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Microgravity, Hydrological and Meteorological Monitoring Of Shallow Groundwater Aquifer in Alain (UAE)

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MICROGRAVITY, HYDROLOGICAL AND METEOROLOGICAL MONITORING OF SHALLOW GROUNDWATER AQUIFER IN AL-AIN (UAE)

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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. Hakim Saibi

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Declaration of Original Work

I, Serin Mosleh Darwish, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Microgravity, Hydrological and Meteorological Monitoring of Shallow Groundwater Aquifer in Al-Ain (UAE)*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Hakim Saibi, in the College of Science at UAEU. This work has not previously been presented or published or formed the basis for the award of any academic degree, diploma or a 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 Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions.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 thesis.

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Abstract

The United Arab Emirates (UAE) is situated within an arid zone where the climate is arid, and the recharge of the groundwater is very low. However, rapid expansion, population growth and agriculture activities have negatively affected these limited water resources. The shortage of water resources has become a serious concern due to the over-pumping of groundwater to meet demand. In this study, a combination of time-lapse measurements of microgravity and depth to groundwater level in selected wells in Al-Ain city was used to estimate the variations in groundwater storage. Relative gravity measurements were acquired using the Scintrex CG-6 Autograv from March 2018 to March 2019. The purpose of this study is to estimate the groundwater storage changes in the shallow aquifer based on the application of microgravity method. The microgravity changes from March 2018 to March 2019 at four water wells located in Al-Ain are ranging from 128 μGal to 151 μGal referenced to base station (UAEU, E-4 building) data of March 2018. The calculated water storage changes from microgravity changes at four wells during the same period are ranging from 3.05 m to 3.60 m, which had a good correlation with observed water level changes at four wells from Falaj Hazza (Al-Ain, UAE) ($R^2 = 0.67$). Water storage changes can be estimated from microgravity changes using this equation: $\Delta S = 0.0239\ \Delta g$.

Keywords: Al-Ain, groundwater aquifer, microgravity, water storage.

Title and Abstract (in Arabic)

مراقبة الجاذبية الصغرى، والهيدرولوجية والرصد الجوي لطبقة المياه الجوفية الضحلة في مدينة العين (الإمارات العربية المتحدة)

الملخص

تقع دولة الإمارات العربية المتحدة ضمن إقليم جغرافي يتميز بالجفاف وضعف إعادة تخزين المياه الجوفية. إلاّ أن عوامل كثيرة كالتوسع العمراني المتسارع، والنمو السكاني، والزراعة قد أثّرت سلباً على هذا المصدر المحدود، وأضحى النقص في مصادر المياه مثار قلقٍ شديد وذلك بسبب الإفراط في استخراج المياه الجوفية من أجل تلبية الطلب على الماء. في هذه الدراسة ، تم استخدام الربط بين قياسات الفاصل الزمني للجاذبية الصغرى وعمق مستوى المياه الجوفية في مجموعة من الآبار المحددة في مدينة العين لتقييم وتقدير التغيرات في مخزون المياه الجوفية. تم *الحصول* على قياسات الجاذبية النسبية باستخدام Autograv Scintrex CG-6 وذلك للفترة الممتدة من شهر مارس 2018 إلى مارس 2019. إن الهدف من هذه الدراسة يكمن في تقييم التغيرات التي تطرأ على المخزون المائي في مستودعات المياه الجوفية الضحلة بتطبيق منهجية الجاذبية الصغرى. تتغير الجاذبية الصغرية خلال الفترة المذكورة آنفاً في أربعة آبار واقعة في مدينة العين بمقدار يتراوح بين 128µ غال و151µ غال، ويشار إليها بالمحطة الأساسية (UAEU,E-4 building) بيانات شهر مارس 2018. إن مخزون المياه الذي تم حسابه يختلف عن تغيرات الجاذبية الصغرى في أربعة آبار خلال نفس الفترة بمقدار يتراوح بين 3.05 م و3.60 م، وهو ما يدل على وجود علاقة متبادلة قوية بين تغيرات مستويات المياه الملحوظة في أربعة آبار في فلج هزاع (العين، الإمارات العربية المتحدة) (R^2=0.67). فالتغيرات التي تطرأ على مخزون المياه يمكن تقديرها بناءاً على التغيرات التي تطرأ على الجاذبية الصغرى وذلك من خلال استعمال هذه المعادلة: $\Delta S=0.0239\Delta g$.

مفاهيم البحث الرئيسية: مدينة العين، طبقة المياه الجوفية، الجاذبية الصغرى، مخزون المياه.

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I also thank my co-advisor Prof. Mohamad Mostafa Mohamed in reviewing this thesis.

Meteorological data were provided by the National Centre of Meteorology and Seismology (NCMS). Their continuous support, by providing the data, is appreciated.

My thanks extend to the Geology Department for providing the gravimeter to be used in this work.

Dedication

I dedicate my thesis work to the memory of my sister, Dr. Dalia, who always believed in my ability to be successful in the academic arena.

A special feeling of gratitude to my beloved parents and siblings who have supported me throughout the entire process.

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List of Abbreviations

ρw	Density of water
Δρrw	Change in density of the rock and water slab
Δg	Change in microgravity
Δh	Change in water-level
ΔS	Change in groundwater storage
μgal	Microgal
AGEDI	Abu Dhabi Global Environmental Data Initiative Climate Change
b	Thickness of Bouguer slab
BCM	Billion Cubic Meters
EAD	Environment Agency – ABU DHABI
G	Universal gravitational constant
g	Force of gravity
Δg	Change in microgravity
M	Mass of earth
mGal	Milligal
MCM	Million Cubic Meters
NCMS	National Centre of Meteorology and Seismology
r	Distance to the Earth’s center of mass
SCAD	Statistic Centre Abu Dhabi
UAE	United Arab Emirates

Chapter 1: Introduction

1.1 Overview

The depletion of groundwater in arid area has become a serious problem. In these areas, groundwater is an incredibly important and precious source for freshwater. Groundwater is the primary source of water in the United Arab Emirates (UAE). However, the rapid population growth, domestic demand, agriculture, and economic expansion have been significantly affected these limited water resources. According to the UAE Ministry of Environment and Water, by 2030 the total annual water demand will be 8.8 BCM (Mohsen et al., 2016). Moreover, the United Arab Emirates has an arid climate which characterized by high evaporation rate and low amount of rainfall. Thus, the rate of groundwater recharges is insignificant compared to the high rate of extraction from a groundwater aquifer.

Therefore, several water management challenges have been arisen due to the growing gap between high demand and water supply. These challenges including the scarcity of groundwater that has been outstripping the reserves, increasing of water salinity, degradation of water quality and high cost of potable water production. Thus, reliance on desalination plants is increasingly being used in the UAE to meet the water demand under the conditions of the freshwater scarcity.

Groundwater exploration is very important to monitor and manage the changes in groundwater storage. There are several techniques applied for groundwater exploration, either by direct or indirect methods. These methods are classified into surface and subsurface techniques. Surface methods are including surface geophysical methods such as gravity, electromagnetic and electrical resistivity methods. While the subsurface method includes aquifer test drilling and borehole geophysical logging techniques. Comparatively, subsurface methods are very expensive. Thus, the surface methods are easy to operate and provide us with many information (aquifer morphology and aquifer lithology) (Goldman and Neubauer, 1994).

The gravity method is one of the main used and preferred geophysical technique to monitor and estimate the groundwater storage changes. For regional aquifer scale studies (aquifer storage), a gravity satellite is used such as GRACE, Gravity Recovery and Climate Experiment (Handayani et al., 2018). Gravity method provides a direct estimation of water mass variations with time-based on microgravity time-lapse measurements. This method has advantages over the drilling methods. It is a relatively cheap, noninvasive and nondestructive method. Gravity method is a very effective geophysical tool to solve the fluctuations of groundwater problems and for the water management considerations.

In this study, we identified the geology, meteorology and hydrogeological characteristics of the shallow aquifer in the study area. Then, we present the microgravity changes from March 2018 to March 2019 from four selected water wells in Al-Ain city. These microgravity changes are plotted and compared with water well records and meteorological data (evaporation and precipitation). After that, aquifer storage changes were calculated from the gravity changes.

1.2 Statement of the Problem

In United Arab Emirates groundwater is often representing the only conventional source of fresh water supply to domestic, agriculture and industrial sectors. Thus, the intensive abstraction from groundwater resulting in a severe rise in water demand. According to a recent report by Environment Agency-Abu Dhabi

(EAD), the overall groundwater levels experienced a stable decline in the period 2005 to 2016. Certainly, the water level of Al-Ain city over the period of 1999 through 2016 has declined by more than 45 meters and reached about 103 meters below sea level as of January 2016. Due to the lack of adequate management, groundwater is intensively exploited leads to lowering the water aquifer tables. Hence, the potential for future use is reduced. Also, it is expected to increase water stress in the region due to the rapid human and economic development. Therefore, a proper groundwater exploration is essential to manage and overcome these challenges associated with water resources. Likewise, understanding and monitoring the groundwater is the basis of any efforts to protect and sustainably manage the precious resource.

In this master thesis, microgravity method is used to explore and monitor four wells in Falaj Hazza area located in Al-Ain city. Groundwater in Al-Ain region has been over-exploited due to the rapid population growth, agriculture activities and high rate of water pumping. Therefore, the application of microgravity method allows us to investigate the variations in groundwater storage. To the best of the knowledge of the researchers, no previous work considered the use of gravity method to monitor groundwater storage changes in the UAE. The changes in groundwater storage are measured continuously by detecting the anomaly differences at the same wells over time using gravimeter. The results reported in this thesis would help to develop the relationship between monthly microgravity changes with hydrological and hydrogeological characteristics of the shallow phreatic aquifer to estimate the water storage variations.

1.3 Relevant Literature

1.3.1 Introduction

Historically, gravity has played a key role in exploration geophysics and it's also important in studies of a dynamic process in the Earth's interior. The concept of gravity method is relatively simple, quick and inexpensive of high precision measurements. Although, the application of gravity method required different types of corrections for data reduction. Gravity is the attraction force that exists between any object towards the earth's center or towards any other body mass. The strength of the attraction force depends on the distance between two bodies and their masses. Gravity g is referred to the acceleration of gravity on the earth's surface at sea level which is 9.8 m/s^2. The value of g varies at different locations on earth, in response to the differences in the density of earth materials, the shape of the earth and its rotation. The gravity method involves measuring the differences in the earth's gravitational field with high-accuracy instruments at the 10 μGal or smaller. The gravity anomalies result from the variations in densities between a geologic feature of interest and the surrounding rock and therefore, local structural traps or fluid movement in the reservoir over specific location can be estimated (Aminzadeh and Dasgupta, 2013).

The applications of gravity methods are widely used in hydrocarbon explorations, hydrogeological applications, and other applications. In higher accurate and precious measurements, microgravity method has been effectively used for monitoring changes in groundwater storage. Thereupon, changing in groundwater mass is the most common factor affects the gravitational force on the earth's surface. These variations can be measured with high-resolution gravimeter that capable to detect anomalies as small as 10 μgal effectively. The extremely precise of the measurements is achieved by removing the internal instrumental and external environmental effects on gravity from the data. Besides, microgravity method used to estimate other parameters such as the effective porosity of aquifer and the groundwater flow (Styles et al., 2005). Thus, changes in gravity allow for a direct estimation of subsurface water storage changes.

1.3.2 Newton's Law of Gravitation

The basis of the gravity method is outlined by two laws derived by Sir Isaac Newton in 1687, which is generally referred to as the *Principia*. Newton's Universal law states that the gravitational force is directly proportional to the product of their masses and inversely proportional to the square of the distance between them (Equation 1).

$$F = \frac{G \times m_1 \times m_2}{r^2} \qquad (1)$$

Where F is the gravitational force between the masses of the objects (m_1) and (m_2), G is the gravitational constant equal to $6.67 \times 10^{-11}\ N\ m^2\ kg^{-2}$ and (r^2) is the square of the distance between the centers of the two masses. The second law is Newton's law of motion states that the force (F) acting on an object is equal to the mass of an object (m) time the acceleration (a). This shows that the more mass an object has, the greater the force required to accelerate it. If any object accelerated downward, then it is known as the acceleration of gravity (g). The value of g is 9.8 m/s^2 or about 980,000 mGal on the surface of the earth at the sea level.

$$F = mg \qquad (2)$$

The value of (g) is dependent upon the location, therefore there are slight variations of its value on the earth surface. These variations are caused by the earth's shape and rotation. Firstly, the earth has an elliptical shape that would result in larger values at the poles than at the equators, since the radius at the equator is greater than at the poles by 20 km approximately. In addition, the earth's rotation causes a change in gravitational acceleration with the latitude (Reynolds, 2011). Then, when any mass is rotated, an outward force is experienced on it identified as a centrifugal force. Consequently, the centrifugal force is small and goes to zero at the poles and relatively large at the equators (Talley, 2011).

1.3.3 Gravity Units

The S.I unit of acceleration due to gravity is m/s^2 corresponds to N/kg, whereas other units are still widely used. The c.g.s unit of g ($1\ cm/s^2$) equals to Gal, in honor to Galileo. Usually, a geophysicist in the field of geophysics use the units of milliGal (0.001 Gal, $10\ \mu m/s^2$). Also, gravity unit "g.u." or $\mu m/s^2$ is commonly used (Milsom, 2007).

1.3.4 Gravity Measurements

The gravitational field is measured mainly by two types of gravimeter: absolute gravimeter and relative gravimeter. Absolute gravimeters measure the gravity value directly, while the relative gravimeters measure the variations of gravity. Generally, measured relative measurement is easier in comparison with the absolute measurements since the absolute gravimeter is time-consuming, expensive and difficult to operate. Altogether, both type of gravimeters effective for gravity measurements at a point or many over the earth's surface.

1.3.4.1 Absolute Gravimeter

There are two types of absolute measurements used, the oldest type is swinging pendulum and the other type is the free-falling body. Examples of absolute gravimeters are FG5 and A10.

1.3.4.1.1 Pendulum Method

In 1656, Christiaan Huygens has constructed a pendulum clock based on the principle of the isochronism of the pendulum discovered by Galileo. A Pendulum was used firstly as gravimeter by Galileo to measure the acceleration of gravity. Huygens has developed a theory that explains the behavior of pendulum in 1673. The period of swing a pendulum (T) depends on its length and to the acceleration due to gravity. The period of the oscillation to complete a cycle expressed by the following formula:

$$T = 2\pi\sqrt{\frac{k}{g}} \qquad (3)$$

Where k is a proportionality constant of the pendulum's length and mass distribution and g is the acceleration of the gravity. Once the pendulum is swing, the gravity force tends to return it to the vertical position. The oscillation will keep on due to the pendulum's momentum until the gravity returns it downward. Moreover, a long period of osculation is needed to achieve high accuracy of gravity measurement. However, in spite of the accuracy of the pendulum's measurements, the main limitation within its measurements remains with the length determination. Nonetheless, the measurement of the absolute gravity begun with the pendulum unit at the end of the nineteenth century (Jan Lastovicka, 2009). Figure 1 shows the Huygens's diagram for the clock design (Yoder, 2005).

1.3.4.1.2 Falling Body Method

The value of absolute gravity can be measured directly by dropping an object in a vacuum and measuring the time required for dropping an object to fall at a specified distance. The gravitational acceleration of a free-falling body is independent of mass as it recognized by Galileo. The relation between the time of the falling is direct proportion to the distance. The acceleration of gravity is proportionality constant. Hence, the gravitational acceleration can be estimated by measuring the distance and time of a falling body. Despite, Galileo used this method, but he made gravity measurements based on pendulums. In general, the operation of this method required very high precise measurements of time and distance. As a result, an advanced technique has been developed capable of accurate measurements of time and distance. This absolute instrument is manufactured by Micro-g LaCoste called FG5 absolute gravimeter that measures the vertical acceleration of gravity. The FG5 gravimeter is a high precision, transportable and adequate to achieve a 0.001 mGal accuracy (Figure 2) (Jan Lastovicka, 2009).

The operation system of the instrument is based on dropping a test mass vertically inside a vacuum chamber for a distance of 20 cm. Then, the position of the specific mass is detected by laser interferometer as a function of time. Thus, the gravity acceleration of the test mass is measured from the trajectory directly.

1.3.4.2 Relative Gravimeter

Relative gravimeters are mostly in use for gravity exploration rather than the absolute gravity since it is considered to be more portable (Figure 1). Relative gravity measurements made between two different stations to measure the difference in gravity. Examples of relative gravimeters are CG-3, CG-5, and CG-6. All gravity measurements at stations are reduced relative to the base station. Most of the relative meters are based on a mass-spring system. Spring gravimeters are classified into stable and unstable. In stable gravimeter, a mass is suspended from a spring and the force of gravity will stretch the spring by an amount that is proportional to the gravitational force. The constant of proportionality is known as the elastic spring constant (κ). Hence, the difference in gravity can be determined by measuring the spring extension (Hooke's law) (Reynolds, 2011).

$$\delta g = \kappa \delta \iota / m \quad (4)$$

Figure 1: CG-6 Autograv (Scintrex Limited, 2016)

On the other hand, unstable gravimeters are more sensitive compared to the stable type. For unstable gravimeters, an additional force is applied in the same direction of gravity and opposing the restoring force of the spring. A proof mass is attached to the horizontal beam that suspended by a zero-length spring and additional pairs of springs applied to return the sensitive elements to equilibrium. One of the most common spring instruments is a quartz spring gravimeter as in Scintrex CG-6

Autograv, therefore it was used in this study (Figure 1). The CG–6 relative gravimeter measures relative differences in gravitational attraction using a fused-quartz elastic system. The quartz springs are easy to operate and faster to be manufactured. The CG-6 gravimeter has a reading resolution of 0.1 μGal with an accuracy of ±5 μGal. The instrument makes automatic corrections for instrument tilt, tide, temperature and drift.

1.3.5 Applications

In this section, some of the case studies are described to illustrate the applications to which the gravity method can be used. It has found numerous applications in environmental, geothermal and engineering studies including detection of underground cavities, groundwater, and geothermal reservoir monitoring.

1.3.5.1 Detection of Cavities

Cavities may be produced either naturally by the dissolution in limestone cavities or by man-made, such as tunnels. The gravity method has proven to be an effective detection and delineation of voids and cavities. A case study in Inowroacl (Poland) demonstrates the applicability of microgravity method to detect the underground cavities. The cavities were developed to the ground surface causing a major source of property damage (Reynolds, 2011). Another case study was presented in Zaragoza (Spain), where the dissolution of gypsum lead to subsidence and collapse of karstic structures. Thus, microgravity technique allows defining the geometry of the sinkhole at the depth of 20 m (Mochales et al., 2008). Also, microgravity survey was carried in Iraq, to locate the cavity and weak zones under an electrical power station (Salih, 2002).

1.3.5.2 Geothermal Reservoir Monitoring

Microgravity method has been using to monitor the changes in mass balance in the geothermal reservoir. In the Kamojang geothermal field, Indonesia, microgravity measurements have been conducted to explain the changes in production and injection activities. Based on the results, the negative changes in gravity values indicated the mass loss from the geothermal reservoir resulted from the exploitation activities, while the measurements made for the injection wells showed positive values of gravity (Sofyan et al., 2010). Nishijima et al. (2015) conducted absolute and relative microgravity measurements to monitor the geothermal reservoir in Ogiri geothermal power plant (Kyushu, Japan). The repeated gravity measurements allow detecting the changes of gravity during stopping the production and reinjection wells. Thus, the gravity indicated increases by 30 μgal in the production areas, while it decreases by 20 μgal in the reinjection areas (Nishijima et al., 2015).

1.3.5.3 Mineral Exploration

Gravity method has a key role in determining the amount of minerals and detecting their locations. Basically, the contrast of the deposits density from their surrounding structures is the main principle in mineral exploration. According to Hildenbrand et al. (2000), they estimate the relationship of the crustal features in order to locate the mineral depositions in the Western United States.

1.3.5.4 Hydrogeological Applications

Gravity method can be used to appraise changes in groundwater resulted from the addition or subtraction in water mass. According to El Alfy et al. (2016), microgravity method was applied to estimate the geospatial variation of groundwater in Riyadh, Saudi Arabia. Accordingly, the use of the highly portable Grav-Map gravimeter allowed for a large gravity survey which included measurements at 42 stations closed to existing observation wells. The microgravity measurements at these stations ranged from 0.0042 mGal to 0.9579 mGal (Alfy et al., 2016). Another study conducted by Champollion et al. (2018) for the quantification of epikarst water storage variations in France, by measuring the gravity at the surface and inside the cave. The results from microgravity method showed that the changes in water storage occur in the unsaturated zone mostly located within the first 12 meters. Also, gravity measurements were effective to identify the aquifer thickness (Champollion et al., 2018). In northeastern Colorado, water table fluctuations were correlated with temporal gravity in an unconfined alluvial during pumping of the aquifer and infiltration at the recharge ponds, and after the recharge ponds were dry. Gravity was observed to be lower during pumping by 46 μGal and higher by as much as 90 μGal at the recharge ponds (Gehman et al., 2009). Therefore, microgravity method is a very useful tool to monitor the variations in groundwater storage and providing information about the physical properties of the aquifers, such as their lithology and thickness.

1.3.6 Hydrogeology

1.3.6.1 Water Resources in the UAE

In the UAE, water resources can be classified into two types which are conventional and non-conventional water resources. Since a long time, the UAE mainly was dependent on conventional water resources and in particular groundwater. However, the country depends intensively on non-conventional water resources, especially desalinated water to meet the ever-increases on water demand.

1.3.6.1.1 Conventional Water Resources

The conventional water resources in the UAE include seasonal floods, Falajes, springs, and groundwater. There are no perennial surface water resources in the country since the rate of rainfall is low and only a few numbers of Falajes and springs provide a limited renewable supply of water.

1.3.6.1.1.1 Floods, Falajes and Springs

The conventional water resources include 125 Mm^3/yr from floods, which primarily occurs with strong, short lasting, rainstorms in the eastern and northern regions. The formation of seasonal floods occurs near the mountains and it may be referred to the availability of a high amount of rainfall. The Aflaj (singular: Falaj) discharge are accounted for 20 Mm^3/yr, where it varies across the falajes due to the amount of rainfall and the location of the source aquifer. The annual contribution of permanent springs was estimated as (3 Mm^3/yr), while the discharge of the seasonal springs (22 Mm^3/yr) (Rizk and Alsharhan, 2003).

1.3.6.1.1.2 Groundwater

Groundwater is considered to be the main source of conventional water in the country. The shallow aquifers are considered as a renewable aquifer, which are primary depends on the rainfall. In contrast, the non-renewable resources occur in the deep aquifers. In general, the dependency on groundwater is reduced due to the over-pumping practices resulting in a reduction of its quantity and quality. Therefore, the country relies mainly on non-conventional water resources besides the conventional resources to meet long-term water demand and manage the deficit in conventional water resources.

The main groundwater recharge mechanisms are summarized as (1) infiltration of periodic surface flow along Wadis that drain the Oman Mountains, (2) subsurface flow from lateral flow in alluvial channels at the mouths of the drainage basins (gaps) along the mountain front, and (3) lateral flow through fractured bedrock along the mountain front. Consequently, these main mechanisms produce three types of flow systems which are local, intermediate, and regional (Figure 2). The local flow system occurs in the eastern mountains, such as Al Fujairah springs, while the intermediate flow system exists in Al-Ain and the groundwater of regional flow system discharged into the coastal regions. In general, the groundwater movement direction is from East to West for all flow types (Mohamed, 2014).

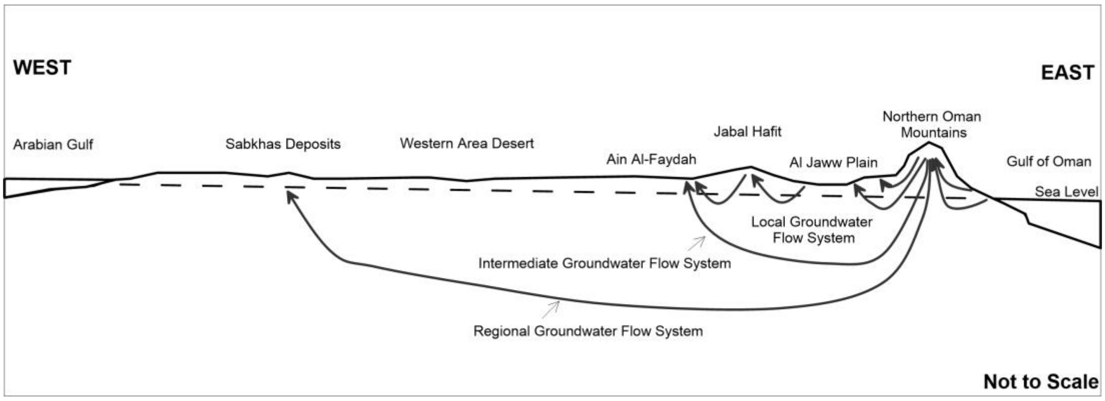


Figure 2: Regional groundwater systems in Abu Dhabi (Alsharhan et al., 2001)

The formations of groundwater can be classified into the Tertiary sediments and Quaternary unconsolidated clastic sediments (Elmahdy and Mohamed, 2015). Figure 3 shows the types of aquifers in the UAE. The main aquifers in the UAE are northern and eastern limestone aquifer, eastern and western gravel aquifer, ophiolite aquifer in the east and sand dune aquifer in the south and west. The description of the various types of the aquifer in the following sections.

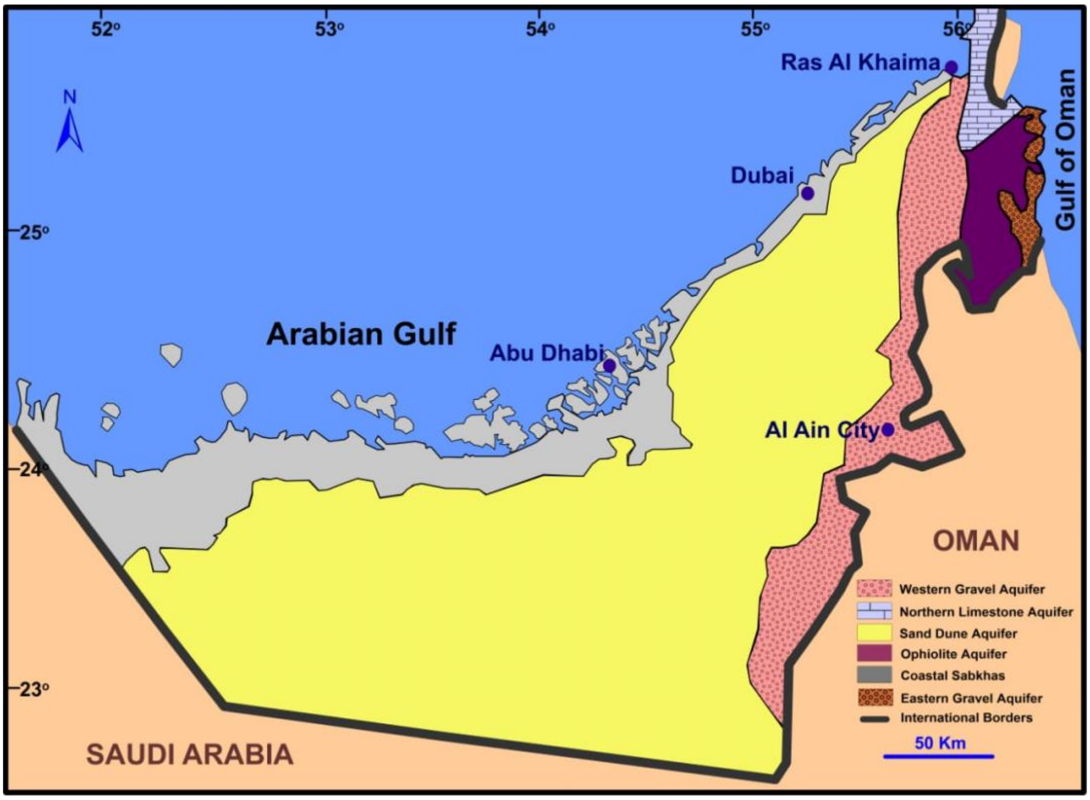


Figure 3: Groundwater aquifers in the United Arab Emirates (Elmahdy and Mohamed, 2015)

1.3.6.1.1.2.1 Limestone Aquifer

There are two major limestone aquifers located in the UAE, which are Wadi Al Bih aquifer in Ras Al Khaimah and Jabal Hafit limestone aquifer in Al-Ain. Wadi Al Bih aquifer belongs to Ru'us Al Jibal Group of Permian to Triassic age. It is composed of fractured limestone and dolomite with hard and non-porous rock at the surface. Jabal Hafit is composed of a sequence of interbedded limestone and marl with gypsum, dolomite and evaporate formations of Lower Eocene to Miocene age. The Middle Eocene Limestone of Hafit mountain experienced several faults and fractures resulting in secondary porosity (Rizk and Alsharhan, 2003)

1.3.6.1.1.2.2 Gravel Aquifer

The gravel aquifer is divided into eastern and western gravel aquifers. The eastern gravel aquifer is composed of a series alluvial flat. While the western gravel aquifer comprises a sequence of sand and gravel with a thickness of 30 m approximately. The gravel aquifer in Al-Ain region is recharged by the rainfall from the Northern Oman Mountains (Brook and Dawoud, 2005). Our study area is located within this gravel aquifer.

1.3.6.1.1.2.3 Ophiolite Aquifer

The Semail ophiolite which known as the Oman-United Arab Emirates ophiolite complex extends from the north-east of Oman to Dibba. According to Elctrowatt (1981), the Semail ophiolite described as being medium-grained gabbro and fine to medium-grained diorites (Rizk and Alsharhan, 2003). The consolidated rocks of Semail ophiolite (igneous and metamorphic rocks) allows for a surface runoff of several Wadi aquifers. However, the ophiolite complex has been subjects to faulting, where low potential of groundwater occurs in fractures and joints (Roberts et al., 2016).

1.3.6.1.1.2.4 Sand Dune Aquifer

Sand dunes aquifer cover about 74% of the total area of the United Arab Emirates. The elevation of sand dune aquifers increases from the western coast at sea level to 250 m above ground level at Liwa-Al Batin basin in the south-central part of the UAE. The fresh water aquifer is situated in the Quaternary sand dunes between Liwa and Madinat Zayed. Explorations of water discovery done in the Bu Hasa oil field indicate the presence of a similar fresh water mound. Similarly, fresh water lenses found between Al Wagan and Liwa area (Rizk and Alsharhan, 2003).

1.3.6.1.2 Non-Conventional Water Resources

The dependency on desalinated water is increasing in the United Arab Emirates accordingly, UAE has become the second largest desalination producer in the world after the Saudi Arabia. The first desalination plant was established in 1976 in the Emirates of Abu Dhabi with a capacity of 66,0000 gallons/day. According to (EAD), the total production of desalinated water estimated to be 809 MCM/year in 2002. Furthermore, treated wastewater is one of the most important alternatives resource to meet the demand of some activities. It is worth mentioning that the wastewater is treated by advanced treatment capabilities before it used in irrigation of public parks and in the agriculture. There sewage treatment plants are exists in Abu Dhabi, Dubai, and Sharjah and recently in Ajman (Brook and Dawoud, 2005). The total production of treated water is about 150 million per year (Rizk and Alsharhan, 2003).

1.3.6.2 Water Resources in Al-Ain Region

Al-Ain is a city in the eastern region of the Emirate of Abu Dhabi. Abu Dhabi is the largest Emirate in the UAE, occupying 80% of the country's total landmass territory. The main aquifers in this region are the tertiary Quaternary sand and sand with gravel aquifers. Historically, Aflaj systems (man-made channels run underground and flowed by gravity from the source to the demand area) were the main source of water supply for drinking and irrigation in the region. Currently, the Aflaj are used only to irrigate the main oasis areas in the garden city of Al-Ain (Brook and Al Houqani, 2006). Figure 4 is summarized the hydrogeological framework in Al-Ain (Hutchinson, 1998).

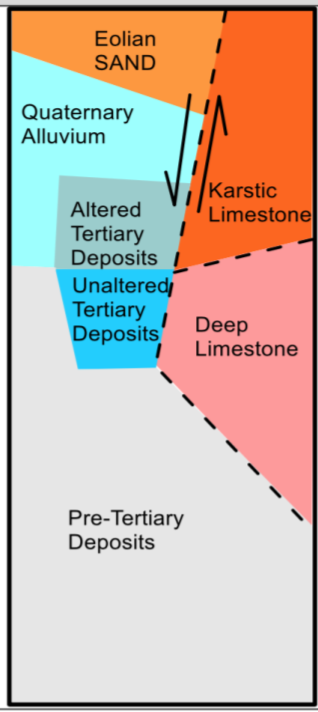
Age	Geologic Sequence	Approximate Thickness (m)	Hydrogeological Unit	
Quaternary	Eolian Sand	25	Unsaturated overburden	
	Alluvium	30	Surficial aquifer system	
Pliocene-Miocene	Post-Fars Upper Fars	200		
Miocene-Oligocene	Lower Fars Formation Asmari Formation	500	Basal Confining unit	
Paleocene-Eocene	Dammam Formation Rus Formation Umm er-radhum Fm.	1200		
Cretaceous	Simsima Formation Qahlah Formation. Juweiza Formation	3000		

Figure 4: Hydrogeologic framework of eastern Abu Dhabi Emirate (Hutchinson, 1998)

The climate is characterized by a low amount of rainfall with an average of less than 100 mm/year and a very high evaporation rate (2-3 m/year). Notably, there are no reliable perennial surface water resources in the region. Hence, it is mainly relying on groundwater, which represents the only renewable water resource. According to the report published by Abu Dhabi Global Environmental Data Initiative Climate Change (AGEDI), the water used in Al-Ain region is estimated to be 1,000 MCM annually (AGEDI, 2015). Additionally, a desalinated water provided to the region is greater than 220 to meet the water demands of a growing population.

Indeed, the annual groundwater abstraction from the shallow aquifers is estimated to be 2200 MCM. In contrary, the aquifers annual recharge has a range from 50 to 140 million cubic meters. Therefore, the rate of groundwater recharge is observed to be less than 4% of total annual water used. Consequently, most of the aquifers comprise non-renewable fossil groundwater (Dawoud and Sallam, 2012). In general, the groundwater table ranges from just below the land surface along the coast to more than 400 m above mean sea level (MSL) in the regions around Al-Ain. In fact, over 100,000 wells across Abu Dhabi Emirate, most of these wells are in Al-Ain region suffered from extreme depletion of groundwater level resulting in depleted areas (Al Madfaei et al., 2017). Figure 5 indicates the fluctuation in groundwater levels between 2005 and 2017, where groundwater levels are generally experienced a steady decline with a severe decline in Al-Ain (EAD, 2018).

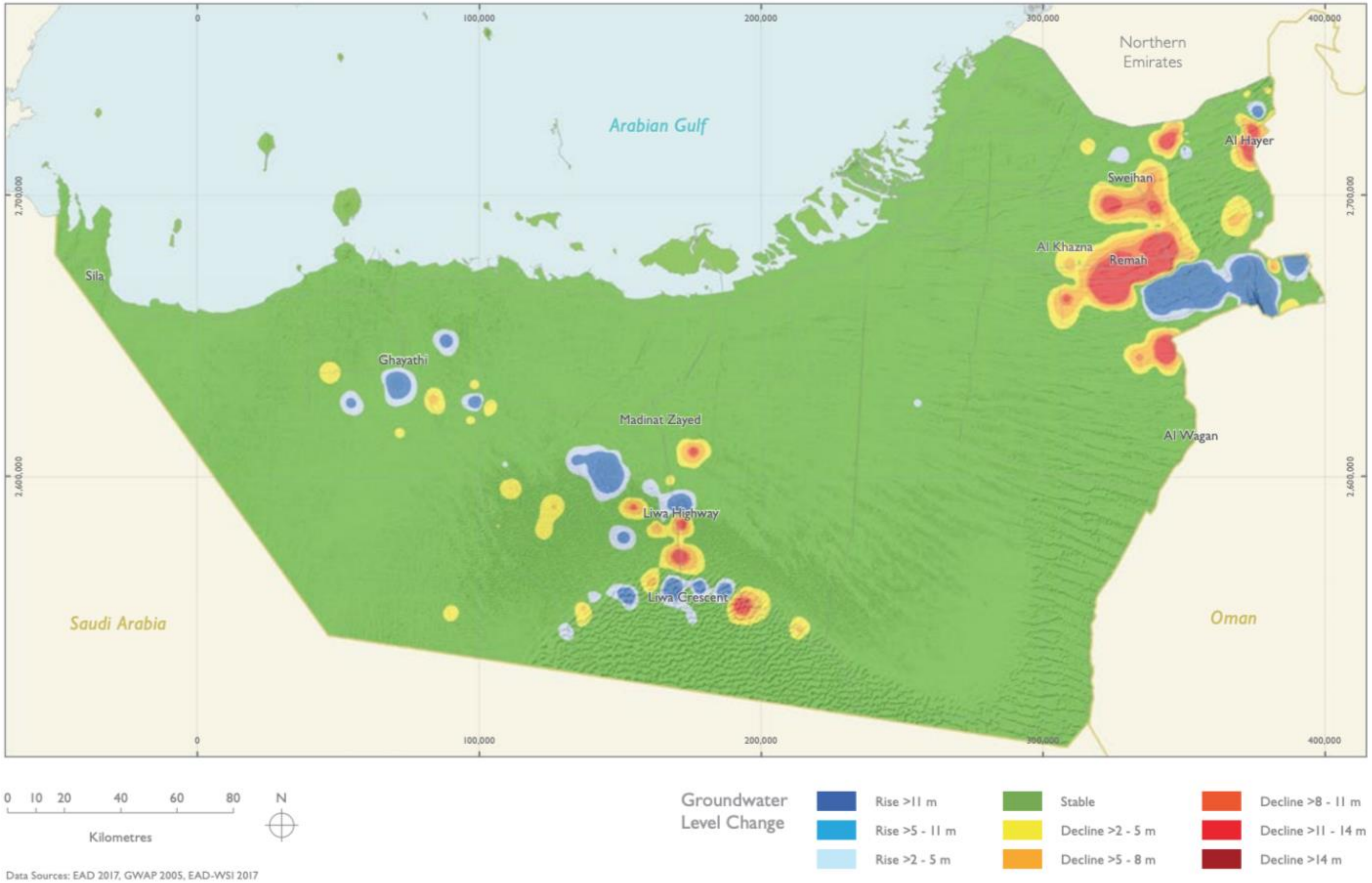


Figure 5: Groundwater levels below ground surface between 2005 and 2017 (EAD, 2018)

1.3.6.3 Climate

The key source of the meteorological data given in this section is from the National Centre of Meteorology and Seismology (NCMS) and reported by the Statistics Centre (2017). The statistics will describe the trend and state of the climate elements including temperature, rainfall, relative humidity, wind speed and evaporation. The analysis of climate data is given below (SCAD, 2017).

1.3.6.3.1 Temperature

As shown in Figure 6, the average maximum temperature is 37.6 ℃ and it was recorded in July 2016, while the average minimum temperature is 18.2 ℃ and was recorded in January 2016. The absolute maximum temperature was 50.7 ℃ in July and the absolute minimum temperature was 3.9 ℃ in January (Table 1). The highest maximum temperature is recorded between May and September.

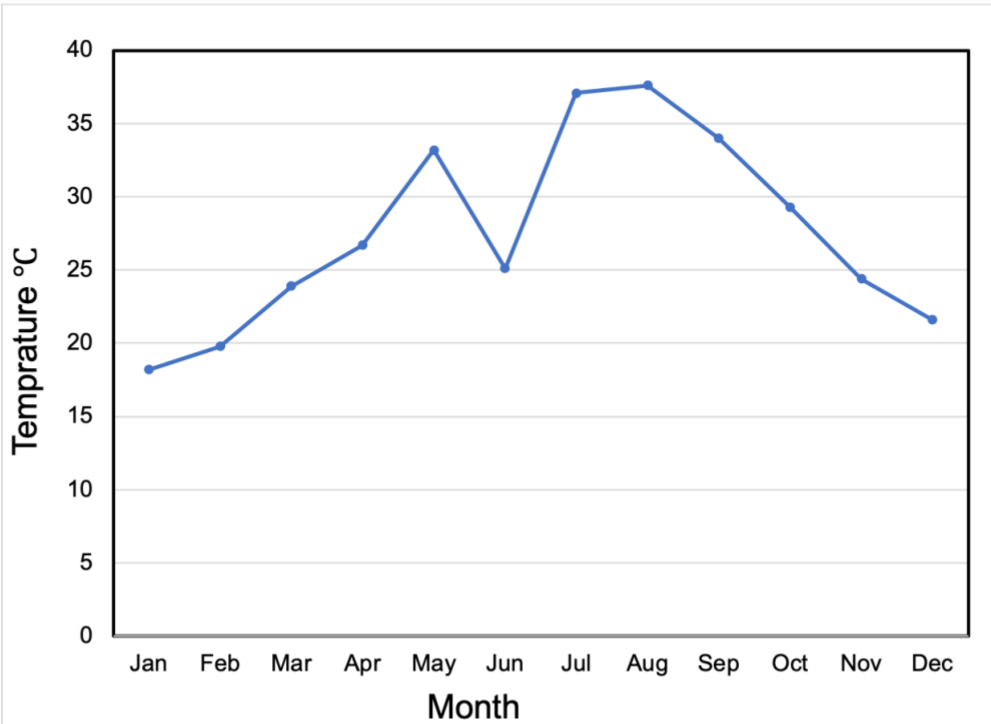


Figure 6: Monthly changes of air temperature in Al-Ain – 2016 (SCAD, 2017)

Table 1: Monthly air temperature, Al-Ain – 2016 (SCAD, 2017)

Month	Monthly average (°C)	Absolute minimum (°C)	Average minimum (°C)	Absolute maximum (°C)	Average maximum (°C)
January	18.2	3.9	12.5	31.8	17.3
February	19.8	7.0	13.1	36.0	19.7
March	24.0	11.3	18.0	37.2	23.0
April	26.7	9.8	19.9	43.5	25.7
May	33.2	18.2	25.3	47.6	33.0
June	35.6	22.0	28.3	49.3	43.1
July	37.0	23.5	30.6	50.7	36.9
August	37.6	20.4	31.0	48.9	37.2
September	34.0	19.5	27.8	48.2	33.4
October	29.1	18.6	22.9	42.2	28.4
November	24.4	13.7	18.7	36.6	23.7
December	21.6	8.9	15.6	37.0	21.9

1.3.6.3.2 Rainfall

Al-Ain city characterized by low and scanty rainfall, which occurs during the winter between November and March. Sometimes, the rain falls in the summer season on the mountains. Table 2 shows the average rainfall changes within one month in 2016, where the maximum average rainfall reached 83.7 mm in March. Figure 7 displays the total amount of rainfall for month in mm.

Table 2: Monthly average rainfall, Al-Ain – 2016 (SCAD, 2017)

Month	Average Rainfall (mm)
January	7.7
February	5.7
March	83.7
April	2.5
May	0.0
June	0.0
July	1.9
August	2.8
September	2.4
October	10.6
November	0.3
December	0.0

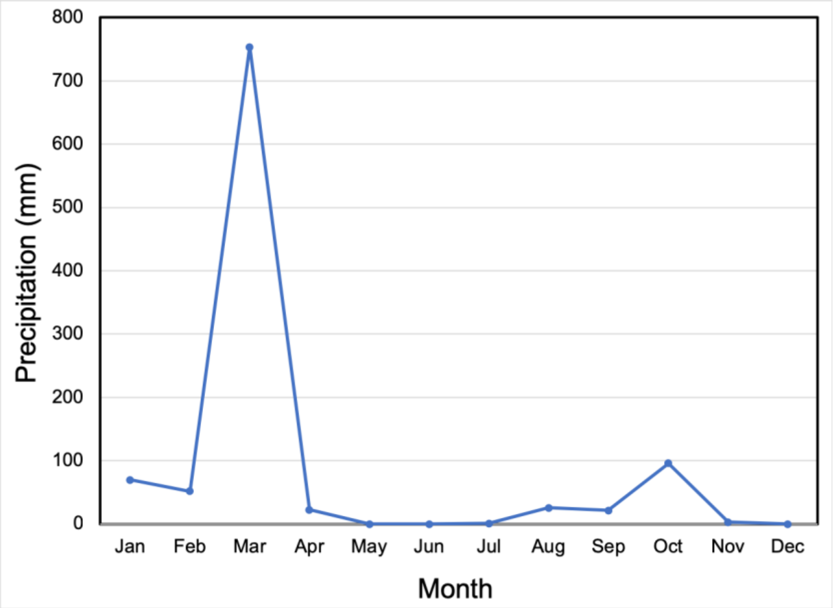


Figure 7: Monthly rainfall in Al-Ain– 2016 (SCAD, 2017)

1.3.6.3.3 Relative Humidity

The changes in relative humidity are low during the day, while it is high in the night due to the decreases in the temperature. In coastal areas, relative humidity is greater than inland areas, where Al-Ain is situated in a non-coastal area characterized by low relative humidity. The relative humidity is defined as the ratio of water vapor in a specific volume of moist air at a certain temperature to the mass of water vapor in the same volume of saturated air at the same temperature. Table 3 indicates the values of relative humidity in 2016 which is expressed as a percent. The highest average relative humidity recorded in Al-Ain was 59.0% in July. While the lowest value recorded in August was 23.2%.

Table 3: Monthly average relative humidity, Al-Ain – 2016 (SCAD, 2017)

Month	Relative Humidity (%)
January	59.0
February	51.2
March	47.1
April	34.8
May	26.4
June	29.2
July	35.6
August	23.2
September	39.9
October	44.4
November	51.7
December	54.9

1.3.6.3.4 Evaporation

The rate of evaporation mainly is affected by the temperatures, surface area, humidity, and wind speed. Hence, the rate of evaporation increases on increasing the temperature, surface area and wind speed and decrease of humidity. Table 4 shows monthly average evaporation recorded in Al-Ain International Airport station during 2017. The highest values of evaporation observed in summer season as shown in Table 4, the maximum average value of evaporation was 21.24 mm in July.

Table 4: Monthly average evaporation in Al-Ain (Al-Ain Airport Station) – 2017

Month	Average evaporation (mm)
January	6.47
February	7.43
March	11.63
April	16.61
May	18.24
June	20.19
July	21.24
August	19.93
September	17.41
October	12.79
November	8.90
December	6.99

1.3.7 Geomorphology and Geology of Study Area

1.3.7.1 Location of Al-Ain

The United Arab Emirates is located in the southeastern part of the Arabian Peninsula between 22° 50′ and 26° 00′ North latitudes and between 51° 00′ and 56° 00′ East longitudes. It is bounded from the north by the Arabian Gulf, on the east by the Sultanate of Oman and the Gulf of Oman, and on the south and the west by the Kingdom of Saudi Arabia. Al-Ain city is situated in the eastern region of Abu Dhabi Emirates, near the border with Oman and at the western margin of the northern Oman Mountains (Figure 8) Al-Ain is the largest inland city in the UAE and the second-largest of Abu Dhabi Emirate. The city is considered as one of the largest and ancient oases of the Arabian Peninsula, due to the abundant supply of surface and subsurface water derived from the Oman Mountains to the east.

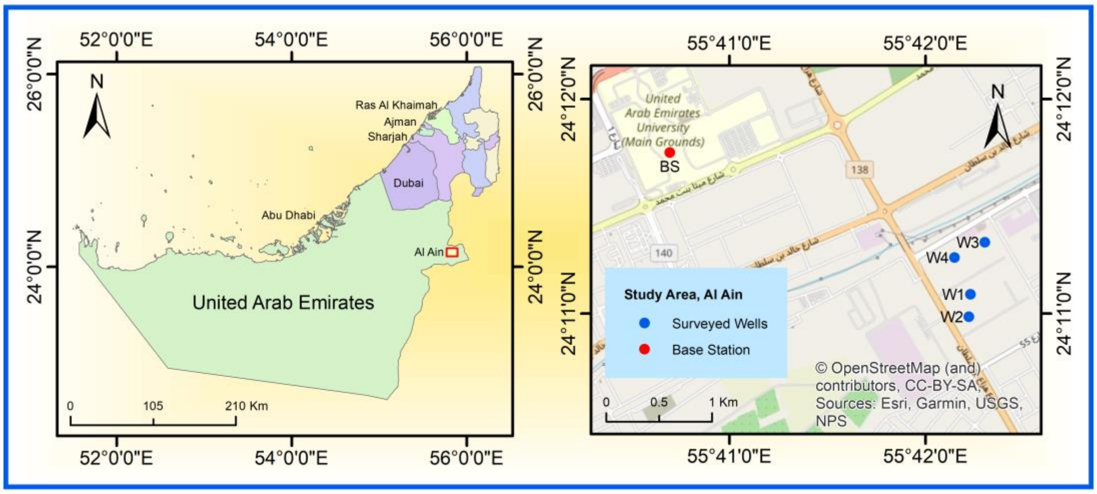


Figure 8: Location map of Al-Ain city and the study area

1.3.7.2 Geomorphology of Al-Ain

The geomorphological provinces of Al-Ain are classified into three main provinces according to El-Ghawaby and El Sayed, (1997) as (a) Al Jaww piedment plain of the Oman Mountains to the east, (b) the hilly area where bedrocks crop out to the south-east, and (c) the dune-covered scarps to the north and south. Al Jaww plain is made up of gravel and sand outwashes from the surrounding mountains and the deposited in the main Wadies (El-Ghawaby and El-Sayed, 1997). Hafit Mountain represents the hilly area in Al-Ain region. It is bounded to the north by Al-Ain city, to the east by Al-Jaww plain and to the south by Oman. Jabal Hafit is determined by its anticline structure with approximate elevation of 1300 m above sea level. Hafit Mountain is almost composed of limestone and marls of Eocene to Miocene age. The core of the Hafit Mountain made up of limestones and dolomites, while the overlying formation is composed of limestone. In general, the most dominated geomorphological units in the UAE are the sand dunes. Al-Ain area is dominated by two types of dunes, which are linear and star dunes. The northern and western parts of Al-Ain are characterized by linear dunes. While the southeastern areas of Al-Ain are dominated by the star dunes. Also, the low lands between the sand dunes are occupied by the interdune, where the groundwater is shallow and favorable for agriculture activities.

1.3.7.3 Geology of Al-Ain region

The geological settings are described according to El-Ghawaby and El Sayed, (1997). Figure 9 shows the geological map of Al Ain area. Quaternary–Holocene deposits in Al-Ain consist of near-surface and surficial sediments of alluvial, aeolian and local Sabkha origin. The range of size for alluvial deposits is from cobbles, boulders and pebbles at the eastern part, where valleys debouch from Al Jaww plain to pebbles and coarse sand where the main valleys become masked by the sand dunes to the west of Al-Ain town. The gravels are mainly cemented by calcium carbonate, calcium magnesium carbonate or gypsum. Most of the alluvium accumulations has been deposited after transport within the Wadi network draining westward and northward from the ophiolitic and carbonate source rocks of the Oman Mountains and Jabal Hafit, respectively.

Al-Ain depression is mainly composed of alluvial gravel deposits indicating old courses of buried paleochannels in other places than the presently active valleys. The Quaternary–Holocene deposits show great variations in thickness due to the effects of subsurface faults and tilting undulations. The Quaternary–Holocene alluvium has been detected in the inter-dune trough zone for a thickness ranges from 10 to 30 m, while it is missing or very thin in dune ridges. Al-Ain is mostly dominated by the desert plain deposits which composed of laminated silt partially cemented with carbonate or salts and underlain by layers of gravel, sand, mud and calcareous rock fragments with stringers of gypsiferous and calcareous material. Sabkha deposits are developed on the interdune areas as an inland Sabkha partially covered with aeolian sand deposits, where the surface is marked by an encrustation of salt with scattered authigenic crystals of gypsum that protrude from it at different localities. Shallow trenches in other Quaternary deposits indicate the presence of these Sabkhas in mud layers (El-Ghawaby and El-Sayed, 1997).

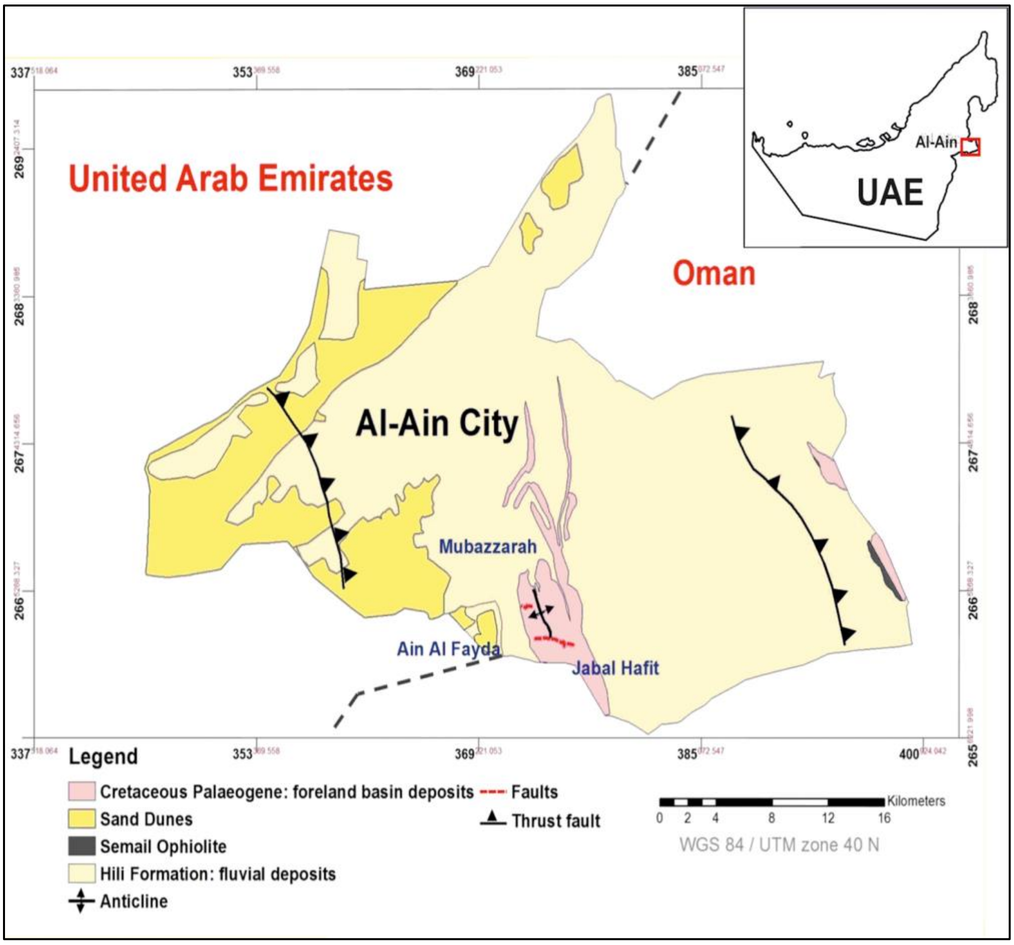


Figure 9: Geological map of Al-Ain (modified after Thomas et al., 2014)

1.4 Aims of the Study

The aims of this study are to document the results of the application of microgravity methods and provide analyses of storage changes based on microgravity measurements from March 2018 to March 2019, in four groundwater wells located in Al-Ain city, United Arab Emirates. In order to achieve these aims, the following objectives have been set:

1. To use a microgravity method in combination with water-level data monitoring to understand the relationship between gravity changes and hydrological data changes in Al-Ain.
2. To monitor groundwater storage changes caused by mass distribution of groundwater either from the injection or pumping.
3. To monitor groundwater storage changes directly and without observation wells in Al-Ain is interesting in saving budget and can be extended to other regions in the UAE.
4. The results of this study will be useful for water management considerations and additional future investigations, such as groundwater modeling.

Chapter 2: Methods

2.1 Time-Lapse Relative Microgravity Survey

In groundwater investigations, changes in groundwater storage are estimated through time-lapse gravity surveys. Relative-gravity survey allowed for the estimation of the increases and decreases in the volume of aquifer storage due to groundwater recharge and withdrawal, respectively. The variations in gravity are measured relative to a base station which must be located away from the study area to eliminate the effects of water mass changes in the aquifer. The survey must be initiated and ended at the base station. There are several factors affect the measurements of gravitational acceleration, including tide, instrument drift and altitude. Although, for groundwater exploration, time-lapse relative gravity surveys have the advantage of limited corrections required for gravity data. For example, altitude and terrain effects are canceled out when the gravimeter is placed at the same position for each survey. Despite, some corrections must be applied for instrument drift and Earth tides.

2.2 Field Procedures

In this study, a gravimeter called the CG-6 Autograv by Scintrex and Micro-g LaCoste was used during microgravity field survey. The survey consists of four microgravity monthly monitoring at 4 wells from March 2018 to March 2019, during consecutive wet and dry periods. In addition, hydrological and meteorological data had accompanied gravity data to monitor variations of groundwater storage.

The CG-6 is the latest generation microgravity meter from Scintrex ltd., providing fast, reliable and precise gravity measurements. The CG-6 measures relative differences in gravitational attraction using a fused quartz sensor, it is easy to operate, lightweight (5.5 kg including batteries), and has a reading resolution of 0.1 μGal (Figure 10).

Figure 10: The CG-6 Autograv (Scintrex Limited, 2016)

An external tablet computer allows to set-up the gravimeter and stores the setup settings. The Lynx LG Land Gravity processing software support the CG-6 system which is installed in the tablet. It has many advanced features for recording, presenting and correcting CG-6 data. LynxLG software allows the operator to apply several standard corrections to the gravity data as shown in Table 5 (Scintrex Limited, 2016). There are several corrections are not necessary to be applied in temporal gravity survey including a Bouguer correction, a latitude correction, a free air correction, and a terrain correction, because these corrections are dependent on station location, where gravity surveys are concerned with the changes in gravity through time at the same station.

Table 5: Table of gravity corrections

Parameter	Formula	Description
Tilt	$C\ (1): (1 - \cos(L\ (1) * A) * \cos(L\ (c) * B)) * D$ A = The X level calibration factor. B = The Y level calibration factor. D = Gravity Constant (9.806e5. C(l) = Level Correction in mGal. L(c) = Observed Y Level. L(l) = Observed X Level.	Level correction is based on the X and Y level tilt off of vertical. When the meter is well leveled, the indicator is close to the center and the numeric values are close to zero.
Temperature	$C\ (t) : A * T\ (o)$ A = Temperature factor in mGals/mK. C(t) = Meter Temperature Correction in mGal. T(o) = Observed meter temperature.	The Temperature correction factor is based on the sensor temperature. This correction factor is set by the factory for the Gravilog sensor and should not be changed by the user.
Drift	$C\ (d): A * (D\ (n) - D(r))$ A = The sensor drift admittance factor mGals/day. C(d) = Drift Correction in mGal. D(r)= Drift Time Zero. D(n): Current times in seconds from January 1st, 1904.	This correction compensates for the long-term meter drift rate.
Tide	-	The effect of tide (sun and moon attraction) is computed by two types of tidal corrections (Berger and ETGTAB).

To conduct this survey, the basic steps are summarized as: (1) creating station for a gravity points, (2) leveling the gravimeter and connecting the built-in GPS to find the latitude, longitude, time, date and elevation, (3) taking the measurements with the gravimeter, (4) recording the data measured and (5) retrieving data by connecting the CG-6 Autograv with computer by a cable.

During a field survey, the gravimeter was placed on a tripod and the height of the gravimeter to the ground surface was measured at each station after leveling the instrument. Gravity changes related to aquifer mass changes may be affected with the differences in gravimeter height between positions of the same station (1-cm difference in instrument height produces about 3 mGal changes in gravity) (Gehman et al., 2009). However, a correction for instrument height changes not required because the gravimeter was placed at a fixed height above each station.

The first station measured was defined as the base station, which located at UAEU-E4 lab and identified as BS. At the base station, the CG–6 gravimeter was remained on power and leveled on the tripod. Besides, the gravimeter is stored in the teaching laboratory which is active and considers as a source of the noise. All the measurements were made relative to the base station. Ideally, the base station should be located a sufficient distance from the locations of wells. However, the selection of the base station was based on the easily accessible from the gravity stations comprising the survey. As shown in Figure 11, the locations of the four wells are indicated by blue circles, while the base station is represented with the red circle. The gravity stations are identified by a station name (W1 through W4).

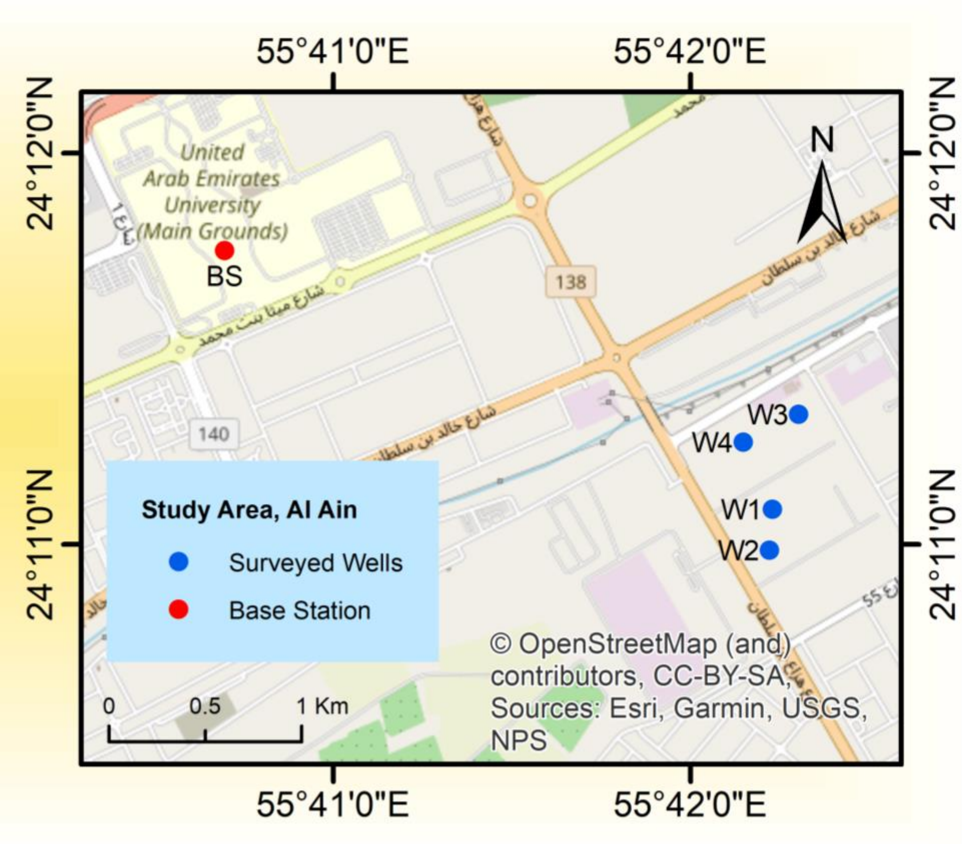


Figure 11: Location map of the four wells and base station

The survey is initiated by measuring the relative gravity at the base station, followed by recording the gravity measurements at the four wells to create a closed loop (Figure 12). After measuring the gravity at the last survey station, the survey was repeated by measuring the gravity at the four wells (two-way measurements). The field acquisition day is ended by making one final reading of the gravity at the base station. This procedure is generally referred to as a looping procedure. The measurements length can be either 30 seconds, 60 seconds or 120 seconds. In our survey, the cycle has a measurement length of 120 sec. After the survey, gravity measurements were repeated at the base station every 60 sec for instrument drift corrections. The CG-6 has automated corrections for the tide, instrument tilt, temperature and drift.

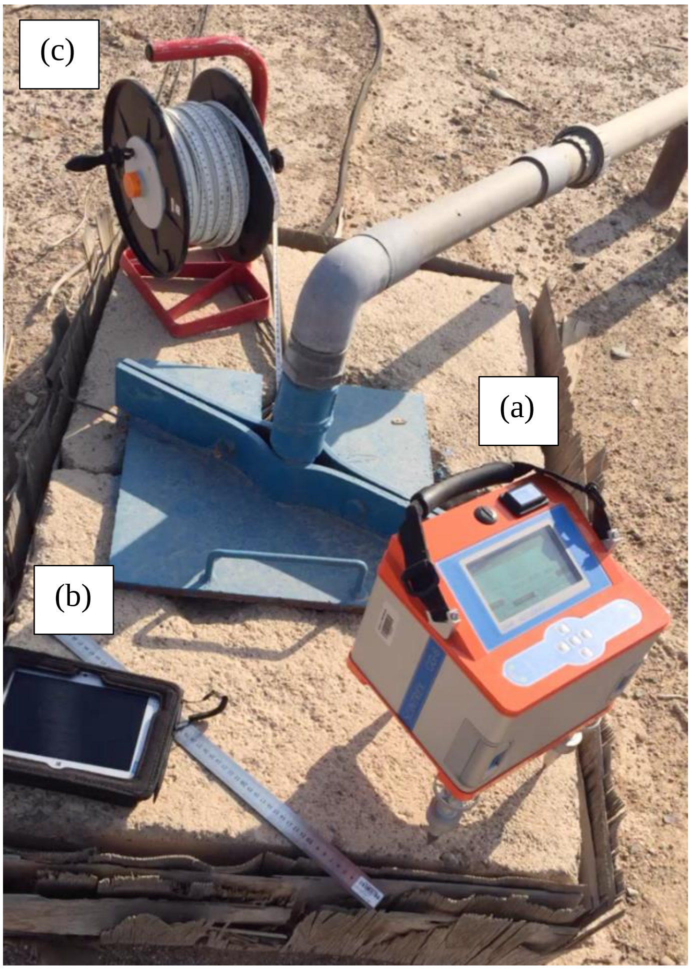


Figure 12: Field setup at well 2, (a) CG-6 Autograv, (b) tablet and (c) sounder water level

Water measurements were taken of depths to water from the top of each well by Sounder Water Level. In measuring, the cable reel was rotated, and the dual conductor wire has dropped slowly into the well. When the probe contacts the water, the circuit closes, and the receiver system buzzer will sound. The water depth is then determined by taking a reading from markings on the wire.

2.3 Methods for Estimating Groundwater-Storage Changes

Microgravity method was used to estimate changes in gravitational acceleration associated with groundwater mass changes. In confined aquifers, the pores are filled with air and therefore, small changes in water storage occur. Then, changes in groundwater storage were assumed to occur in unconfined aquifers beneath a measurement station. The lateral extent is supposed to be greater than the vertical distance of the groundwater mass, accordingly, changes in groundwater storage are assumed to be in the form of an infinite slab. Thus, the thickness of slab is assumed to be the entire thickness of the volume in which groundwater storage occurs. This assumption is referred to as the Bouguer slab equation (Telford et al., 1990):

$$\Delta g = 2\pi G \Delta\rho_{rw} b \qquad (5)$$

Where, Δg is the change in the gravitational potential resulting from a change in groundwater storage mass, $\Delta\rho rw$ is the change in density of the rock and water slab, and b is the thickness of the slab.

Because the groundwater storage changes in the unsaturated zone are small (assumed to be zero), the slab is equal to the change in water table altitude Δh. The change in density is calculated by the product of the effective porosity (φ) and the water density ρw.

$$\Delta\rho rw = \varphi\rho w \qquad (6)$$

Substituting equation 6 into equation 5 for the special case where ($\Delta h = b$) and combining the constant parameters yields:

$$\Delta g = 12.77\varphi\Delta h \qquad (7)$$

Δg is the change in the gravitational potential in μGal,

φ is the effective porosity,

Δh is the change in water-table altitude in feet.

Also, the effective porosity can be estimated for the special case of $\Delta h = b$, by the following equation:

$$\varphi = \Delta S/\Delta h \quad (8)$$

φ is the effective porosity,

ΔS is the groundwater-storage change expressed as the change in the vertical height of water in feet with no rock present,

Δh is the change in water-table altitude in feet.

Thus, by assuming that no mass changes in the unsaturated zone occurred, groundwater-storage would be determined by combining equations 7 and 8:

$$\Delta S = \Delta g/12.77 \qquad (9)$$

The final equation for calculating the effective porosity of an unconfined aquifer at the water table as a function of the change in gravitational potential in microgal and water-level change (Δh), in feet, for cases when $\Delta h = b$:

$$\varphi = \Delta g/12.77\Delta h \qquad (10)$$

Chapter 3: Results and Discussion

3.1 Relative Gravity and Water Level

All the microgravity values and water level measurements from March 2018 to March 2019 at four wells are referenced to base station (UAEU, E-4 building) data of March 2018. Figure 13 shows the relationship between the depths to the groundwater level and the relative microgravity within the study area. Regression analyses revealed a negative correlation for microgravity and depth to groundwater in the four wells. The relation between the changes in water level is inversely proportional to the changes in relative gravity. The values of microgravity increased as groundwater depth decreased due to the rises of groundwater level that fills fractures and voids within rocks and soil and therefore relative gravity. Groundwater table changes are believed to be the primary reason for the observed gravity fluctuations. This resulted relation presented in this work agreed the result with those reported for assessing groundwater variation using microgravity conducted in Riyadh, Saudi Arabia where the relative gravity tend to decrease with increasing depth to groundwater in 42 monitoring wells (Alfy et al., 2016).

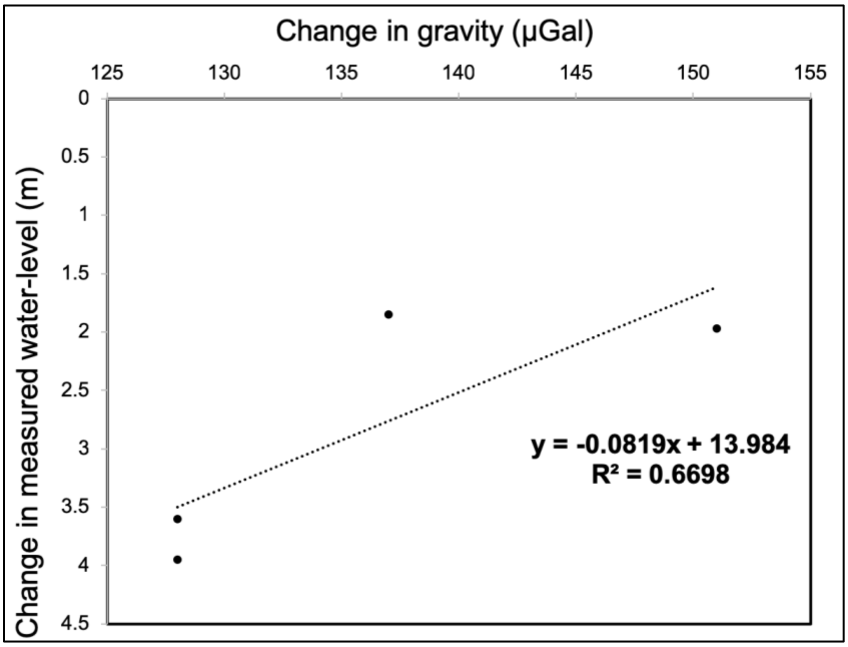


Figure 13: Gravity values related to depths to groundwater at four wells

As shown in Figure 13, microgravity changes (Δg) at the four well stations relative to the base station ranged from 128 μGal to 151 μGal for the entire study period, with an average value and standard deviation of 136 and 10.86, respectively. Water level changes (Δh) ranged from 1.85 m to 3.95 m below the land surface. The highest microgravity-change value was observed in W2 (151 μGal), followed by W1 (137 μGal), while the lower value was observed in both W3 and W4 (128 μGal). A linear model was generated between depth to groundwater (Y) and relative gravity (x). This type of trend line uses a specific equation to calculate the least squares fit through data points. The resultant regression equation is:

$$Y= -0.0819x + 13.984 \qquad (11)$$

The correlation coefficient for depths to groundwater and microgravity values ($R^2 = 0.67$), which mean that microgravity values explain 67% of the variability of the changes in water level. The R^2 value indicates that the model fits the data well. Minitab 17 statistical software used for statistical analysis; Anderson-Darling normality test was applying to check the normality of relative gravity values with a significant level of 0.05 and a 95% confidence level. As shown in the normal probability plot in Figure 14, the p-value is 0.201 which is greater than the significance level 0.05 generally required to accept the null hypothesis and agree that the data follow a normal distribution.

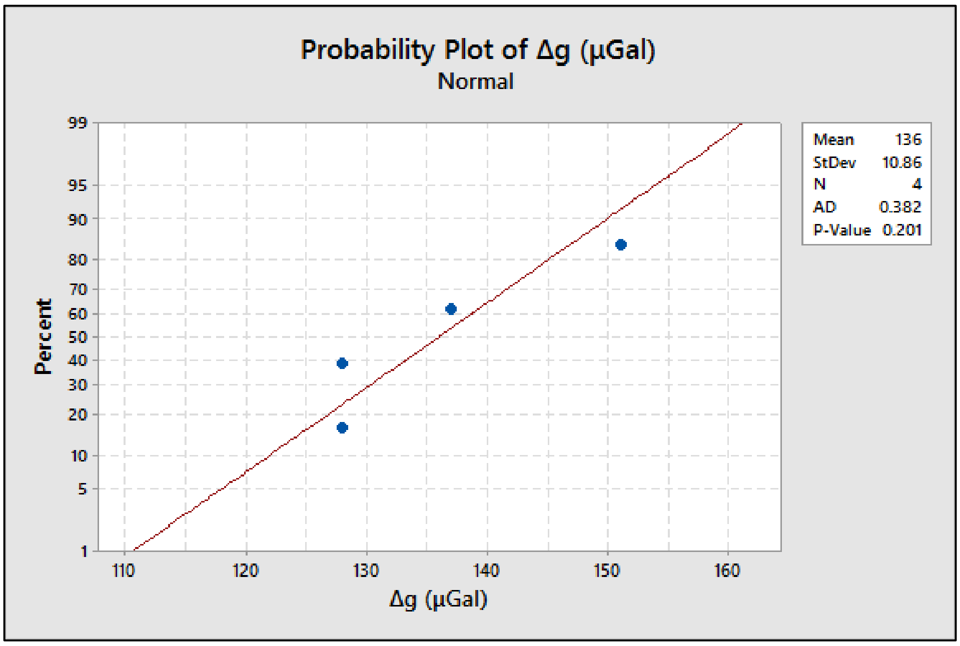


Figure 14: Normal probability plot of gravity-changes

In addition, model adequacy has been investigated by examining the residuals, which are defined as the difference between the experimental values and the fitted value as per the model equation. The residual plots help to determine whether the model is adequate and meets the assumptions of the analysis. The assumption that the residuals are normally and independently distributed must be satisfied before statistically analyzing data.

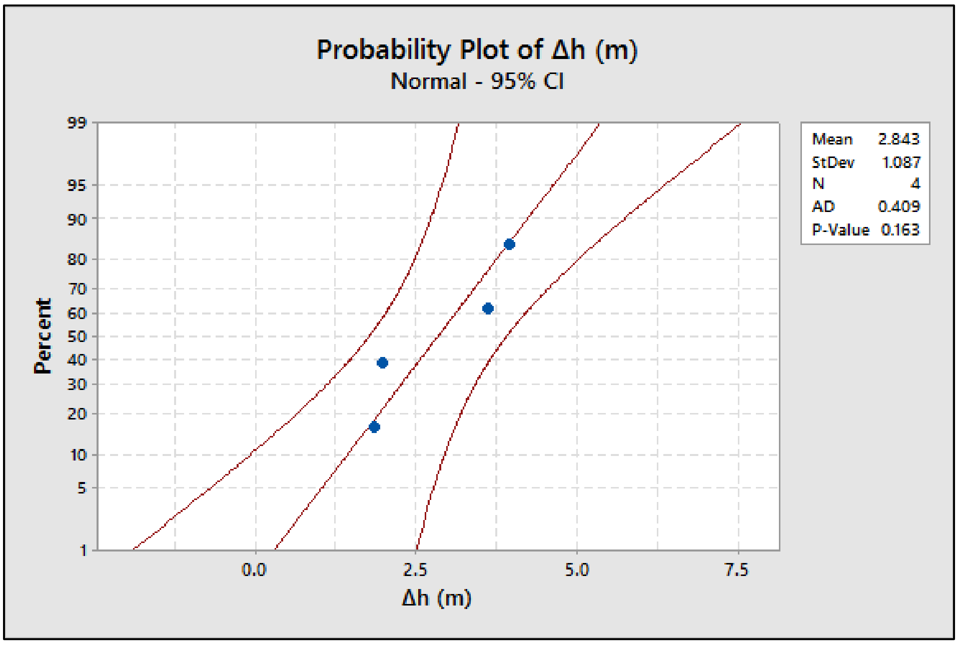


Figure 15: Normal probability plot of residuals

The normal probability plot in Figure 15, shows that the residuals generally appear to follow a straight line, which indicates the difference between observed and fitted values, presented by the diagonal, is small. Furthermore, the p-value is larger than the significance level (0.163). The plot of the residuals versus fitted value, shown in Figure 16, reveals no obvious pattern, which suggests a constant variance of the residuals. It also means that the predicted values of the dependent variable (i.e., water level) by the regression model (Equation 11) was consistent across all the values.

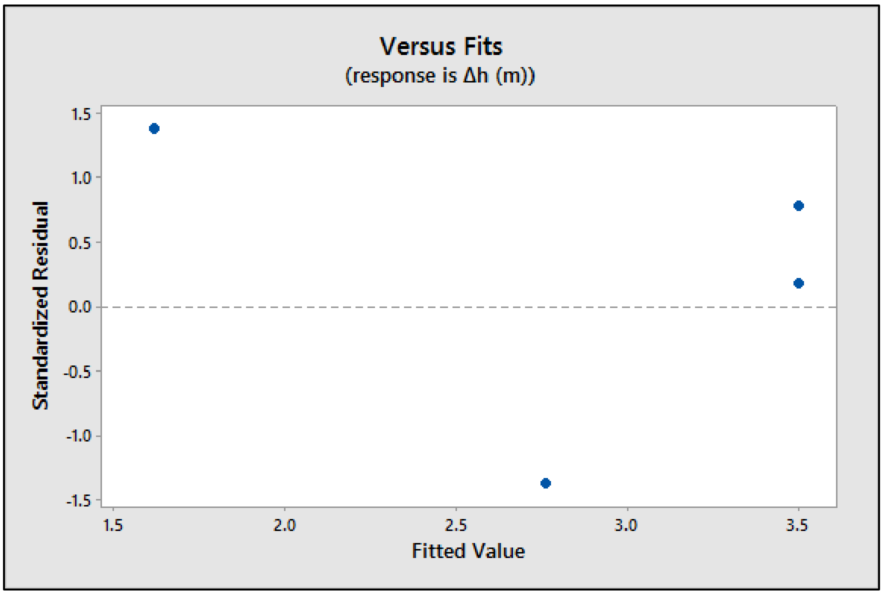


Figure 16: Residual versus fitted value

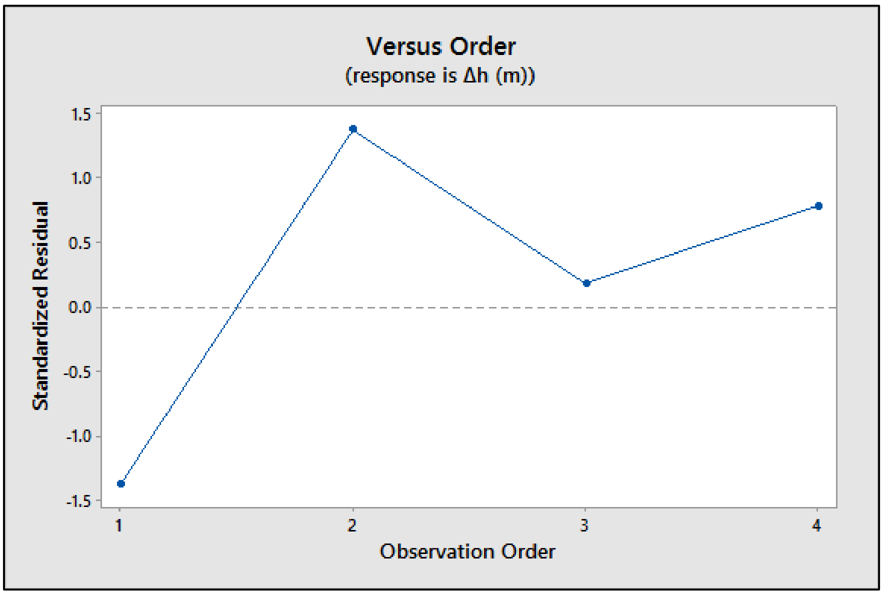


Figure 17: Residual versus observations order

Figure 17 shows the residuals versus the observations order, which clearly indicates that the residuals were randomly distributed around the zero line. This suggests that there is no correlation between the residuals in case of observations order and thus, the residuals are independent.

3.2 Groundwater Storage-Changes Determined from Gravity

Figure 18 shows the relationship between groundwater-storage change (ΔS) and microgravity values (Δg). Groundwater storage-changes are determined from gravity measurements at the four wells (W1 to W4), which are expressed as the change in the vertical height of water with no rock present. Estimated groundwater storage-change at the four wells varied from 3.05 m of water at well three and well four to 3.27 m at well one and 3.60 m at well two. Regression analyses revealed a strong positive correlation for microgravity and groundwater storage in the four wells ($R^2 = 1$). A linear regression model was used to predict the relationship between changes in groundwater-storage and relative gravity.

$$Y = 0.0239x \quad (12)$$

Where Y represents the groundwater storage and x represents the relative gravity. The relation between the changes in groundwater storage is proportional to the changes in relative gravity. Therefore, the addition of mass in the subsurface causes an increase in the measured gravity value, while, the subtraction of mass causes a decrease in the measured gravity (Kennedy et al., 2015).

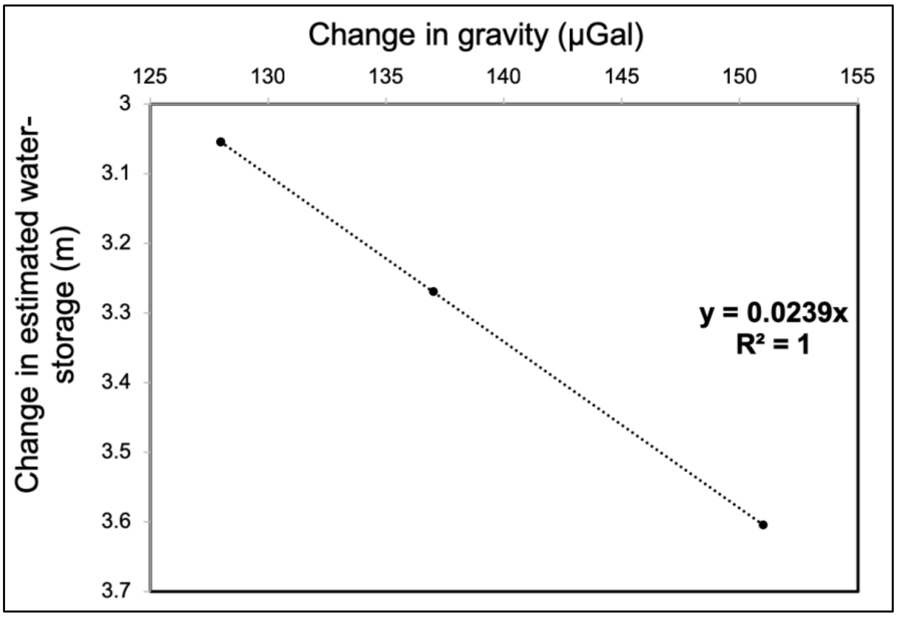


Figure 18: Groundwater-storage change determined from microgravity measurements

In addition, changes in groundwater levels provide an indication of the changes in groundwater storage. The rises in groundwater-storage as determined by gravity measurements were corresponding to the increases in water levels (Figure 19). A negative correlation exists between groundwater level-changes (Δh) and groundwater-storage changes (ΔS), where the correlation coefficient is 0.67. The relation between the changes in water level is inversely proportional to the changes in water storage. Thus, the values of water-storage increased as groundwater depth decreased.

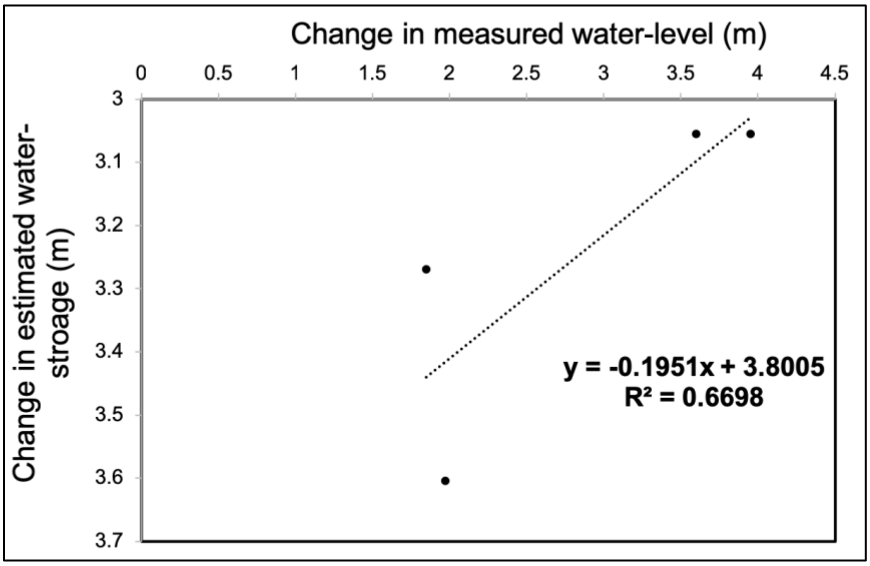


Figure 19: Changes in groundwater- storage estimated from microgravity and changes in water-level

3.3 Meteorological Data

The source of precipitation and evaporation data is from the National Centre of Meteorology and Seismology (NCMS), at Al-Ain Airport station (Located 18.7 km from the study area), during the period of microgravity measurements (March 2018 to March 2019). The study area is characterized by a high rate of evaporation and scanty precipitation. The maximum intensity of rain falls during February 2018 and March 2019, as shown in Figure 20.

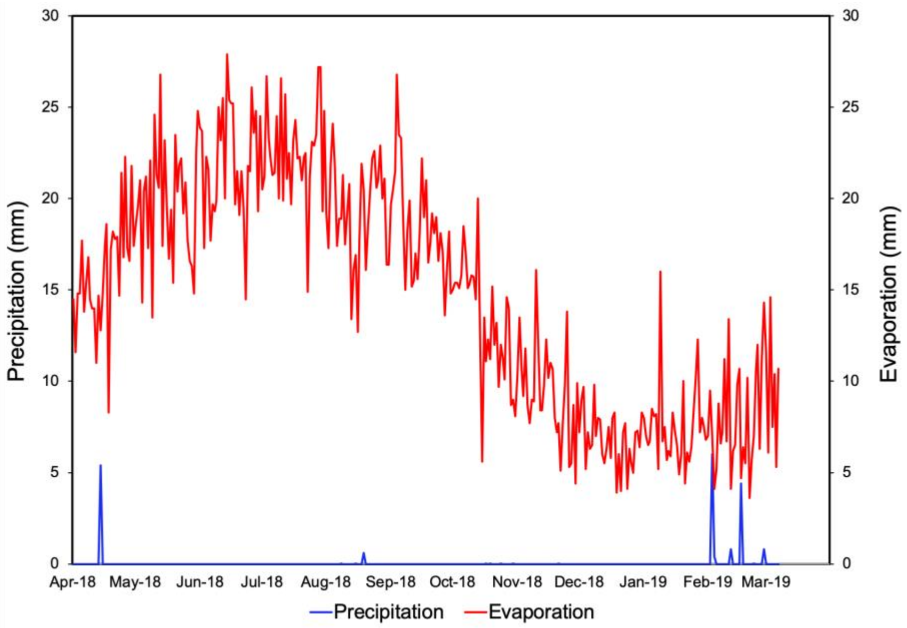


Figure 20: Daily precipitation and evaporation data at Al-Ain Airport Station from April 2018 to March 2019, from the National Centre of Meteorology and Seismology (NCMS)

3.4 Interpretation of Changes of Gravity Measurements in the Wells

The variations in water storage may be linked to seasonal changes in water demand that require wells used for irrigation and public demand to be pumped for longer periods of time and more often in the summer than during the winter. The impacts of the water-storage depletion made evident by declining in the groundwater levels. In our study area, well 1 and well 2 are considered as operational wells. However, well 3 and well 4 are non-operational wells.

Figures 21 and 22 show the monthly changes of the microgravity measurements in well 1 and well 2 with corresponded changes on precipitation, evaporation and water level. Generally, groundwater levels rise during the wet periods and decline during the droughts. Changes in groundwater level (Δh) in well 1 and well 2 commonly decline during the summer (July to September in 2018) ranging from less than 1 m to about 9 m deeper. This lowering of the water level probably referred to several factors, including a high rate of evaporation, low rate of precipitation and large extraction of groundwater. On the other hand, the water level rise during the winter (December 2018 to March 2019) ranging from 1-3 m, approximately, due to the increases of precipitation and decreases of evaporation. Furthermore, the groundwater level apparently increases during the irrigation season due to the secondary recharge from the rainfall. Approximately, most of the microgravity measurements correspond with the increases in water level at the well 1 and well 2. Therefore, high values of microgravity indicate decreases in water depth.

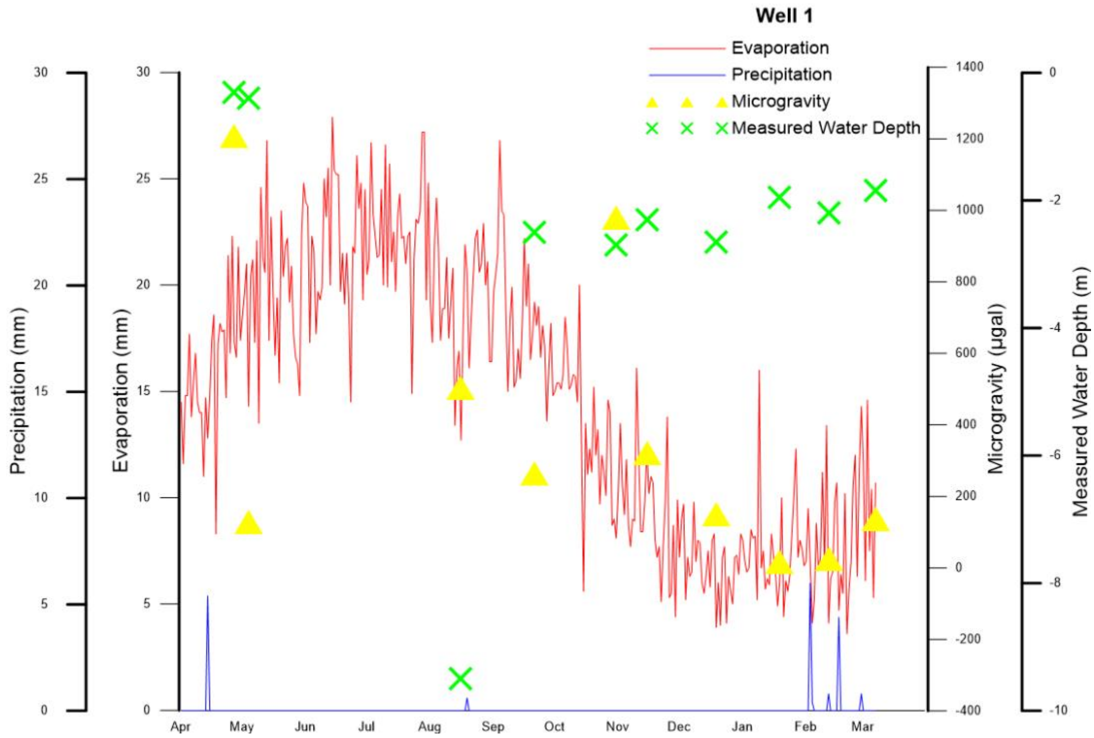


Figure 21: Data of microgravity measurements, water level changes, precipitation and evaporation data at well 1 (from April 2018 to March 2019)

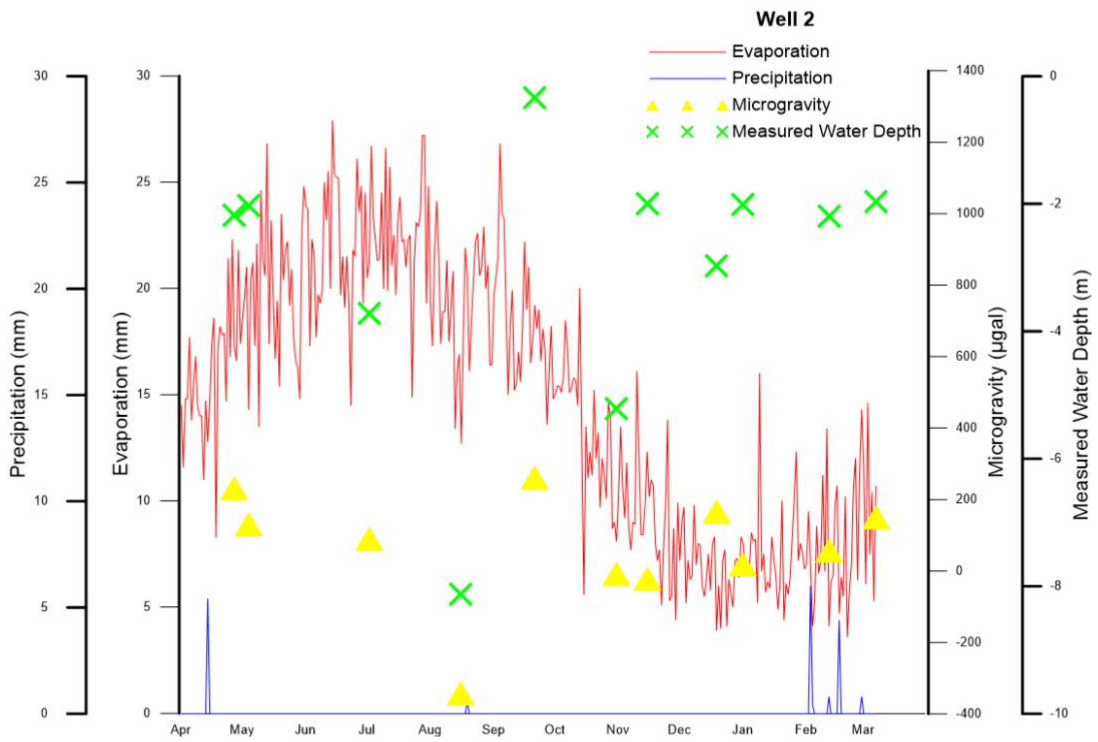


Figure 22: Data of microgravity measurements, water level changes, precipitation and evaporation data at well 2 (from April 2018 to March 2019)

On the other hand, the situation in well 3 and well 4 is different since they are non-operational wells, as mentioned earlier. Based on the data displayed in Figures 23 and 24 for W3 and W4, respectively, water levels were lower in the summer and then the trend shows a gradual increase in water levels during the winter. Changes in groundwater level (Δh) ranging from less than 1 to 4 m over the summer, while in winter it varies from 3 to 5 m, approximately. Accordingly, the declines in water level in the summer may be due to the non-extraction of water since well 3 and 4 they have no pumps. Although, the increases in water level in winter may result from the delay in the rate of infiltration. Moreover, withdrawing water from a well may cause a drop in the water levels of the surrounded wells. Thus, the water levels in W3 and W4 can be lowered due to the pumping from W1 and W2.

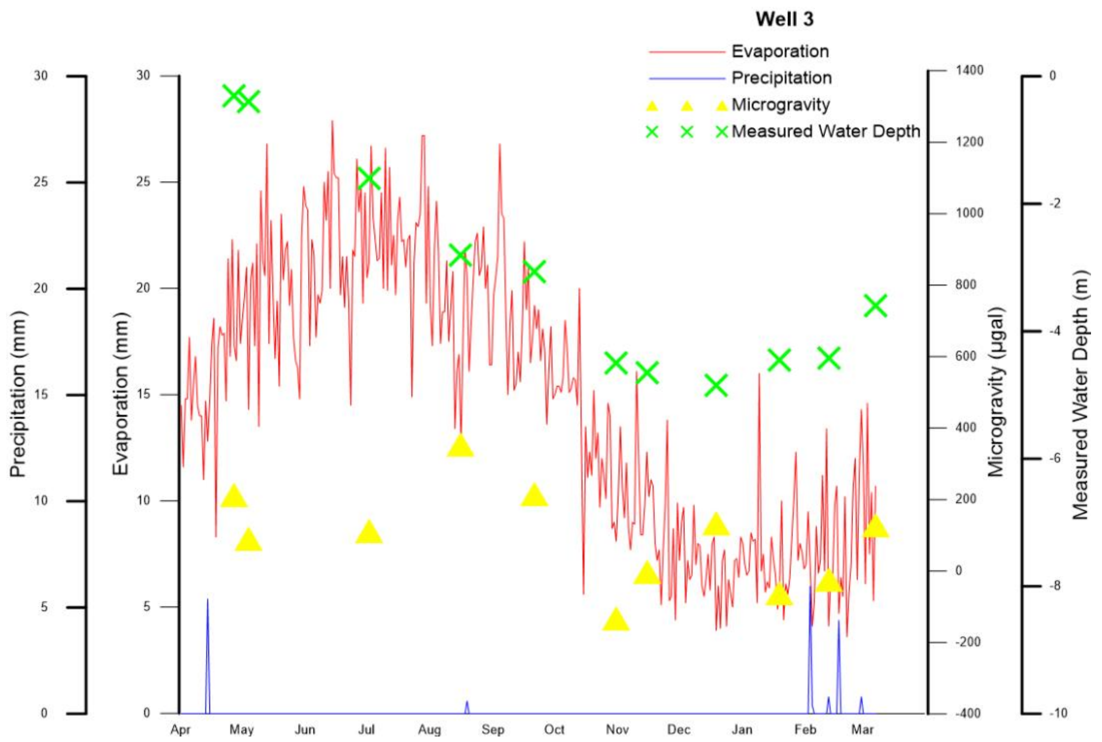


Figure 23: Data of microgravity measurements, water level changes, precipitation and evaporation data at well 3 (from April 2018 to March 2019)

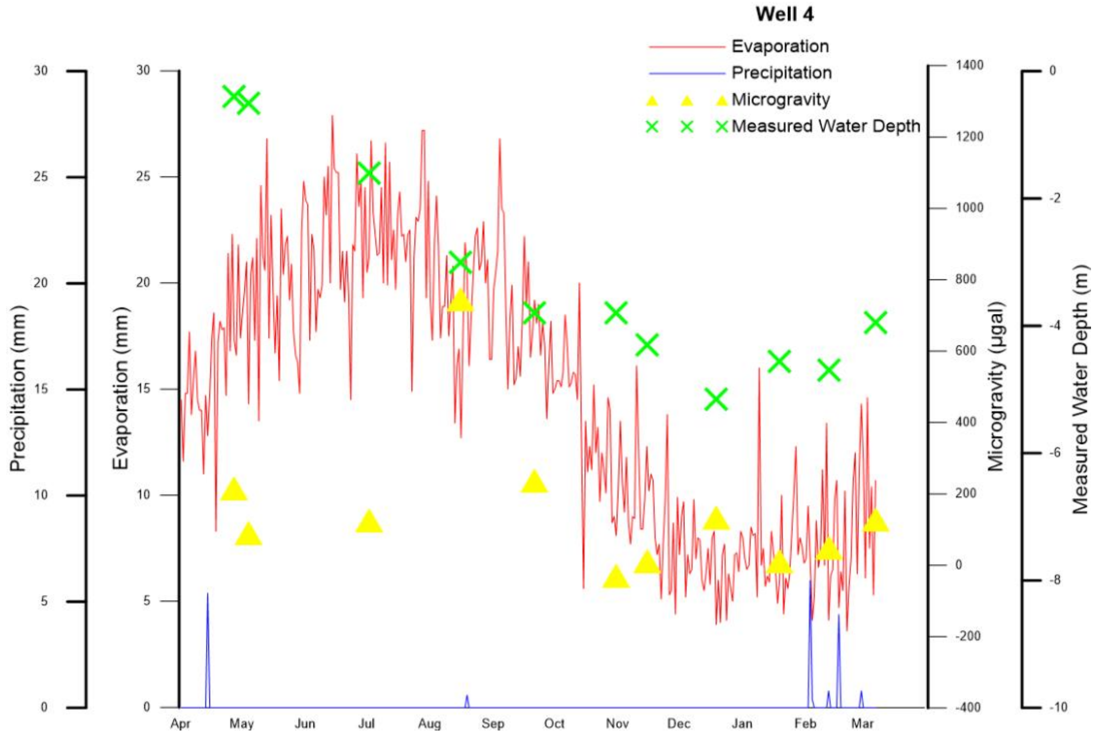


Figure 24: Data of microgravity measurements, water level changes, precipitation and evaporation data at well 4 (from April 2018 to March 2019)

Chapter 4: Conclusions

In this thesis, the main objective was to estimate the variation of groundwater-storage by using time-lapse microgravity measurements. The gravity survey was carried out at four well stations, where the water level was measured simultaneously. The microgravity changes from March 2018 to March 2019 at the well stations are ranging from 128 µGal to 151 µGal referenced to base station data of March 2018, where the water level changes ranged from 1.85 m to 3.95 m. A linear regression model was used to predict the relationship between relative gravity and depth to groundwater in the four wells. Regression analyses revealed a negative correlation for relative gravity and depth to groundwater. The good correlation between depth to groundwater and relative gravity shows that the depth to groundwater is inversely proportional to relative gravity ($R^2 = 0.66$). The calculated water storage changes from microgravity changes at four wells during the same period are ranging from 3.05 m to 3.60 m, which had a good correlation with observed water level changes at four wells from Falaj Hazza ($R^2 = 0.67$). From this study, we conclude that water storage changes can be estimated from microgravity changes using this equation: $\Delta S = 0.0239\ \Delta g$.

The microgravity method provides advantages over traditional groundwater monitoring methods since it is noninvasive and allows for measurements at any location over the wells. However, microgravity measurements will be more informative when they are combined with additional hydrological data. In future work, it is necessary to choose a stable site for a base-station away from the surveyed aquifer to enhance the quality of microgravity measurements.

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