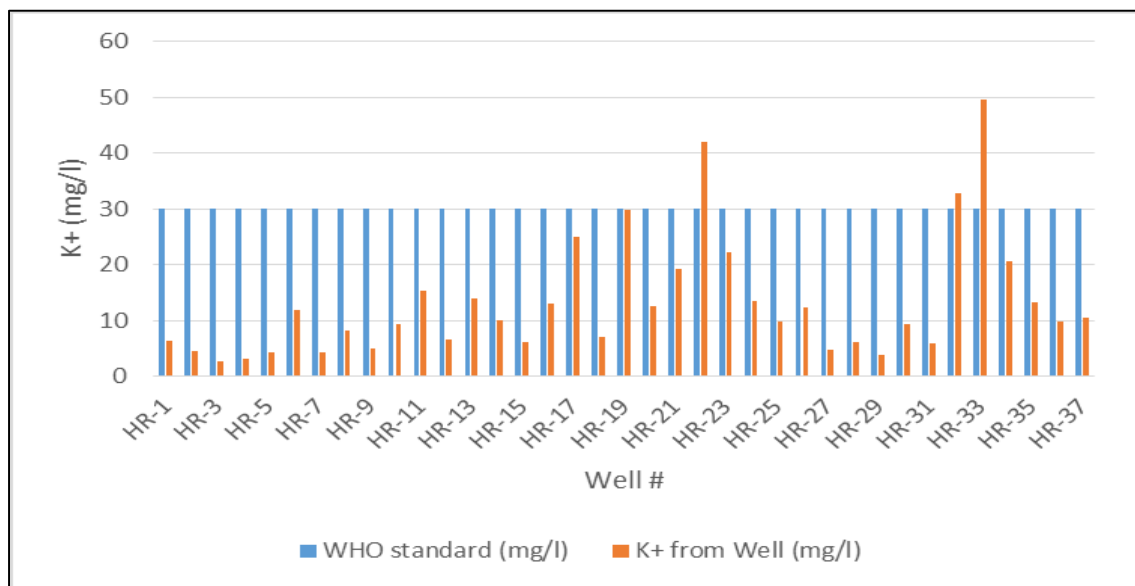


Figure 32: K<sup>+</sup> Concentration in groundwater samples compared to WHO standard

### 4.3. Major Anions

The order of major anions in the study area is illustrated as  $\text{Cl}^-$  (48%),  $\text{SO}_4^{2-}$  (23%);  $\text{HCO}_3^-$  (18%), and  $\text{NO}_3^-$  (11%) as illustrated in Figure 33.

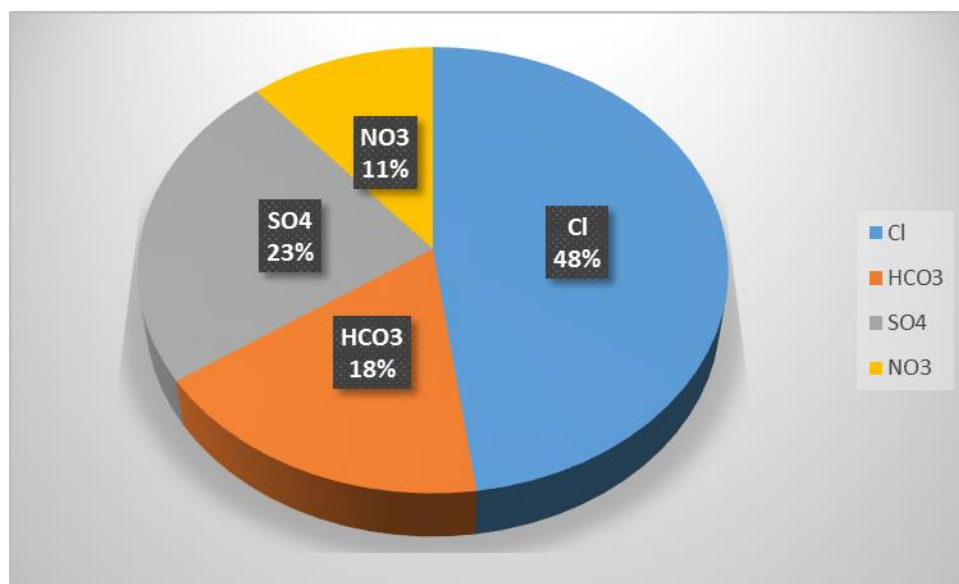


Figure 33: Distribution of major anions in groundwater of the study area

#### 4.3.1. Chloride (Cl<sup>-</sup>)

Rainwater, farming activities, sewage water pollutants, evaporation of return flow, and other human activities are the main sources of  $\text{Cl}^-$  ions in groundwater. The human activities that contribute to the presence of  $\text{Cl}^-$  ions include street salt, effluent from industrial facilities, leaching from municipal landfills and farming chemicals. In addition, sources include rock-water interaction, saline leakage, and minor climatic contributions (Srinivasamoorthy et al., 2014). The  $\text{Cl}^-$  concentration in the collected groundwater samples ranged from 54 mg/l to 3694 mg/l with an average of 678 mg/l as shown Figure

34, which obviously demonstrates that the distribution of  $\text{Cl}^-$  concentrations in the study region are relatively the same in a large portion of the wells.

The highest  $\text{Cl}^-$  concentrations were restricted to the west of the study region. The few spikes in  $\text{Cl}^-$  concentrations may be attributed to varying recharge events (Sherif et al., 2012).  $\text{Cl}^-$  concentration of 80% of groundwater samples are within the WHO (2011) standards (250-600 mg/l) (Figure 4.18). The maximum concentration of  $\text{Cl}^-$  was observed in well No.33 (3649 mg/l), which might be due to the introduction of deep saline water because of over pumping. Furthermore, the backflow from farming irrigation may also cause some presence of  $\text{Cl}^-$  ions, which can be ascribed to the utilization of gypsum manures (Vengosh et al., 2002).

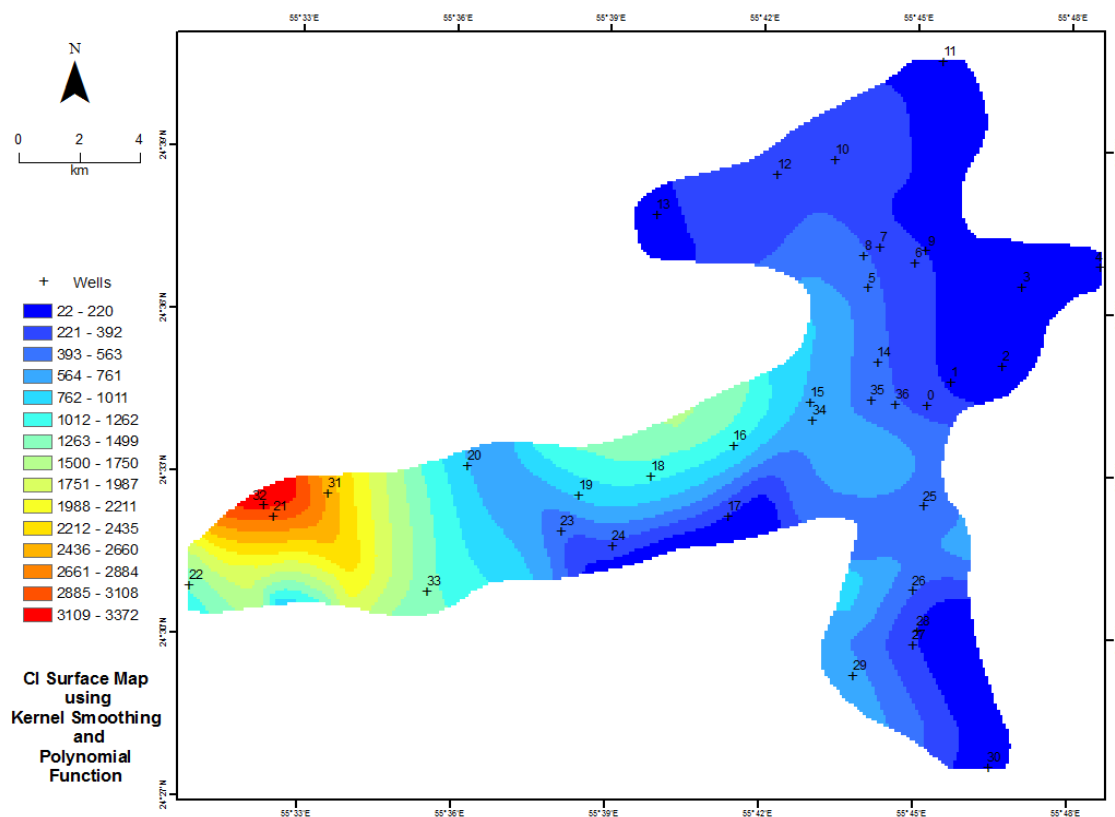


Figure 34: Distribution of  $\text{Cl}^-$  concentration in groundwater samples of the study area

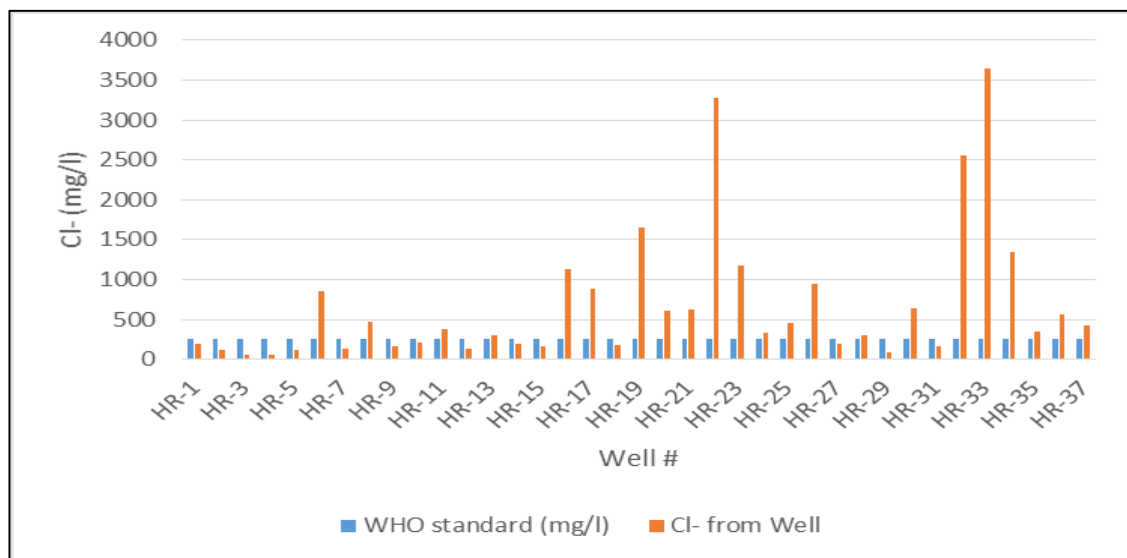


Figure 35: Cl<sup>-</sup> Concentration in groundwater samples compared to WHO standard

#### 4.3.3. Bicarbonate (HCO<sub>3</sub><sup>-</sup>)

HCO<sub>3</sub><sup>-</sup> ion is a plentiful anion in the groundwater. CO<sub>2</sub> in the atmosphere, in the soil, and those produced by weathering procedures of carbonate rocks are considered the main sources of bicarbonate in groundwater (Rao, 1998). Moreover, Lakshmanan et al. (2003) noted that the response of the feldspar minerals with carbonic corrosive in the presence of water (recharge occasions) increases HCO<sub>3</sub><sup>-</sup>. Thus, the HCO<sub>3</sub><sup>-</sup> concentration in the study area ranges from 183 mg/l to 427 mg/l with an average of 249 mg/l.

The increasing of HCO<sub>3</sub><sup>-</sup> concentration toward the north of the study area may be related to the disintegration of carbonate concentrations. This is a result of the study area close proximity to the Oman Mountains as shown in Figure 36. The HCO<sub>3</sub><sup>-</sup> concentrations contrasted with WHO standards (2011) (300 mg/l) as exhibited in Figure 37. The presented information showed that there is little variety between the majorities of the wells. The greater part of the groundwater samples fall within WHO limits.

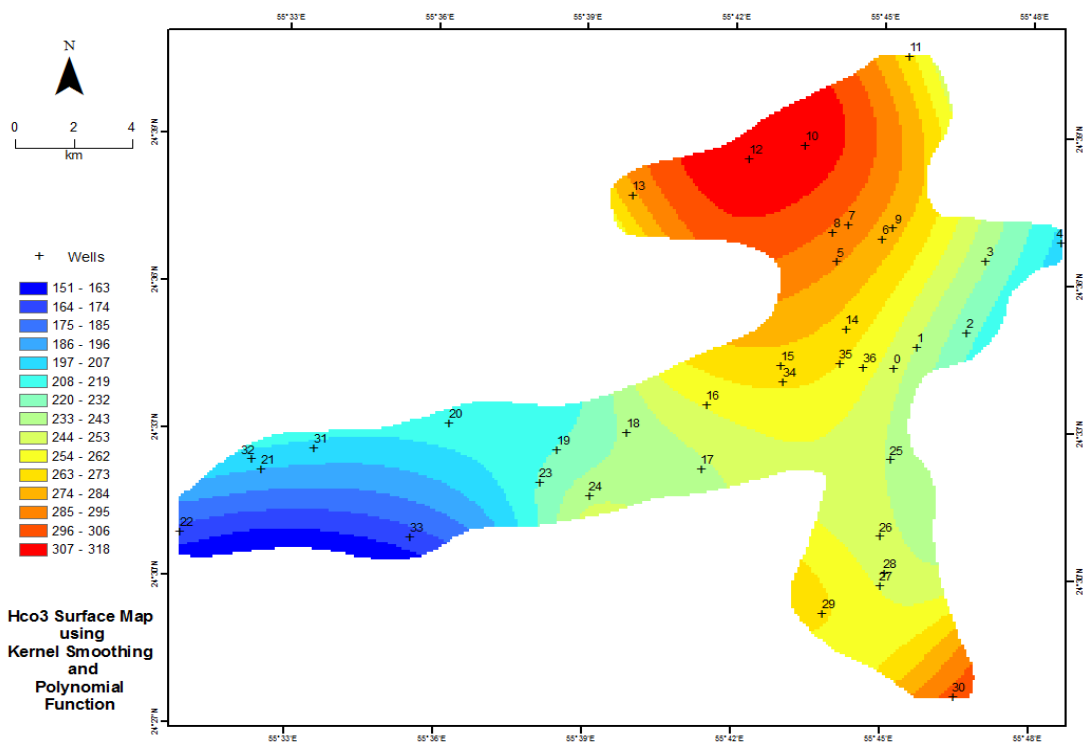


Figure 36: Distribution of HCO<sub>3</sub><sup>-</sup> concentration in groundwater samples of the study area

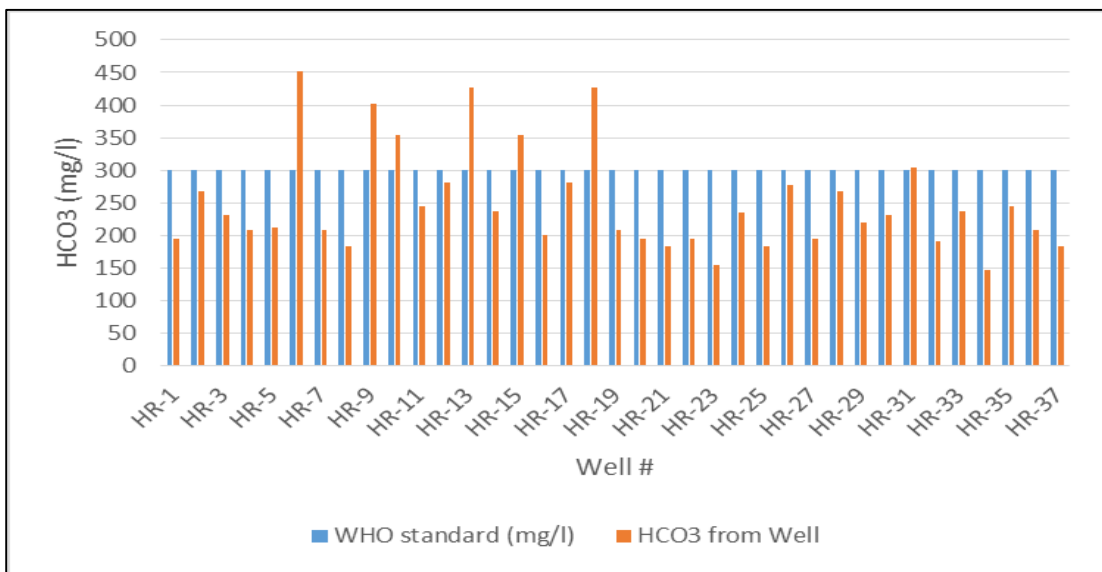


Figure 37: HCO<sub>3</sub><sup>-</sup> Concentration in groundwater compared to WHO standard

#### 4.3.4. Sulphate ( $\text{SO}_4^-$ )

The sources of metallic sulphate are volcanic rocks and sedimentary rocks (Sew, 1985). Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and anhydrite ( $\text{CaSO}_4$ ) are examples of sedimentary rocks, which provide groundwater with sulphate ( $\text{SO}_4^-$ ). When the sulphide minerals interact with water, it is oxidized and yields groundwater with sulphate concentration (Todd, 1980). The sulphate ( $\text{SO}_4^-$ ) concentrations in groundwater of the study area ranged from 38 mg/l to 1467 mg/l with an average of 323 mg/l.

The contour map as shown in Figure 38 demonstrates that the highest values of  $\text{SO}_4^-$  are towards the centre and the west of the study area. This increase may be caused by the disintegration of gypsum and anhydrite inside limestone. Also, it might be attributed to the dissolution of infiltrated waters, filtering from manures and agricultural wastes. Most the samples are relatively within the acceptable limits of the WHO standards (250mg/l) except wells No. 19, 22,30,32,33 as shown in Figure 39. This is could be related to escalated manure on these ranches, which prompts draining into the groundwater.

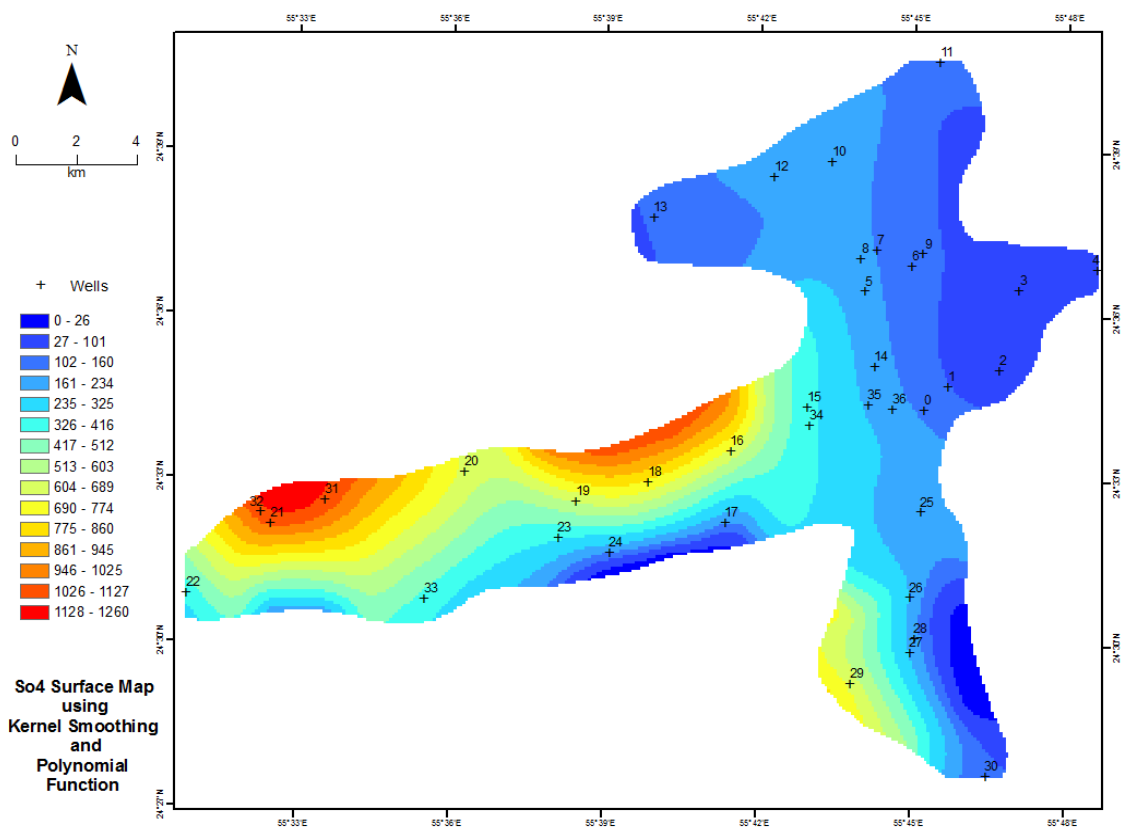


Figure 38: Distribution of SO4- concentration of groundwater samples in the study area

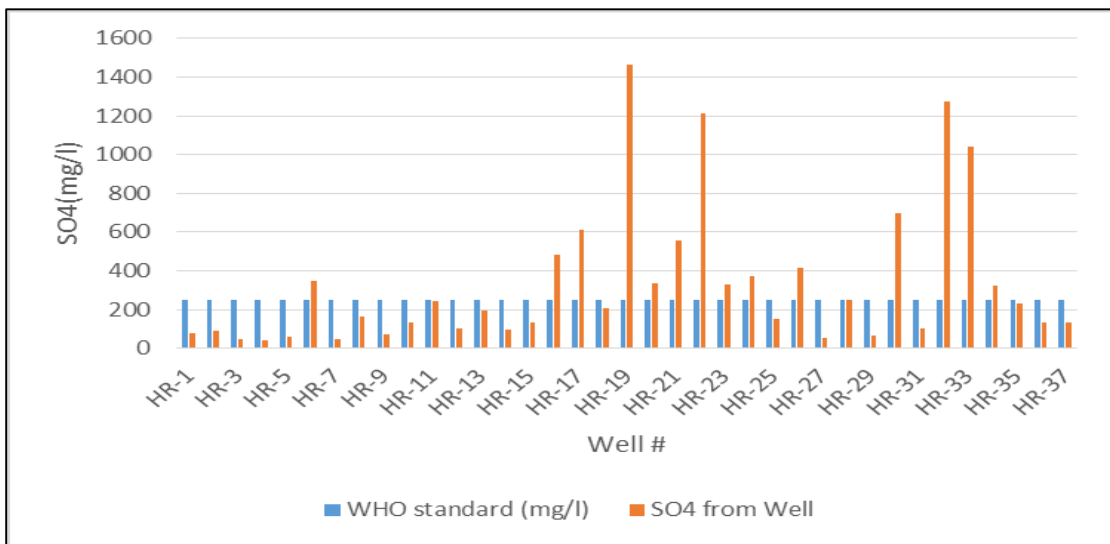


Figure 39: SO4- concentration of groundwater samples compared to WHO standard

#### 4.3.5. Nitrate ( $\text{NO}_3^-$ )

Nitrates ( $\text{NO}_3^-$ ) are found in the environment and are to be considered one of the most important plant nutrients. Animal manures, human wastes, composites, sewage sludge, vegetable yields, and green fertilizer crops are natural nitrogen by-product used in agriculture. The most recognized inorganic nitrogen composites contain  $\text{NO}_3^-$  and/or ammonium ( $\text{NH}_4$ ).  $\text{NO}_3^-$  in groundwater develop upon the use of draining, soil sort, and the measure of water in precipitation or watering system (Mahler et al., 1990). The  $\text{NO}_3^-$  concentration in the study area varied from nil in wells No 3, 4, 5, 10, 11, 13, 14, 26 to 568 mg/l in well No 6 with an average of 158 mg/l. The change in concentrations levels in the study area may be attributed to wrong farming practices.

In comparison to the WHO standard as introduced in Table 4 and Figure 40, as 43% of the collected groundwater samples are suitable for drinking purposes. It is seen that there are five classes of  $\text{NO}_3^-$  concentration, in the study area. Every class is determined whether it is safe for people or domesticated animals to use. The safe concentration of  $\text{NO}_3^-$  in drinking water begins from nil to 44mg/l if it exceeds 440mg/l then it cannot be used.



(NO <sub>3</sub> <sup>-</sup> ) mg/l	Guidelines	No of wells	%
0 to 44	Safe for humans and livestock	16	43
45 to 88	Generally safe for human adults and livestock .Do not use for human infants.	1	0.3
89 to 176	Short-term use of human adults acceptable. Short-term use for all livestock is acceptable unless feed sources are high in nitrate. Long-term use poses a risk.	9	24
177 to 440	Moderate to high risk for human adults. Moderate to high risk for mature livestock if the feed is low in nitrate. Do not use for human infants.	10	27
> 440	Do not use	1	3

Table 4: Drinking water standards with known NO<sub>3</sub><sup>-</sup> concentration in groundwater samples

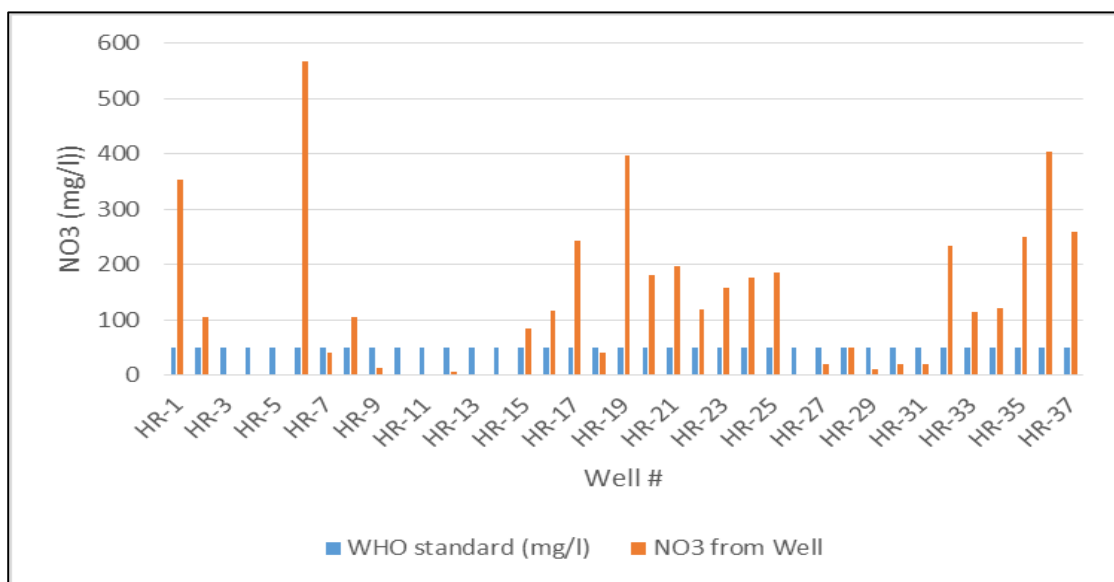


Figure 40: NO<sub>3</sub><sup>-</sup> concentration of in groundwater samples compared to WHO standard

#### 4.4. Ionic Ratio

To find out the impact of saline water and ion exchange upon the groundwater quality the ionic ratio is used. To see the contamination levels a minor ratio of  $\text{Na}^+/\text{Cl}^-$  to seawater value (0.88) shows us seawater intrusion or mixing with deep saline water (Martens et al., 2011). The estimations of  $\text{Na}^+/\text{Cl}^-$  vs  $\text{Cl}^-$  (meq/l) of 37 groundwater samples in the study area range from 0.29 to 1.4. According to Figure (4.22) which demonstrates that, only one sample is more than 1 when it comes to the ratio of  $\text{Na}^+/\text{Cl}^-$  versus  $\text{Cl}^-$ . Majority of the samples (90%) present a lower  $\text{Na}^+/\text{Cl}^-$  ratio versus  $\text{Cl}^-$ . This may be due to the strength of  $\text{Cl}^-$  concentrations, which exist in the groundwater as sodium chloride.

The  $\text{Na}^+$  concentration levels are more than the  $\text{Cl}^-$  concentration levels. This may be because of the cation exchange happening. The cation exchange happens when the profound saline water blends with freshwater from upper aquifer. Another possibility could be because of contamination by agricultural activities. These activities may include compost, human or creature squanders, and horticulture applications (Jones et al., 1999). The other helpful ionic proportion is  $\text{Cl}^-/\text{HCO}_3^-$  that used to study the seawater intrusion phenomenon and its impact on groundwater quality (Todd, 1980).

The samples, which are less than 0.5 represent 95% of the samples are unaffected by sea water intrusion, while those ranging from 0.5 to 1.6 are slightly and moderately affected as shown in Figure 41. Taking into account 37 groundwater samples of  $\text{Cl}^-/\text{HCO}_3^-$  proportions, just two samples of groundwater were unaffected. The seawater intrusion process has influenced most of the samples. Utilizing the proportion of  $\text{Ca}^{2+}/\text{Na}^+$  and  $\text{Cl}^-$

$\text{HCO}_3^-$  vs. TDS to assess the impact of saline water blending with new water and the impact of cation exchange forms (Al Farrah et al., 2011).

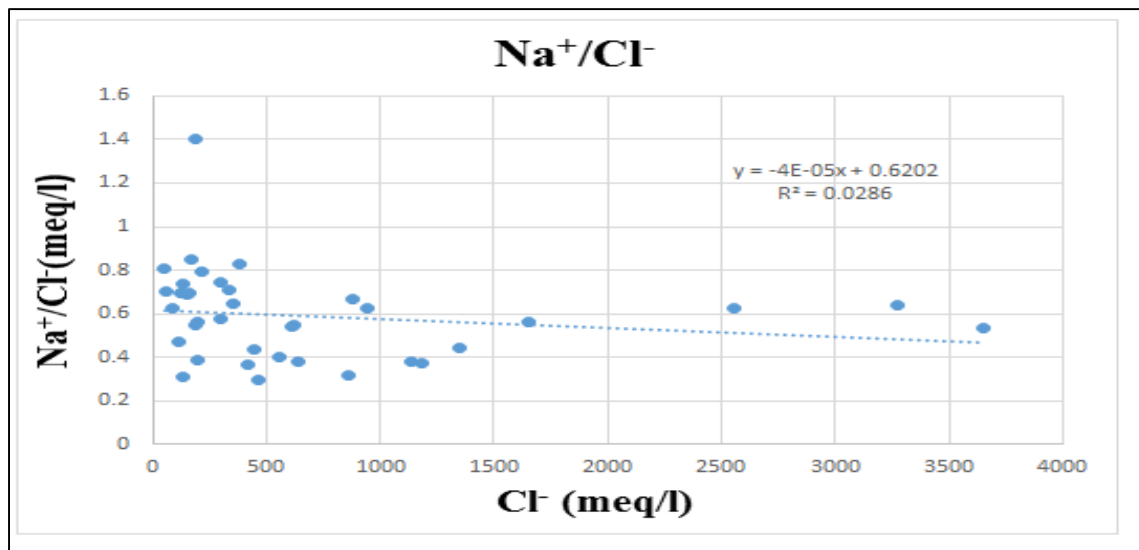


Figure 41: Molar ratio of  $\text{Na}^+/\text{Cl}^-$  vs.  $\text{Cl}^-$  (meq/l) concentration in groundwater samples

The proportion of  $\text{Ca}^{2+}/\text{Na}^+$  (Figure 42) stayed low for most samples and it had negative relationship with the TDS value. This case may be related to the decline of precipitation, assimilation of  $\text{Na}^+$  by muds and by the return stream of the watering system which is a typical process in arid and semi-arid regions (Ghassemi et al., 1995). The  $\text{Cl}^-/\text{HCO}_3^-$  proportion vs TDS value as illustrated in Figure 42 also shows a positive correlation between the two variables.

The proportion of  $\text{Ca}^{2+}/\text{Mg}^{2+}$  vs  $\text{HCO}_3^-$ , demonstrates that the dominant part of samples (Figure 43) is inversely proportional with  $\text{HCO}_3^-$ . Furthermore this may be the way which reflects the presence of additional sources of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  concentrations

supplied by silicate weathering (Zhang et al., 1995). Traces of a  $\text{HCO}_3^-$  proportion were found, which might be due to response of the feldspar minerals with carbonic corrosive water (precipitation). This procedure discharges  $\text{HCO}_3^-$  as shown in Figure 44 (Lakshmanan et al., 2003).

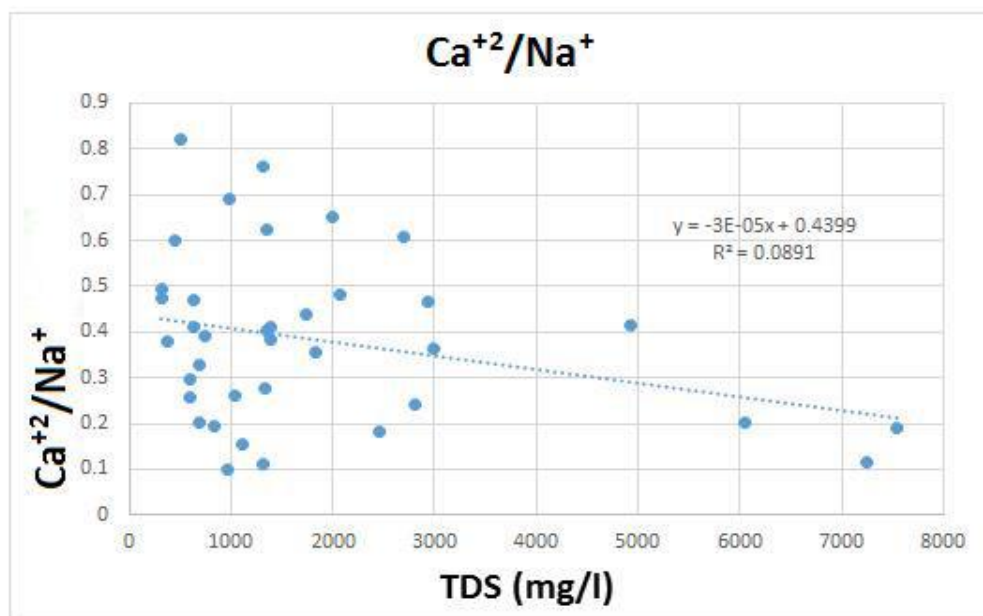


Figure 42: The ratio of  $\text{Ca}^{2+}/\text{Na}^+$  vs TDS in groundwater samples of study area

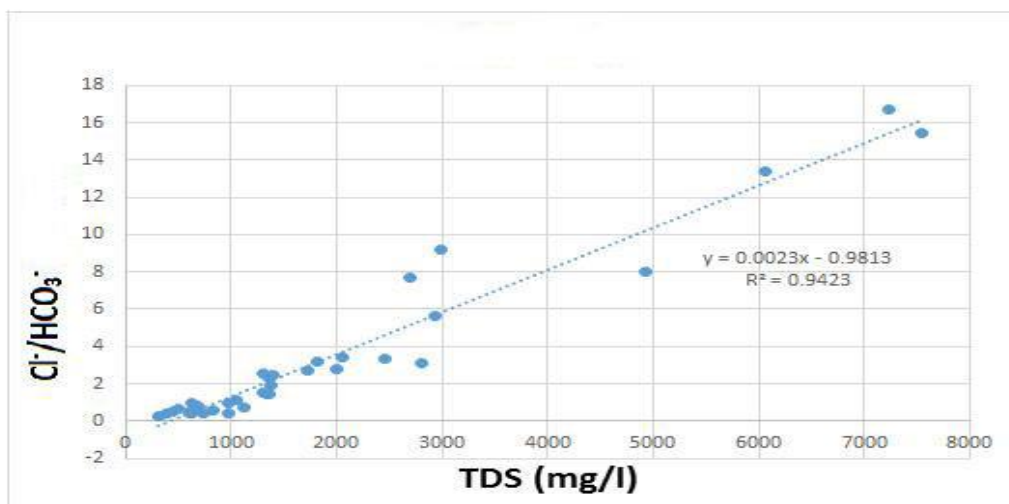


Figure 43: The ratio of  $\text{Cl}^-/\text{HCO}_3^-$  vs TDS in groundwater samples of the study area

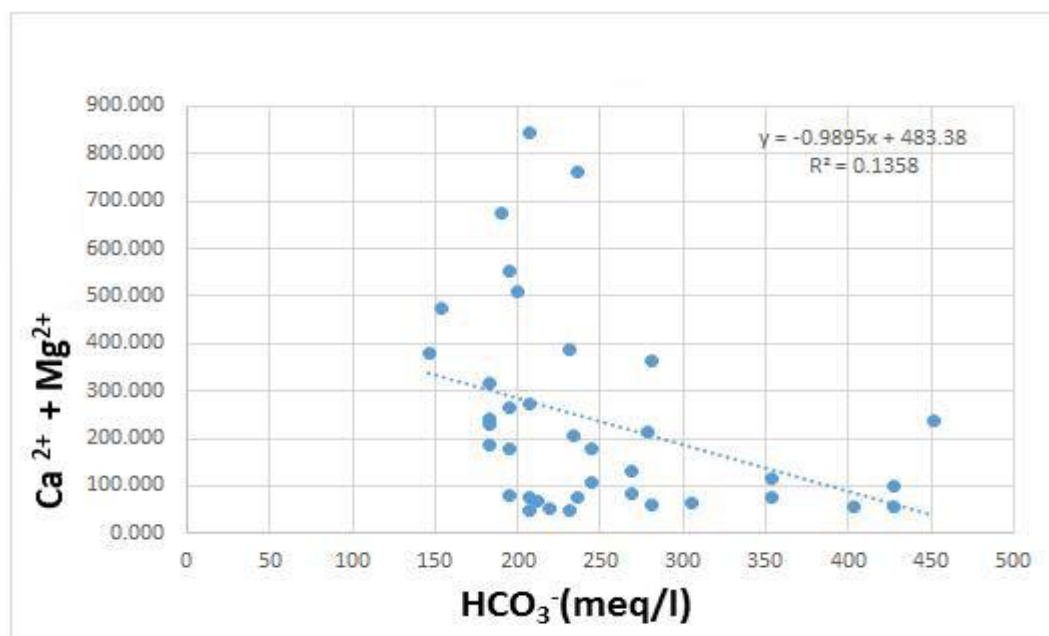


Figure 44: : Ratio of  $\text{Ca}^{2+}/\text{Mg}^{2+}$  vs.  $\text{HCO}_3^-$  of collected groundwater samples of the area

Furthermore, the plot of  $\text{Ca}^{2+}/\text{Mg}^{2+}$  vs.  $\text{HCO}_3^-/\text{SO}_4^-$  is utilized to focus on the ions exchange procedures as shown in Figure 45. That exchange is the procedure, focuses on movement to one side of the plot because of abundance of  $\text{SO}_4^- + \text{HCO}_3^-$ , while if reverse ions exchanged, the focused movement is aligned to one side because of overabundance of  $\text{Ca}^{2+}/\text{Mg}^{2+}$  (Fisher & Mullican, 1997). As indicated by the outcomes, most of groundwater samples ratio of  $\text{Ca}^{2+}/\text{Mg}^{2+}$  vs.  $\text{HCO}_3^-/\text{SO}_4^-$ , which are located in the study area are directly proportional which may be because of the abundance of bicarbonate  $\text{SO}_4^-$  that are situated at some areas of the study region.

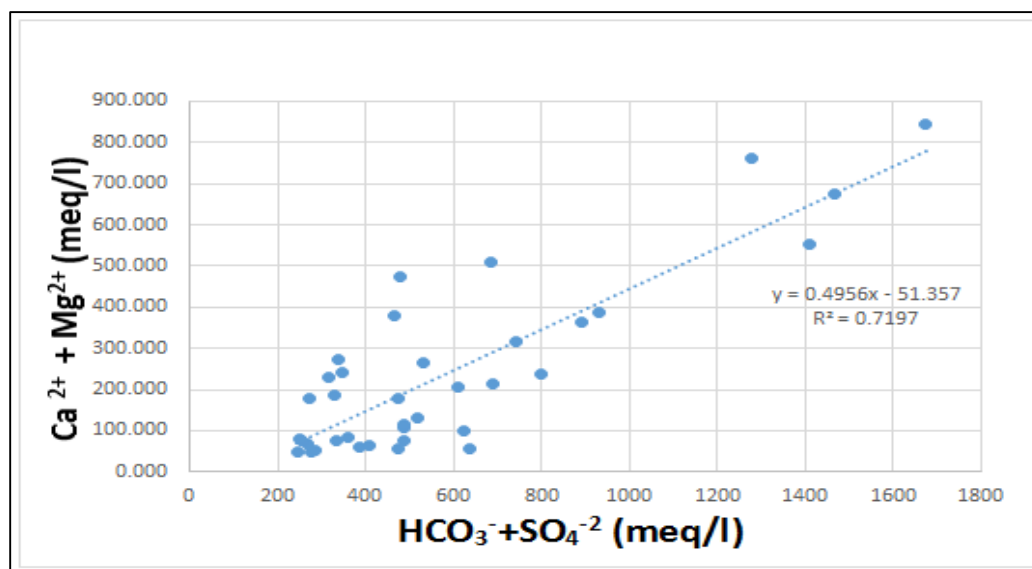


Figure 45: Ratio of Ca<sup>2+</sup>/ Mg<sup>2+</sup> vs. HCO<sub>3</sub><sup>-</sup>+ SO<sub>4</sub><sup>-</sup> in groundwater samples of the area

Figure 46 shows the relation between NO<sub>3</sub><sup>-</sup> vs. TDS. An Increased concentration level of NO<sub>3</sub><sup>-</sup> is apparent from the study of the upper east toward southwest of study area. A slight correlation between NO<sub>3</sub><sup>-</sup> and TDS can be seen for some of the samples. The most noteworthy NO<sub>3</sub><sup>-</sup> fixations were recorded because of the harm effect of some pesticides. As indicated by the proportion of SO<sub>4</sub><sup>-</sup> vs. Cl<sup>-</sup> as illustrated in Figure 47, a positive correlation between the two variables can be seen in most of the samples. The possible additional sources of SO<sub>4</sub><sup>-</sup> are the disintegration of gypsum from the upper aquifer that is usually utilized as a part of the study region.

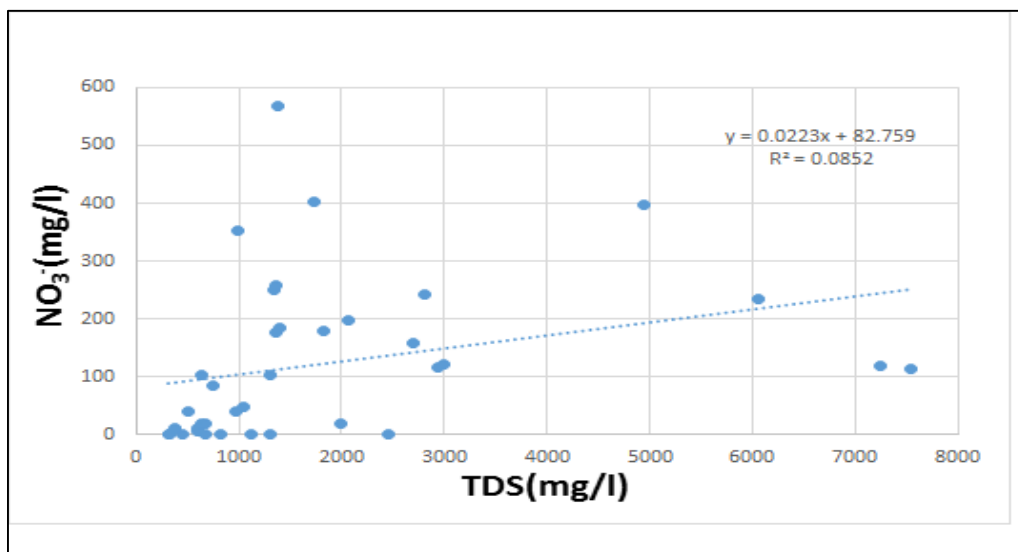


Figure 46: NO<sub>3</sub><sup>-</sup> vs. TDS plot for groundwater samples of the study area

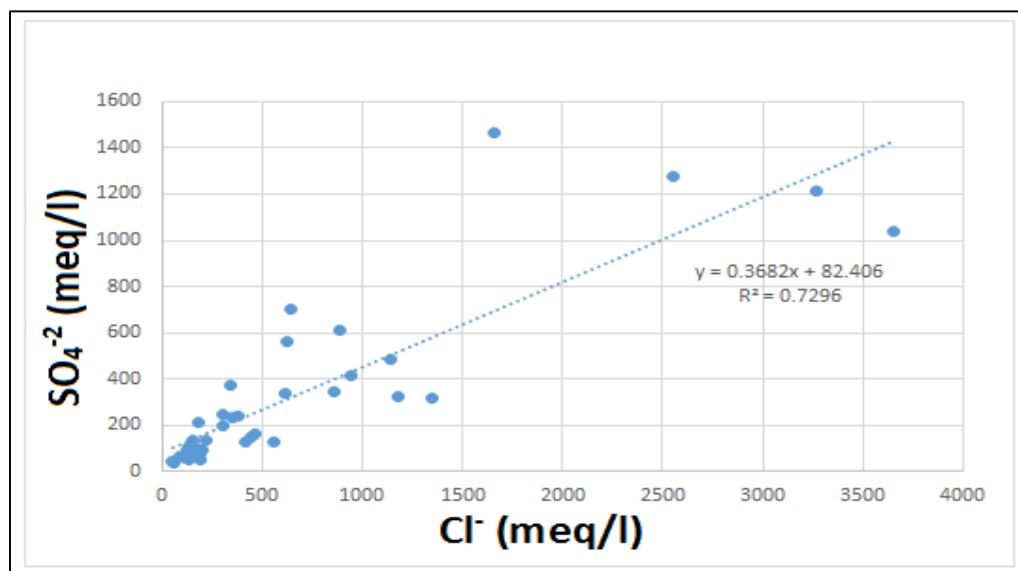


Figure 47: SO<sub>4</sub><sup>-2</sup> ratio vs. Cl<sup>-</sup> for groundwater samples of the study area

#### 4.5. Trace Metals

The high concentrations of trace metals in groundwater could represent a serious hazard to human health. Depending on the geographical and aquifer lithology, this may affect

the levels of trace metals concentration. This may influence the centralization of a few minerals in the groundwater. About 16 trace metals have been examined in this study, these were: Al, As, Ba, Cd, Cr, Co, Cu, Fe, Pb, Mn, Mo, Ni, P, Sr, V, and Zn. Table 5 shows the post-effects of trace metals compared to WHO drinking water standard (2011). The data show that low centralizations of most of the trace metals were found in the 37 samples of groundwater in the study area. No critical concentrations were seen of the 14 trace metals, these were Al, As, Co, Cr, Cu, Fe, Mn, Mo, Ni, P, Pb, V, Ba and Zn.

Elements	Maximum value	Minimum Value	Average mg/l	WHO Standard (2011)	% wells exceeded The limit	Wells No.
Aluminium (Al)	0.02	0.008	0.014	0.1	0%	0
Arsenic (As)	0.132	0.009	0.070	0.01	30%	11
Barium (Ba)	0.265	2.042	0.1535	0.7	0%	0
Cadmium (Cd)	0.016	0.005	0.0105	0.003	5%	2
Chromium (Cr)	0.123	0.03	0.0765	0.05	0%	0
Cobalt (Co)	0.005	0.0047	0.0048	---	---	---
Copper (Cu)	0.021	0.003	0.012	2	0%	0
Iron (Fe)	0.903	0.002	0.4525	1	0%	0
Lead (Pb)	0.025	0.011	0.018	0.01	0%	0
Manganese (Mn)	0.055	0.009	0.032	0.4	0%	0
Molybdenum (Mo)	0.045	0.004	0.0245	0.07	5%	1
Nickel (Ni)	0.019	0.003	0.011	0.07	0%	0
Phosphorus (P)	0.0	0.00	0.00	---	---	---
Strontium (Sr)	46.231	1.144	23.7	---	---	---
Vanadium (V)	0.017	0.002	0.0095	---	---	---
Zinc (Z)	0.762	0.001	0.3815	3	0%	0

Table 5: Post-effects of trace metals compared to WHO drinking water standard



#### 4.5.1. Barium (Ba)

Natural barium mixes are ionic and are hydrolysed in water and this is a minor constituent of salt feldspar (Evans, 1987). The centralization of barium concentrations is restricted by the vicinity of actually happening anions and perhaps at the same time by the adsorption of these particles into metal oxides and hydroxides (Stitch, 1985). Barium is available in both sedimentary and volcanic rocks on the ground that is not found free in nature. It happens in various mixes, generally barium sulphate (barite) and barium carbonate and barium comes from common sources. The acetic acid derivation, nitrate and halides are solvent in water; however, the carbonate, chromate, fluoride, oxalate, phosphate and sulphate are insoluble. The highest concentration was recognized in well No.37 as 0.337 mg/l and the least one was well No.18 as 0.038 mg/l as shown in Figure 48. All the samples are within the WHO standard.

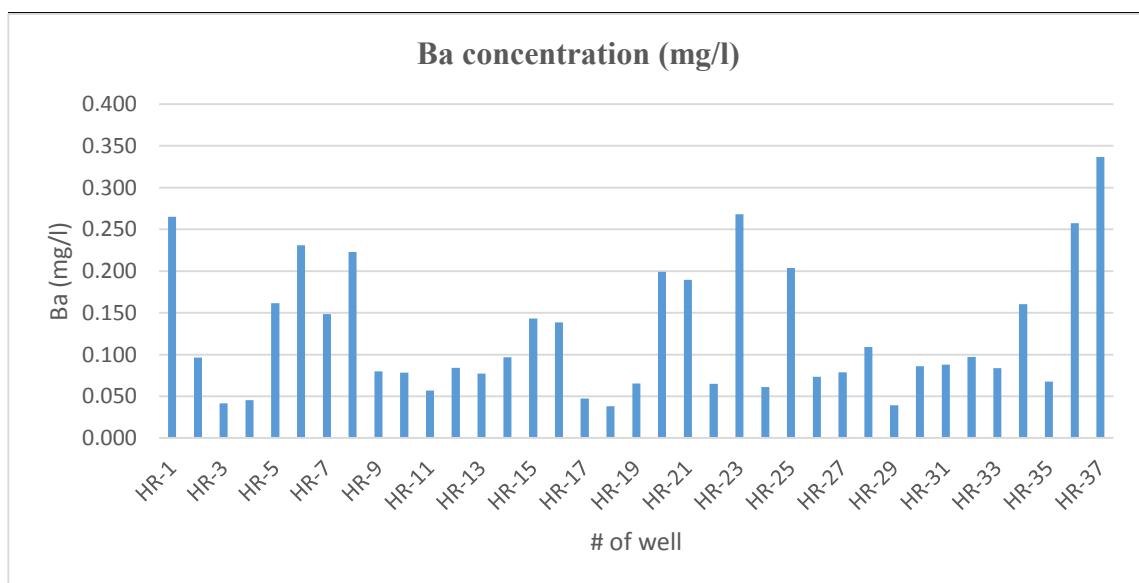


Figure 48: Ba (mg/l) concentration in collected groundwater samples.

#### 4.5.2. Strontium (Sr)

Strontium (Sr) is one of the polyvalent metallic concentrations which originate from sedimentary rocks (El Gawad et al., 2008). Strontium has showed up in normal centralization of 2.661mg/l and the highest concentration is in well No.33 (46mg/l) whereas the least was in well No.3 as (1.144) mg/l. These different concentration levels may be related to dissolving of limestone rocks, which are predominant in this study area.

#### 4.5.3. Cadmium (Cd)

Cadmium is discharged to nature from wastewater; its elevated segment is brought on by water pollution from composts. Moreover, the drinking water pollution may due to the zinc of excited channels and some metal fittings (Bouchard et al., 2011). The high elevated level of cadmium was recorded in well No.1 (0.016mg/l), whereas the least was in half of the wells with a concentration of 0.003 mg/l. The dangerous convergence of cadmium relies on saltiness and hardness. About 95% of the samples were within the WHO standard (0.003 mg/l); 5% of the samples exceeded the WHO standard as shown in Figure 49.

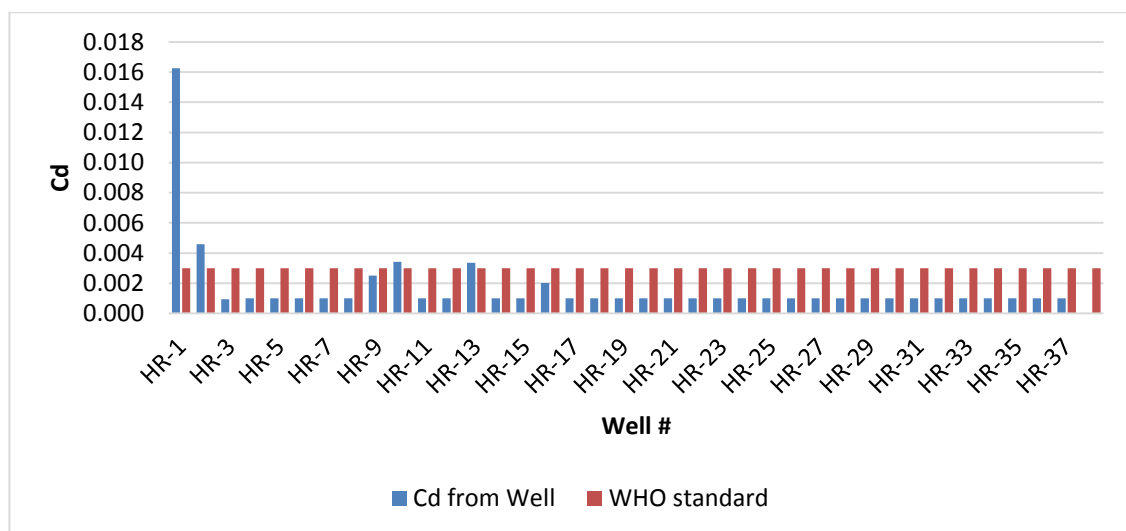


Figure 49: Cd distribution of the groundwater samples for the study area.

#### 4.6. Hydrochemical Water Types

Rock-water interactions, the geography of the surroundings, and contamination sources create types of hydrochemical water. Hydrochemical facies are substances used to show the amounts of water that create a chemical composition. Hydrochemical water type is considered a beneficial technique to determine different types of water, depending upon the ionic organization and proportion of anion and cation (Srinivasamoorthy et al., 2014). 15 proportional rates are arranged from the least to the most significant cationic and anionic concentrations in the hydrochemical formula. This process must be used to distinguish particular water types (Altoviski, 1962). However, Na-Cl is the predominant water type as shown in Figure 50.

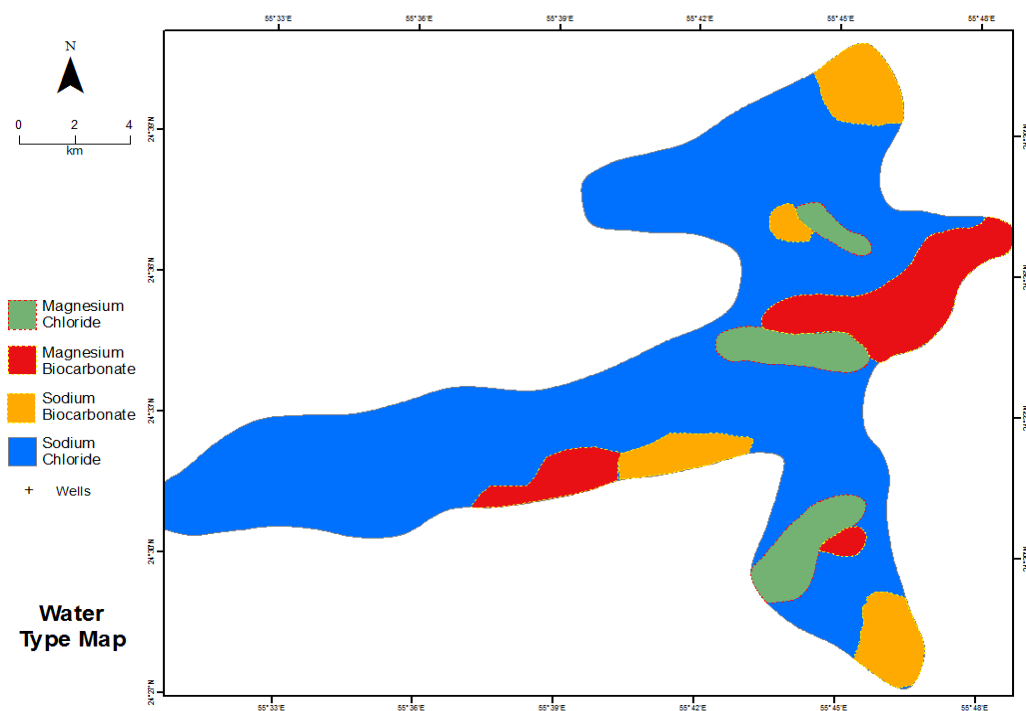


Figure 50: Map shows predominant water type of the collected samples in the area.

The main types of water, which deduced from the results' calculations and analysis, are appropriated in the study area as the following:

- Ca-Na-Magnesium & SO<sub>4</sub>-HCO<sub>3</sub>-Chloride type (1,7,8)
- Ca-Na-Magnesium & SO<sub>4</sub>-Cl-bicarbonate type:(samples2,5,15)
- Ca-Na-Magnesium & Cl-bicarbonate type: (samples 3 and 4)
- Ca-Na-Magnesium & SO<sub>4</sub>- Chloride type: (samples 16 and 30)
- Ca-Na-Magnesium & -HCO<sub>3</sub>- Chloride type: (sample 29)
- Ca-Mg-Sodium & SO<sub>4</sub>-HCO<sub>3</sub>-Chloride type (6,13,14,24)
- Ca-Mg-Sodium & SO<sub>4</sub>-Cl-bicarbonate type:(sample 12)
- Ca-Mg-Sodium & Cl-bicarbonate type: (sample 9)
- Ca-Mg-Sodium & SO<sub>4</sub>-Chloride type: (samples 19,20,21,23,34)
- Mg-Sodium & SO<sub>4</sub>-HCO<sub>3</sub>-Chloride type (10,11,28,35)
- Mg-Sodium & SO<sub>4</sub>-Cl-bicarbonate type:(samples18,31)
- Mg-Sodium & SO<sub>4</sub>-Chloride type: (samples 17,22,26,32 and 33)
- Na-Magnesium & SO<sub>4</sub>-Cl-bicarbonate type: (sample 29)

The principle of the Piper diagram (Figure 51) is a three-shaped illustration, two triangles and one diamond shape, where the triangles represent the cations (left triangle), the anions (right triangle), and the mixture of both is represented by the diamond shape. The interpretation of the anions and cations can be deduced from the Piper Diagram with the following results:

- Most samples contain sodium and magnesium in hydrochemical water types regarding cations concentrations, while most also contain chloride in hydrochemical water types regarding anions concentrations.

- Alkalis ( $\text{Cl}^-$  and  $\text{SO}_4^{2-}$ ) exceeded alkaline earth (Ca and Mg), having chloride as the predominant anion followed by sulphate. The reason chloride dominates is because the contamination of agricultural wastewater in the groundwater.
- Strong acids (sodium) exceeded weak acids (bicarbonate), having sodium as the predominant cation. The contamination of groundwater by agriculture effluents is the reason for sodium dominance.
- Sodium chloride is the prevalent water type, which attributes to other concentrations. In order to express the dominance of water types, a zonation map was created as shown (Figure 50). Sodium-Chloride type is the predominant type followed by Magnesium-Chloride.

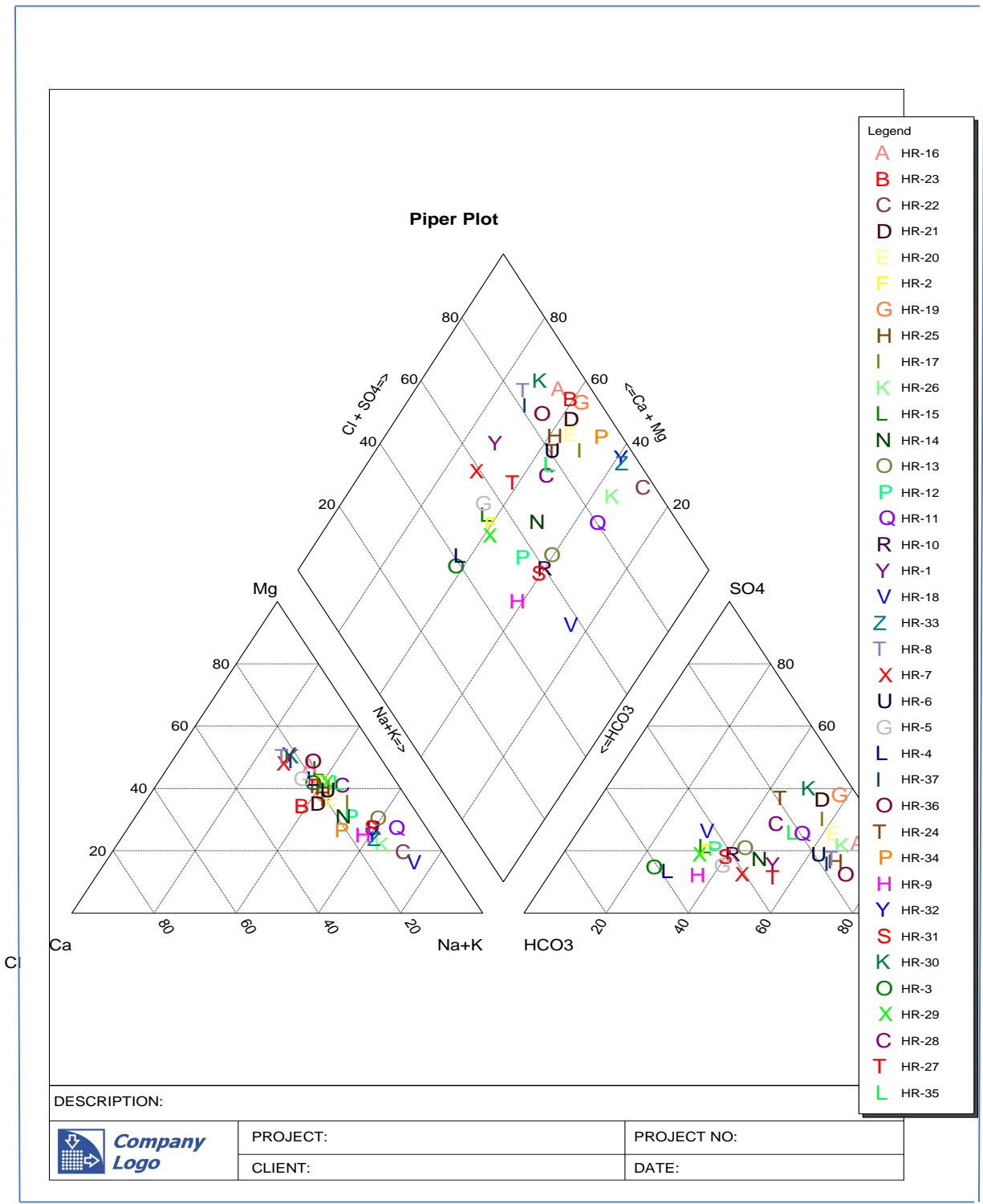


Figure 51: Piper diagram of groundwater samples of study area.

#### 4.7. Water Genesis- Hypothetical Salt Combinations

Water genesis is considered one of the most important techniques in deducing the chemical process that affects water. Sulin's principle is represented by two equal squares. One square indicates marine meteoric genesis including  $\text{Na}_2\text{SO}_4$  and  $\text{NaHCO}_3$ , and marine water genesis including  $\text{CaCl}_2$  and  $\text{MgCl}_2$ . Groundwater samples are expressed in milli equivalent percent and represented by meq% (Sulin, 1948). Out of the 37 samples collected, 25 samples were designated as marine origin (e.g., samples 1, 5, 6, 7, 8, 14, 16, 17, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 30, 32, 33, 34, 35, 36, 37), while the remaining 12 are of meteoric origin (e.g., samples 2, 3, 4, 9, 18, 10, 11, 12, 13, 15, 29, 31) as shown in Figure 52.

All marine origin ( $(\text{Na}/\text{Cl}) < 1$ ) samples are marine water origin of magnesium chloride ( $\text{MgCl}_2$ ) permanent salt. It is calculated by  $(\text{Cl}-\text{Na}/\text{Mg}) < 1$ . It reveals that 13 of the samples of salt combinations are as shown in following:

1.  $\text{NaCl} > \text{MgCl}_2 > \text{MgSO}_4 > \text{Mg}(\text{HCO}_3)_2 > \text{KCl}$  (well no.1)
2.  $\text{NaCl} > \text{Mg}(\text{HCO}_3)_2 > \text{MgSO}_4 > \text{MgCl}_2 > \text{KCl}$  (well no.5)
3.  $\text{NaCl} > \text{MgCl}_2 > \text{MgSO}_4 > \text{KCl} > \text{Mg}(\text{HCO}_3)_2$  (well no. 6)
4.  $\text{NaCl} > \text{MgCl}_2 > \text{Mg}(\text{HCO}_3)_2 > \text{MgSO}_4 > \text{KCl}$  (wells no. 7,27)
5.  $\text{MgCl}_2 > \text{NaCl} > \text{MgSO}_4 > \text{CaSO}_4$  (well no.8,36,37)
6.  $\text{NaCl} > \text{Mg}(\text{HCO}_3)_2 > \text{MgSO}_4 > \text{KCl} > \text{Na}_2\text{SO}_4$  (well no.14)
7.  $\text{NaCl} > \text{MgCl}_2 > \text{MgSO}_4 > \text{CaSO}_4 > \text{KCl}$  (well no.16,25)
8.  $\text{NaCl} > \text{MgSO}_4 > \text{MgCl}_2 > \text{CaSO}_4 > \text{KCl}$  (well no.17,19,20,26)
9.  $\text{NaCl} > \text{MgSO}_4 > \text{CaSO}_4 > \text{MgCl}_2 > \text{KCl}$  (well no.21,22,32,35)
10.  $\text{NaCl} > \text{MgCl}_2 > \text{CaSO}_4 > \text{CaCl}_2 > \text{KCl}$  (well no.23,34)
11.  $\text{NaCl} > \text{MgSO}_4 > \text{CaSO}_4 > \text{KCl} > \text{MgCl}_2$  (well no.24)
12.  $\text{NaCl} > \text{MgSO}_4 > \text{Mg}(\text{HCO}_3)_2 > \text{MgCl}_2 > \text{KCl}$  (well no.28)
13.  $\text{MgSO}_4 > \text{NaCl} > \text{MgCl}_2 > \text{CaSO}_4 > \text{KCl}$  (well no.30)

Permanent salts may exist due to leaching of the rocks present in the area, which are rich in sulphate minerals like gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and carbonate minerals. Dolomite is a carbonate mineral that is rich in calcium and magnesium  $\text{CaMg}(\text{CO}_3)_2$ . In addition, calcium and magnesium exchange cations through water-rock interaction from old marine origin (AbdelLattif, 2003). The presence of  $\text{MgCl}_2$  from the marine water origin in the study area indicates that the groundwater has been pumped heavily. This leads to dissolution of salt minerals of deep marine deposits and increases the groundwater salt concentration (Salman et al., 2013).

The second origin is meteoric water origin ( $(\text{Na}/\text{Cl}) > 1$ ) of sodium sulphate ( $\text{Na}_2\text{SO}_4$ ) water type ( $(\text{Na}-\text{Cl}/\text{SO}_4) < 1$ ) and  $\text{NaHCO}_3$ . It reveals the following hypothetical salt combinations:

1.  $\text{NaCl} > \text{Mg}(\text{HCO}_3)_2 > \text{MgSO}_4 > \text{Na}_2\text{SO}_4 > \text{KCl}$  (wells no.2)
2.  $\text{Mg}(\text{HCO}_3)_2 > \text{NaCl} > \text{Na}_2\text{SO}_4 > \text{KCl} > \text{MgSO}_4$  (wells no. 3)
3.  $\text{Mg}(\text{HCO}_3)_2 > \text{NaCl} > \text{Na}_2\text{SO}_4 > \text{MgSO}_4 > \text{KCl}$  (well no. 4)
4.  $\text{NaCl} > \text{CaCl}_2 > \text{Na}_2\text{SO}_4 > \text{CaCl}_2 > \text{NaHCO}_3 > \text{KCl}$  (well no. 9)
5.  $\text{NaCl} > \text{Mg}(\text{HCO}_3)_2 > \text{Na}_2\text{SO}_4 > \text{KCl}$  (well no. 10)
6.  $\text{NaCl} > \text{MgSO}_4 > \text{Mg}(\text{HCO}_3)_2 > \text{Na}_2\text{SO}_4 > \text{KCl}$  (wells no.11,15)
7.  $\text{NaCl} > \text{Mg}(\text{HCO}_3)_2 > \text{Na}_2\text{SO}_4 > \text{MgSO}_4 > \text{KCl}$  (well no. 12,13)
8.  $\text{NaCl} > \text{Na}_2\text{SO}_4 > \text{NaHCO}_3 > \text{Mg}(\text{HCO}_3)_2 > \text{KCl}$  (well no. 18)
9.  $\text{NaCl} > \text{Mg}(\text{HCO}_3)_2 > \text{MgSO}_4 > \text{Na}_2\text{SO}_4 > \text{KCl}$  (well no. 29)
10.  $\text{NaCl} > \text{Mg}(\text{HCO}_3)_2 > \text{Na}_2\text{SO}_4 > \text{KCl} > \text{NaHCO}_3$  (well no. 31)

A variety of salt concentrations was noted, indicating ion exchange processes in the study area. The wide range of permanent salts ( $\text{CaSO}_4$  and  $\text{MgSO}_4$ ) indicates the presence of sulphate and carbonate minerals. Sodium dominance in all water types and



origin indicates the infiltration of meteoric water from irrigation seepage into the recharge basin (AbdelLattif, 2003). A zonation map of the two origins shows the majority of meteoric origin of sodium sulphate water type (Figure 52). Marine origin magnesium chloride-water type coincides with the heaviest agricultural activities, as they both overlap the same area.

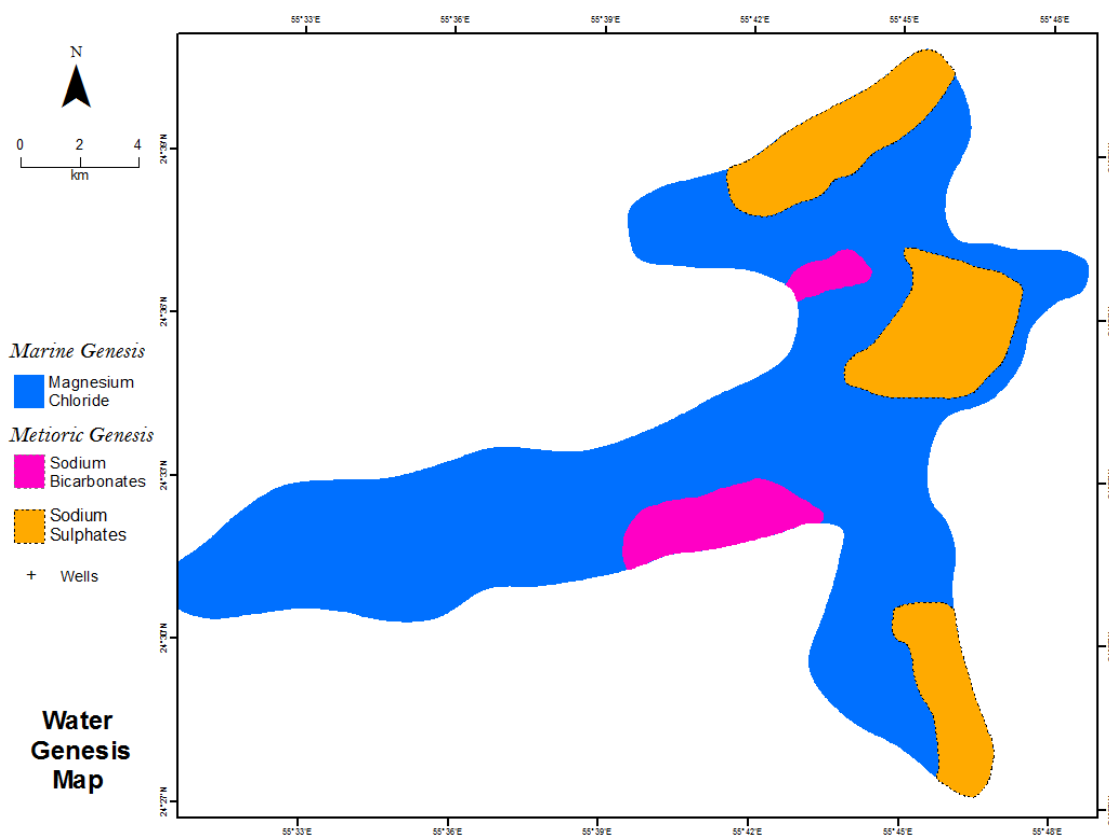


Figure 52: The water Genesis map for the collected groundwater samples of the study area

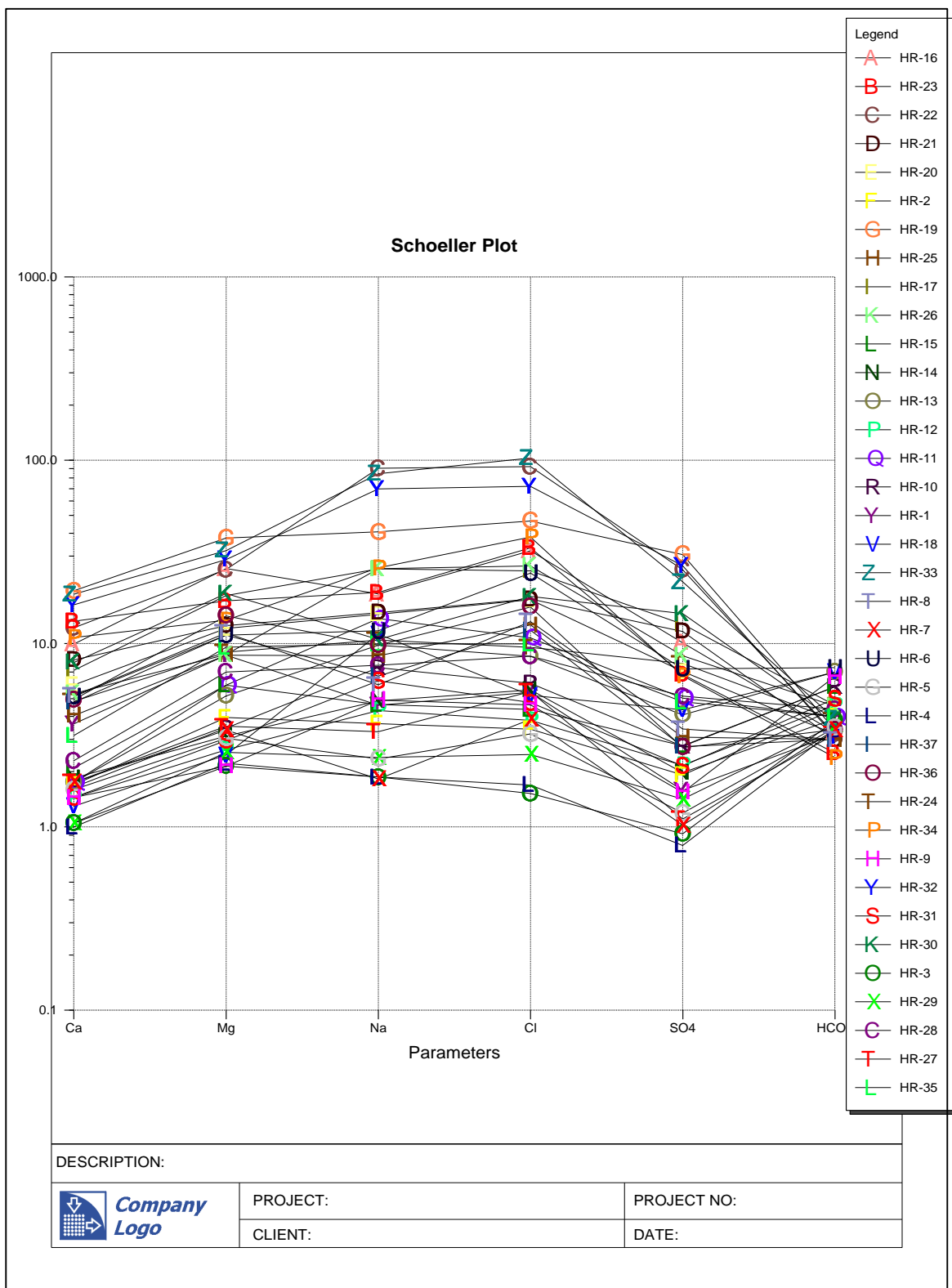


Figure 53: Schoeller Plot for the collected groundwater samples

## **4.8. Irrigation Water Quality**

The wide human practice of well-pumping produces compounds constituents that decrease the yield and fertility of the soil. The presence of compound constituents in the soil is likewise influenced by the nature of the plants being watered, the type of soil, the atmosphere, and the technique for irrigation and seepage.

As soon as irrigation water contacts the dirt, salts seep into the root-zone where the plant-roots absorb the water and retain almost no salt from the dirt. In other words, water vanishes from the dirt surface, yet the salts stay behind, decreasing the soil fertility. This phenomenon results in an incremental build-up of salt in the root-zone, slowly poisoning the plants and strangling the plant's absorption of water. Only a basic understanding of irrigation water is adequate to justify the need for administrative changes to ensure groundwater sustainability (Jalali, 2011).

Irrigation water quality is important so that data concerning the nature of water and its impact on soils and yields are analysed. Consequently, numerous parameters can be used to characterize irrigation water quality and to evaluate salinity risks. This entire study will determine the right administrative procedures needed to ensure sustainability. Understanding the chemistry of groundwater is very important to evaluate its quality for irrigation purposes. The following methods will be used to analyse and deduce the results of the groundwater samples of the study area.

### **4.8.1. Sodium adsorption ratio (SAR)**

A simple method of evaluating the concentration of sodium in water is sodium adsorption ratio (SAR). A useful index of the sodium hazard of water for soils and crops can be

measured by the calculation of SAR of the groundwater samples. Higher saltiness decreases the osmotic plant activity and hinders water to the plant's branches and leaves, bringing about mediocre fruition (Marghade et al., 2011). Plants are sensitive in varying degrees to soil salinity, as the salinity exceeds a certain limit; plant growth is impaired, thus lowering their productivity.

Sodium adsorption ratio (SAR), alongside pH, describes salt-influenced soils. Taking these measurements is effortless task that provides data on the relative concentrations of  $\text{Na}^+$ ,  $\text{Mg}^{++}$  and  $\text{Ca}^{++}$  in soil arrangements. The SAR is processed utilizing the accompanying equation as (Trim, 1985).

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{(\text{Ca} + \text{Mg})/2}} \quad (1)$$

When the SAR exceeds the limit (12), genuine soil issues emerge, and plants have great difficulty absorbing water (Sherif et al., 2012).

The SAR estimations of 37 samples ranged from 1.15 to 20.89 with an average of 5.08. The data is plotted on the Wilcox Diagram (Figure 54). Most of the groundwater samples in the study area were found in the C3 S1 zone (2, 7, 10, 14, 19, 22, 25, 27, 29, 31, 32, 34, 35) showing medium to high saltiness (Table 6) in the water, which can be utilized for irrigation in about 60% of the samples with minimal peril caused by sodium interchange with the crops in those areas (Kumar et al., 2007).

The smallest number of samples was found in the C4-S2 zone (6, 11, 20, 21, 23, 24, 25) and indicated the highest salinity of all the samples. The most extraordinary cases of extreme salinity were wells No 3, 8, 25, 30, and 37 that lie in C4-S1 zone, indicating

inevitable harm if the water from these wells were to be used for irrigation. The higher saltiness of this water decreases the osmotic movement of plants and keeps water from the branches and leaves, which will obviously, diminish profitability and crop development (Marghade et al., 2011).

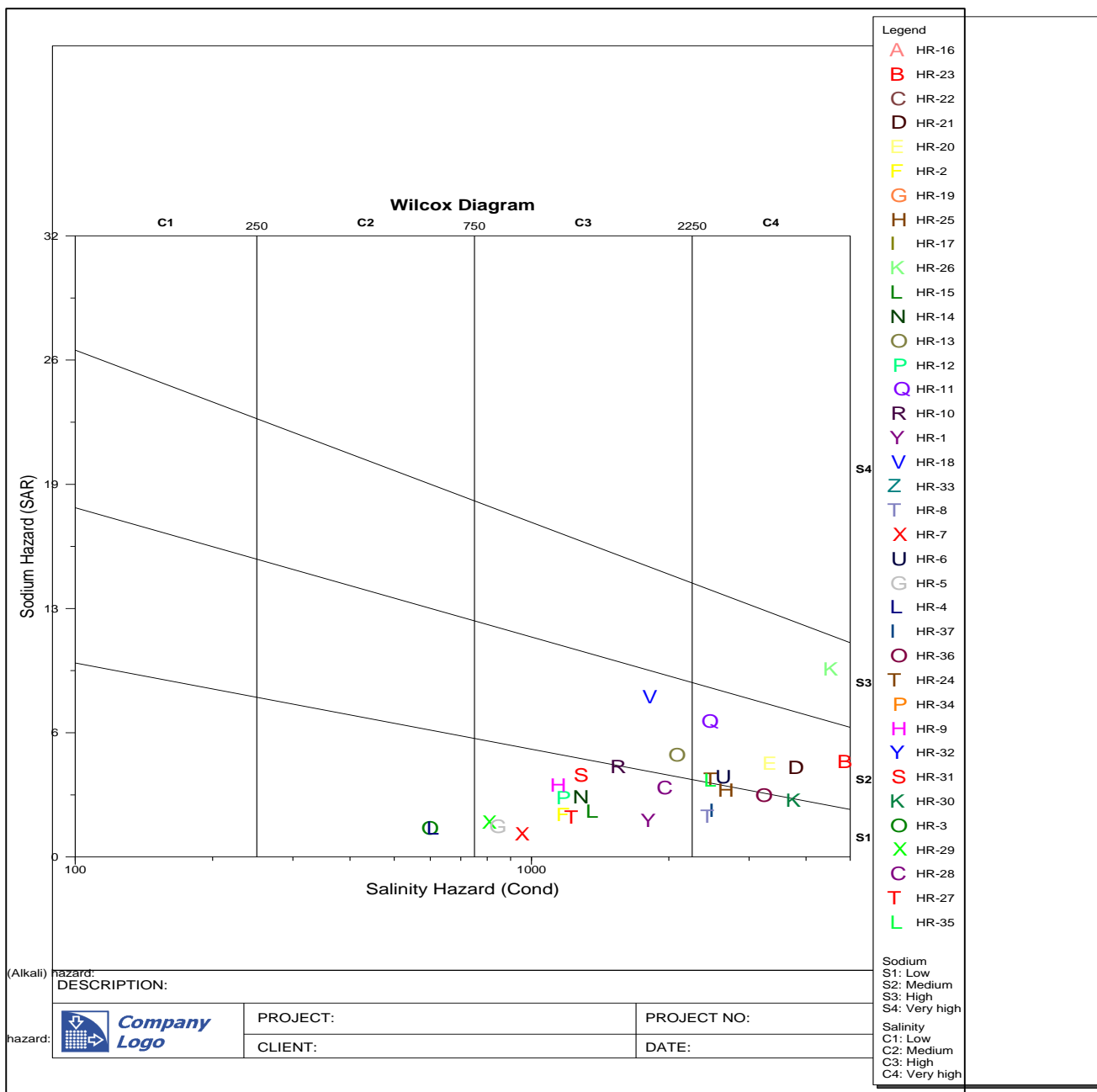


Figure 54: Wilcox Diagram for the collected groundwater samples of the study area

Water Types	Sample location number as shown in Figure 50	Total No. of samples	Samples %
C1S1 (Good)	Nil	Nil	Nil
C2S1 (Good)	13,4	2	6.5%
C3S1 (Good)	2, 7, 10, 14, 19, 22, 25, 27, 29, 31, 32, 34, 35	13	43%
C4S1 (Good)	3, 8,25,30,37	5	16.5%
C3S2 Moderate)	13,18	2	6.5%
C4S2 (Moderate)	6, 11, 20, 21, 23, 24, 25	7	23%
C4S3 (Bad)	30	1	3.3%

Table 6: Classification of groundwater samples based on USSL

#### 4.8.2. Total hardness

A study of total hardness in groundwater demonstrated that the presence of  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  particles has a direct effect on the temporary and continuous hardness of the water (Srinivasamoorthy et al., 2014). Heating can be used to remove temporary hardness, which is caused by the presence of calcium carbonate in water. Permanent hardness is very difficult to remove and doing so require many complicated techniques, such particle exchange forms. Hardness of water constrains the employment of water for mechanical purposes; bringing on scaling of pots, boilers and watering-system funnels.

In a few studies, a significant connection was seen between the water hardness and heart complications/disease/ailments. Conversely, many epidemiological studies have recommended that water hardness protect against illnesses (WHO, 2006). The total hardness (TH) in mg/l can be compared to the acceptable standards (Todd, 1980), using the equation  $\text{TH (mg/l)} = 2.497 \text{ Ca}^{++} + 5.115 \text{ Mg}^{2+}$ . The fluctuation of TH from soft water

(< 75 mg/l) to hard water (>300 mg/l) is demonstrated in Table 7. The most acceptable level of TH is 80-100 mg/l CaCO<sub>3</sub> (Freeze & Cherry, 1979). The TH in the study region ranges from 159.4 mg/l to 2844 mg/l with an average of 800 mg/l. Most wells had a tendency to lie within the hard and very-hard class.

	<b>Rang (mg/l)</b>	<b>Class</b>	<b>No of wells</b>	<b>Percentage</b>
<b>TH</b>	<75	Soft	0	0%
	75 – 150	Moderately hard	0	0%
	150 – 300	Hard	12	32.5%
	>300	Very hard	25	67.5%

Table 7: Classification of groundwater collected from the study area based on the TH

#### 4.8.3. Magnesium ratio (MR)

The measure of the impact of magnesium in groundwater is communicated as the magnesium ratio (MR). This ratio classifies the groundwater quality for irrigation from suitable  $\leq 50$  to inadmissible  $\geq 50$  (Haritash et al., 2008). Paliwal (1972) utilized the following equation to find the MR, which can be used to identify the quality of groundwater:

$$MR = \frac{Mg \times 100}{Ca \times Mg} \quad (2)$$

The MR values in the study area are shown in Table 8. The MR values range from 0 to 6.6, demonstrating a 100% of the wells fall within the allowable limit of 50 mg/l and results in a good impact on harvest yield.

MR (mg/l)	Range	Class	No of wells	Percentage
	<50	Suitable	37	100%
	>50	Unsuitable	0	0%

Table 8: Magnesium Ratio (MR) of GW samples in the study area.

#### 4.8.4. Sodium percentage (Na<sup>+</sup> %)

Sodium percentage (Na<sup>+</sup> %) is described as percent sodium or dissolvable sodium rate, where all ionic concentrations are expressed in meq/l.

$$\text{Na}^+ \% = \frac{(\text{Na}^+) + (\text{K}^+)}{(\text{Ca}^{2+}) + (\text{Mg}^{2+}) + (\text{Na}^+) + (\text{K}^+)} \times 100 \quad (3)$$

According to the Wilcox Chart, (1955) nil of the wells fall within the unsuitable class, whereas 40% of the groundwater samples are within the good class, 40% are within the permissible class, and 19% are within the doubtful class as indicated in Table 9.

	Range	Classes	No of wells	%
Na <sup>+</sup> %	< 20	Excellent	0	0%
	20 – 40	Good	15	40.5%
	40 – 60	Permissible	15	40.5%
	60 – 80	Doubtful	7	19%
	80	Unsuitable	0	0%

Table 9: Na+ percentage of collected groundwater samples of the study area

#### 4.8.5. Electrical conductivity (EC)

According to the acceptable standard, there are five classes used to evaluate groundwater quality (James et al., 1982). Concentration of EC for the collected groundwater sample of the study area ranged from- 600 μS/cm to 13200 μS/cm as shown in Table 10. 6% of the



wells are within the good class, 40% of the groundwater samples are within the permissible class, and 19% of the groundwater samples are within the doubtful class; moreover, about 35 % are unsuitable for irrigation purposes.

	Range( $\mu\text{s/cm}$ )	Classes of water	No of wells	%
<b>EC</b>	< 250	Excellent	0	0%
	250 – 750	Good	2	6%
	750 – 2000	Permissible	15	40%
	2000 - 3000	Doubtful	7	19%
	>3000	Unsuitable	13	35%

Table 10: Classification of groundwater quality based on EC

#### 4.9. Environmental Isotopes in Groundwater

Thirty-seven groundwater samples were collected to assess the groundwater quality and to look to the recharge mechanism for the study area. The ranges of isotopic composition of oxygen in groundwater samples were -4.41 % to 1.94 %. The values of  $\delta^{18}\text{O}$  and  $\delta\text{D}$  were measured for the collected groundwater samples suggesting two main zones. The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  relationship for groundwater samples is established (Fig. 4.41) and defined by the following regression equation  $\delta\text{D} = 3.26 \delta^{18}\text{O} + 2.6$ . The slope for the groundwater samples is  $3.26 < 8$ , in comparison to the local meteoric water line (LMWL) ( $\delta\text{D} = 8 \delta^{18}\text{O} + 15$ ) of the UAE (Murad & Krishnamurthy, 2004), which suggests different degrees of evaporation. However, the ranges of hydrogen isotopes were -13.33 % to 11.16 % as shown in Table 11.

<b>ID</b>	<b><math>\delta^{18}\text{O}</math></b>	<b><math>\delta\text{D}</math></b>	<b>d-excess</b>
HR1	0.78	7.48	1.26
HR2	0.23	6.12	4.28
HR3	-0.11	4.74	5.60
HR4	-0.33	5.03	7.70
HR5	-0.26	4.36	6.46
HR6	1.06	11.16	2.69
HR7	0.44	7.96	4.43
HR8	-3.58	-9.01	19.64
HR9	-3.65	-9.49	19.75
HR10	-4.09	-10.94	21.76
HR11	-3.86	-11.13	19.76
HR12	-4.41	-13.33	21.92
HR13	-3.63	-9.53	19.49
HR14	-3.85	-9.29	21.54
HR15	-0.83	-6.56	0.11
HR16	-0.26	1.06	3.11
HR17	-0.37	-0.08	2.89
HR18	-0.01	2.67	2.73
HR19	0.20	2.26	0.65
HR20	0.83	4.17	-2.51
HR28	1.94	7.07	-8.46
HR29	-0.44	0.79	4.33
HR30	0.33	4.06	1.39
HR31	1.71	6.60	-7.11
HR32	1.50	6.22	-5.81
HR33	1.35	3.83	-6.94
HR34	1.40	6.70	-4.52
HR35	0.50	4.98	0.99
HR36	-3.13	-7.75	17.28
HR37	-3.44	-7.94	19.57

Table 11:  $\delta^{18}\text{O}$ ,  $\delta\text{D}$ , d-excess for GW samples in the study area.

Figure (4.38), indicates that there are two zones of samples in the study area. The first zone of the study area was represented by most of the groundwater samples located below the LMWL and to the west of the study area. In this area of the study, the isotopic enrichment of oxygen and hydrogen in arid and semi-arid environments is due to the evaporation process, which occurs in most of the samples in the study.

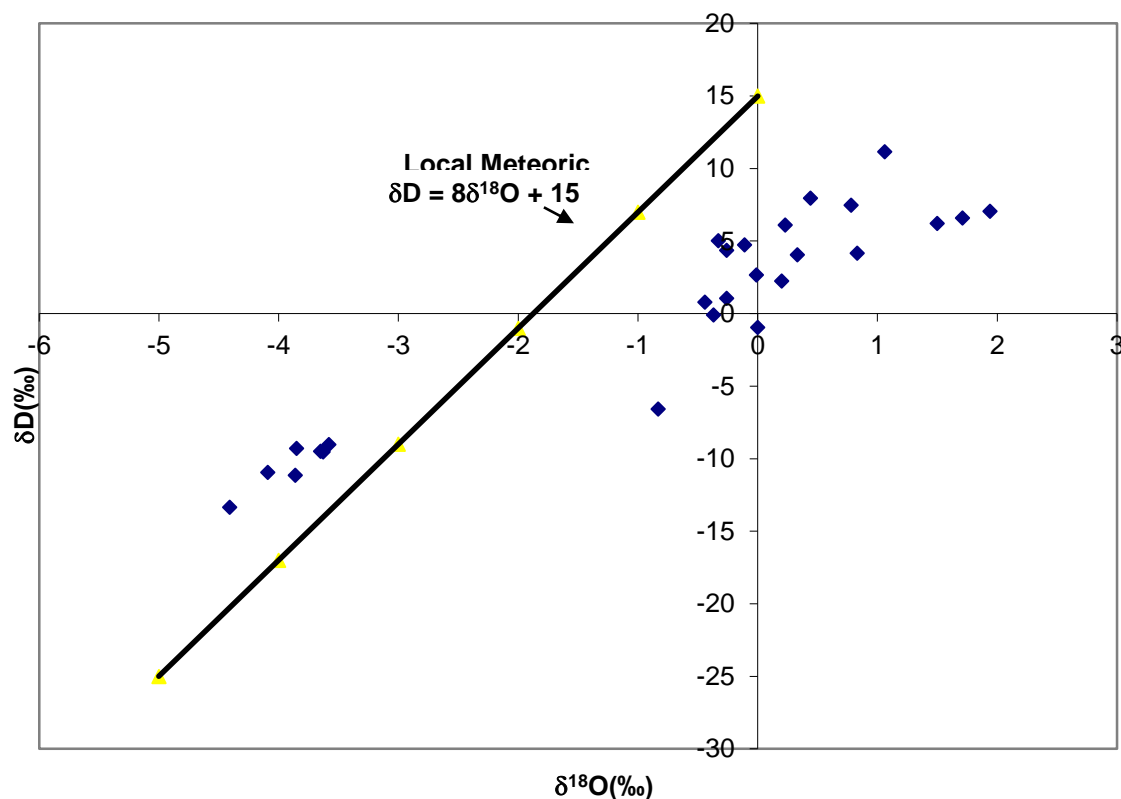


Figure 55: Regression line of  $\delta\text{D} - \delta^{18}\text{O}$  of GW samples in the study area.

However, transpiration can concentrate the salt and does not enrich the isotopic compositions of oxygen and hydrogen. The second zone of the study area is located above the LMWL in close proximity to the Northern Oman Mountains, which reveals quick infiltration into the major aquifer of the study area, which keeps rainfall from being exposed to the evaporation process. This can be applied for the samples No. 8, 9, 10, 11,

12, 13, 14, 36, and 37. The main source depending on the proceeding results suggests Mediterranean Sea source.

The groundwater salinity could be evaluated by plotting the relationship between chloride, representing the salinity, and  $\delta D$  as shown in Figure 56. The scatter distribution of chloride concentration with enrichment of isotopic composition of  $H^+$  suggests that there are different sources affecting groundwater in the study area (Cindrich & Gudmundssori, 1984; Murad et al., 2011).

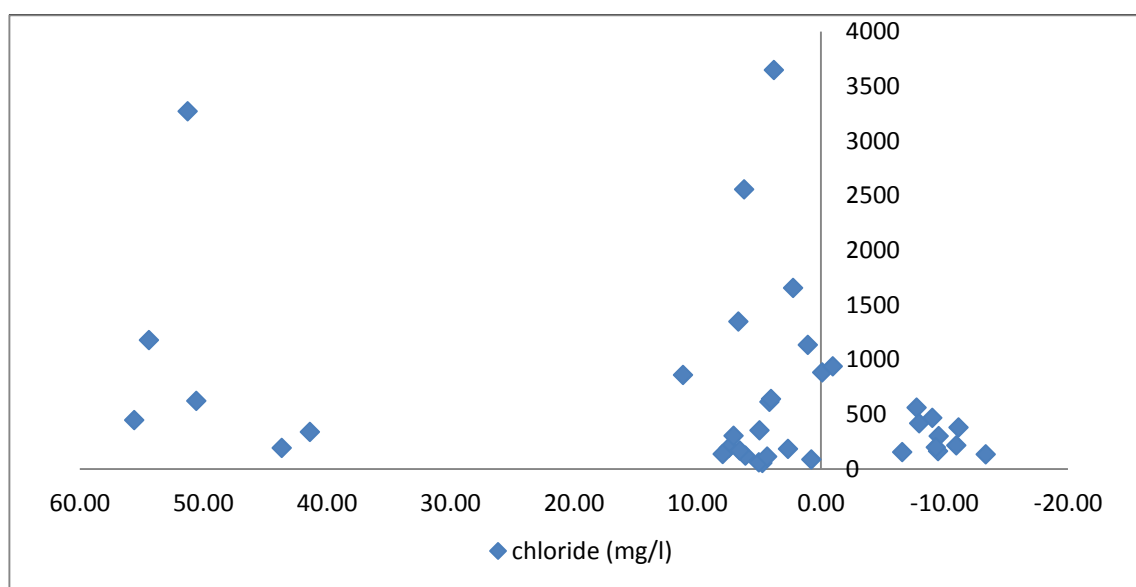


Figure 56: Regression line of  $\delta D$  and  $Cl^-$  (mg/L) for groundwater samples.

## Chapter 5: Conclusions and Recommendation

### 5.1. Conclusions

The current study assesses the groundwater quality using physical and chemical properties and hydrogen and oxygen isotopes testing. The study showed high amounts of TDS reaching 7500 mg/l in well number 33. High salinity deriving from high TDS values was observed in many samples in the area. The main reasons of high TDS values are high anions and cations present in the groundwater due to high agriculture activities and heavy pumping of groundwater with no balance of recharge leading to increasing of salts accumulation.

The data analysis and generated findings of this research study reached the following conclusions

- The current study assesses the groundwater quality using physical parameters, chemical parameters and hydrogen and oxygen isotopes testing.
- The study showed high amounts of TDS in most of the samples.
- The main reasons of high TDS values are high anions and cations present in the groundwater due to high agriculture activities and heavy pumping of groundwater with no balance of recharge leading to increasing of salts accumulation.
- The cations present in the groundwater samples took an order of  $\text{Na}^+ > \text{Mg}^{+2} > \text{Ca}^{+2} > \text{K}^+$ , while anions took an order of  $\text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{-2} > \text{NO}_3^-$ .
- The dominance of all ions was sodium and chloride, followed by magnesium, calcium and sulphate.
- The groundwater in the area was shown to have two water origins, which are paleo-marine origin of magnesium chloride and meteoric water origin of  $\text{Na}_2\text{SO}_4$  and  $\text{NaHCO}_3$  water type.

- The analysis showed the dominance of sodium and chloride in the area due to agricultural effluents, which gives good reasoning of high salinity in the studied area.
- Analysis showed that the groundwater is not suited for domestic use due to high concentration of the Total Hardness that has health risk in most of the samples. In addition, most of the groundwater samples were found to be suitable for irrigation.
- Using isotope analysis for oxygen and hydrogen suggests there are two zones of samples in the study area. The first zone of the study area was represented by most of the groundwater samples located below the LMWL and to the west of the study area. In this area of the study.
- The isotopic enrichment of oxygen and hydrogen in arid and semi-arid environments is due to the evaporation process, which occurs in most of the samples in the study. The second zone of the study area is located above the LMWL in close proximity to the Northern Oman Mountains, which reveals quick infiltration into the major aquifer of the study area, without evaporation

## **5.2. Recommendations**

Governmental agencies and Environmental authorities have implemented many efforts regarding groundwater conservation and sustainability. Periodic assessment for groundwater is considered one of the main strategies used to find better management regulations.

Agriculture sector should be managed better to have sustainable groundwater consumption. For better management, the government should:

- Develop a strategic plan for improving the quality of groundwater.
- Implementation of strict regulations regarding pumping of groundwater and decrease the drilling of unauthorized new wells.

- Implementation of strict rules for using fertilizers based on their quantities and types.
- Complete monitoring and periodic testing of groundwater, which will help us to gain better understanding the best use of the groundwater.
- Educating the farm owners and all workers associated with farming on health hazards and not repeating previous wrong practices.
- Ensure that the public is educated and made aware of the importance of the future of water sustainability.

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## Appendix

### A. Physical Parameters

					$\mu\text{S/cm}$	
Sample ID	X	Y	pH	Temp	Cond	TDS
HR-1	652403	6181308	7.85	31.1	1818	985.76
HR-2	651916	6182168	8.11	31.5	1186	637.02
HR-3	651542	6184007	8.19	32.8	600	317
HR-4	649976	6184655	8.24	33.7	616	322.62
HR-5	649489	6187452	8.06	32.9	845	447.4
HR-6	650209	6179060	7.97	36.2	2630	1381.1
HR-7	649671	6180744	8.16	34	950	499.5
HR-8	649404	6179472	7.94	35.5	2490	1311.8
HR-9	649588	6178896	8.24	34.1	1146	603.72
HR-10	648365	6181085	8.06	32.8	1549	826.68
HR-11	647780	6177761	7.92	32.3	2430	1310.1
HR-12	645731	6181568	8.07	37.5	1170	601.9
HR-13	648147	6175685	8.08	32.8	2088	1119.16
HR-14	649089	6171358	8.04	33.6	1289	682.48
HR-15	651631	6179488	7.75	31.1	1377	743.14
HR-16	652503	6177096	7.6	36.9	5540	2932.8
HR-17	653443	6174370	7.74	34.3	5210	2807.2
HR-18	654814	6174248	8	33.2	1821	971.22
HR-19	654157	6171426	7.51	34.2	9040	4932.8
HR-20	654631	6168833	7.95	32.2	3360	1824.7
HR-21	654228	6164771	7.95	32.5	3800	2063
HR-22	655483	6157800	7.57	30.9	12800	7241
HR-23	656583	6164916	7.78	31.5	4910	2701.2
HR-24	655352	6168222	7.97	33.1	2530	1360.6
HR-25	655564	6170091	8.04	37.1	2670	1391.9
HR-26	654343	6181303	7.8	34	4560	2455.2
HR-27	655987	6180992	8.29	40.3	1254	634.28
HR-28	657044	6181045	8.24	33.8	1966	1045.62
HR-29	656765	6181192	7.92	32.3	805	382.6
HR-30	657708	6178930	7.68	35.8	3780	1999.6
HR-31	659279	6183891	8.18	33.8	1286	679.52
HR-32	654957	6159742	7.63	31.3	10800	6056
HR-33	655291	6157435	7.53	30	13200	7544
HR-34	656721	6163442	7.91	33.4	5520	2996.4
HR-35	652838	6177210	8.12	35.4	2500	1337
HR-36	652379	6179299	8.1	34	3240	1732.3
HR-37	652419	6180195	7.99	34.8	2560	1357.2

## B. Major Cations

Sample ID	K	Na	Ca	Mg
HR-1	6.452	105.543	72.973	104.714
HR-2	4.541	83.776	34.485	48.259
HR-3	2.767	43.217	21.334	25.861
HR-4	3.184	42.518	20.122	27.479
HR-5	4.293	54.002	32.371	37.374
HR-6	11.779	270.004	103.169	134.802
HR-7	4.370	42.450	34.777	41.422
HR-8	8.257	136.697	104.179	139.146
HR-9	4.905	113.462	29.319	25.869
HR-10	9.440	170.232	32.741	41.592
HR-11	15.340	315.393	34.657	72.242
HR-12	6.584	99.275	29.389	32.321
HR-13	14.059	224.956	34.990	63.342
HR-14	9.967	111.629	36.762	37.721
HR-15	6.077	107.313	41.896	71.557
HR-16	13.116	428.596	199.383	311.636
HR-17	24.919	587.204	142.521	221.650
HR-18	6.936	258.663	26.097	29.826
HR-19	29.784	935.105	388.636	456.782
HR-20	12.589	332.420	118.534	146.997
HR-21	19.332	338.982	162.970	152.309
HR-22	41.981	2079.870	244.061	307.887
HR-23	22.205	436.586	264.915	208.236
HR-24	13.546	240.234	96.683	108.938
HR-25	9.848	196.905	80.835	104.916
HR-26	12.305	588.904	107.173	106.469
HR-27	4.770	75.687	35.482	42.520
HR-28	6.064	174.606	45.559	85.302
HR-29	3.908	54.680	20.780	30.869
HR-30	9.431	242.390	158.093	227.615
HR-31	5.869	144.064	28.909	36.114
HR-32	32.721	1603.110	325.954	348.737
HR-33	49.681	1941.210	371.734	390.863
HR-34	20.507	594.805	215.873	162.570
HR-35	13.233	228.994	63.150	115.715
HR-36	9.802	224.649	98.837	172.242
HR-37	10.434	153.605	95.588	134.546

### C. Major Anions

Sample ID	Cl	SO4	HCO3
HR-1	191.597	76.04	195.2
HR-2	121.066	92.464	268.4
HR-3	53.674	43.629	231.8
HR-4	60.257	38.293	207.4
HR-5	113.756	57.383	212.28
HR-6	860.349	348.502	451.4
HR-7	136.585	49.184	207.4
HR-8	466.645	163.763	183
HR-9	163.771	73.565	402.6
HR-10	214.882	132.232	353.8
HR-11	381.213	242.474	244
HR-12	134.962	104.473	280.6
HR-13	301.657	196.218	427
HR-14	198.386	95.169	236.68
HR-15	155.239	133.415	353.8
HR-16	1136.296	484.571	200.08
HR-17	882.599	612.134	280.6
HR-18	184.53	209.188	427
HR-19	1654.35	1467.229	207.4
HR-20	614.755	338.132	195.2
HR-21	621.36	559.046	183
HR-22	3269.872	1212.3	195.2
HR-23	1178.611	326.099	153.72
HR-24	337.931	374.069	234.24
HR-25	447.856	148.047	183
HR-26	939.857	412.092	278.16
HR-27	193.811	53.079	195.2
HR-28	302.566	248.4	268.4
HR-29	87.899	67.599	219.6
HR-30	640.812	699.317	231.8
HR-31	169.149	103.239	305
HR-32	2555.83	1276.436	190.32
HR-33	3649.114	1041.984	236.68
HR-34	1349.392	320.451	146.4
HR-35	352.725	231.07	244
HR-36	560.532	129.862	207.4
HR-37	418.756	131.434	183



### D. Trace Metals and Nitrogen

Sample ID	Al	As	Ba	Cd	Co	Cr	Cu	Fe	Mn
HR-1	0.02	0.009	0.265	0.016	0.005	0.074	0.021	0.017	0.017
HR-2	0.01	0.009	0.096	0.005	0.0047	0.039	0.008	0.017	0.003
HR-3	0.01	0.053	0.042	0.001	0.005	0.035	0.006	0.017	0.001
HR-4	0.01	0.009	0.046	0.001	0.005	0.035	0.007	0.017	0.001
HR-5	0.01	0.009	0.162	0.001	0.005	0.051	0.003	0.017	0.001
HR-6	0.017	0.132	0.231	0.001	0.005	0.033	0.003	0.043	0.008
HR-7	0.01	0.009	0.149	0.001	0.005	0.042	0.007	0.017	0.009
HR-8	0.01	0.102	0.223	0.001	0.005	0.062	0.011	0.045	0.002
HR-9	0.01	0.009	0.08	0.003	0.005	0.029	0.003	0.017	0.002
HR-10	0.01	0.009	0.078	0.003	0.005	0.03	0.003	0.283	0.01
HR-11	0.01	0.009	0.057	0.001	0.005	0.06	0.003	0.057	0.002
HR-12	0.01	0.009	0.084	0.001	0.005	0.078	0.003	0.017	0.009
HR-13	0.01	0.009	0.077	0.003	0.005	0.055	0.015	0.017	0.009
HR-14	0.01	0.009	0.097	0.001	0.005	0.068	0.009	0.017	0
HR-15	0.01	0.032	0.143	0.001	0.005	0.031	0.002	0.017	0.009
HR-16	0.017	0.009	0.139	0.002	0.005	0.049	0.003	0.903	0.007
HR-17	0.005	0.041	0.047	0.001	0.005	0.064	0.006	0.139	0.006
HR-18	0.01	0.089	0.038	0.001	0.005	0.023	0.004	0.017	0.001
HR-19	0.026	0.009	0.065	0.001	0.005	0.057	0.007	0.026	0.004
HR-20	0.003	0.061	0.199	0.001	0.005	0.086	0.007	0.002	0.007
HR-21	0.014	0.009	0.19	0.001	0.005	0.108	0.005	0.173	0.001
HR-22	0.01	0.009	0.065	0.001	0.005	0.067	0.005	0.054	0.002
HR-23	0.03	0.029	0.268	0.001	0.005	0.082	0.012	0.005	0.007
HR-24	0.004	0.075	0.061	0.001	0.005	0.058	0.007	0.017	0.001
HR-25	0.004	0.009	0.204	0.001	0.0054	0.067	0.005	0.035	0.002
HR-26	0.014	0.009	0.073	0.001	0.005	0.038	0.003	0.021	0.001
HR-27	0.01	0.009	0.079	0.001	0.005	0.049	0.003	0.004	0.001
HR-28	0.008	0.009	0.109	0.001	0.005	0.079	0.005	0.017	0.005
HR-29	0.01	0.009	0.039	0.001	0.005	0.053	0.003	0.017	0.001
HR-30	0.01	0.034	0.086	0.001	0.005	0.123	0.006	0.011	0.001
HR-31	0.01	0.009	0.088	0.001	0.005	0.043	0.003	0.007	0.001
HR-32	0.03	0.059	0.097	0.001	0.005	0.07	0.008	0.025	0.002
HR-33	0.034	0.009	0.084	0.001	0.0075	0.051	0.007	0.017	0.055
HR-34	0.01	0.009	0.16	0.001	0.005	0.12	0.007	0.007	0.001
HR-35	0.01	0.009	0.068	0.001	0.005	0.08	0.011	0.015	0.002
HR-36	0.01	0.009	0.257	0.001	0.005	0.078	0.009	0.004	0.001

Sample ID	Mo	Ni	Pb	Sr	V	Zn	Br	F	NO <sub>3</sub>
HR-1	0.045	0.016	0.025	4.816	0.017	0.001	N/A	N/A	352.683
HR-2	0.039	0.003	0.011	2.239	0.007	0.001	N/A	N/A	104.049
HR-3	0.017	0.003	0.011	1.144	0.005	0.001	N/A	0.09	N/A
HR-4	0.018	0.003	0.011	1.198	0.003	0.001	N/A	0.069	N/A
HR-5	0.008	0.003	0.011	1.88	0.007	0.001	0.243	0.071	N/A
HR-6	0.018	0.003	0.011	4.906	0.003	0.197	2.845	0.118	568.066
HR-7	0.018	0.003	0.011	2.053	0.007	0.001	0.319	0.062	40.221
HR-8	0.004	0.003	0.011	5.552	0.005	0.001	1.342	N/A	103.999
HR-9	0.013	0.015	0.011	1.79	0.007	0.001	0.391	0.25	12.005
HR-10	0.017	0.016	0.011	2.291	0.008	0.001	0.46	0.163	N/A
HR-11	0.018	0.003	0.011	3.443	0.005	0.001	0.961	0.221	N/A
HR-12	0.011	0.003	0.011	2.251	0.013	0.001	0.275	0.313	6.276
HR-13	0.018	0.003	0.011	2.993	0.006	0.001	0.684	0.167	N/A
HR-14	0.018	0.003	0.011	2.426	0.003	0.001	0.496	0.209	N/A
HR-15	0.018	0.007	0.011	3.067	0.003	0.001	0.4	0.064	85.31
HR-16	0.018	0.017	0.011	13.558	0.004	0.762	3.964	N/A	117.248
HR-17	0.018	0.019	0.038	10.992	0.002	0.537	2.518	N/A	242.277
HR-18	0.006	0.003	0.011	1.504	0.002	0.185	0.367	0.106	40.095
HR-19	0.018	0.014	0.011	16.857	0.003	0.17	4.477	N/A	396.235
HR-20	0.018	0.003	0.011	6.888	0.003	0.295	1.523	N/A	180.407
HR-21	0.018	0.003	0.011	7.873	0.003	0.187	1.644	N/A	197.845
HR-22	0.005	0.003	0.011	25.445	0.011	0.001	5.854	N/A	119.182
HR-23	0.018	0.003	0.06	11.34	0.003	0.025	1.848	N/A	158.02
HR-24	0.018	0.003	0.011	5.237	0.003	0.001	1.024	N/A	176.312
HR-25	0.018	0.003	0.011	5.138	0.003	0.013	1.137	N/A	184.518
HR-26	0.018	0.003	0.011	5.495	0.002	0.012	1.494	N/A	N/A
HR-27	0.018	0.003	0.011	2.445	0.003	0.001	0.602	0.067	19.245
HR-28	0.008	0.003	0.011	4.364	0.003	0.001	0.801	N/A	49.263
HR-29	0.018	0.003	0.011	1.643	0.003	0.001	0.176	0.062	10.169
HR-30	0.018	0.003	0.011	9.933	0.003	0.08	1.884	N/A	19.487
HR-31	0.018	0.003	0.023	2.591	0.003	0.001	0.43	0.123	18.707
HR-32	0.011	0.003	0.011	18.689	0.007	0.108	4.874	N/A	234.62
HR-33	0.018	0.003	0.011	46.231	0.007	0.001	6	N/A	113.271
HR-34	0.018	0.012	0.011	14.858	0.008	0.051	0.91	N/A	120.337
HR-35	0.018	0.003	0.011	6.416	0.003	0.06	0.945	N/A	250.767
HR-36	0.018	0.003	0.011	8.636	0.003	0.084	1.424	N/A	403.403