ESTIMATING RATE OF GROUNDWATER DEPLETION IN THE EASTERN PROVINCE AQUIFER SYSTEM USING GRACE-INSAR DATA

BY

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For God, ummah, nation and alma mater

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LIST OF ABBREVIATIONS

DEM **:** Digital Elevation Model

DInSAR **:** Differential Interferometric Synthetic Aperture Radar

EIA : US Energy Information Administration

ESA : European Satellite Agency

FAO : Food and Agriculture Organization of the United Nations

GLDAS : Global Land Data Assimilation System

GRACE : Gravity Recovery and Climate Experiment

GW : Groundwater

InSAR : Interferometric Synthetic Aperture Radar

JPL : Jet Propulsion Laboratory

LOS : Line-of-Sight

LSM : Land Surface Model

PSI **:** Persistent Scatterers Interferometry

SBAS **:** Small Baseline Subset

SLC : Single Look Complex

SM : Soil Moisture

TOPS : Terrain Observation with Progressive Scans

TWS : Terrestrial Water Storage

UAE : United Arab of Emirates

UER : Umm er Radhuma

UNESCWA : United Nations Economic and Social Commission for Western Asia

UT CSR : University of Texas Center for Space Research

VIC : Variable Infiltration Capacity

WWAP : United Nations World Water Assessment Programme

ABSTRACT

Full Name : [Arya Pradipta Prasetyo]

Thesis Title : [Estimating Rate of Groundwater Depletion in the Eastern Province Aquifer System Using Grace-Insar Data]

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The over exploitation of freshwater resources might not only threaten the sustainability of fossil aquifers, but also attribute to ground subsidence. In an arid area with less ground measurements, these issues can be monitored by integrating recent satellite observations. This study is focused on observing groundwater storage change and land subsidence development in the Eastern Province through GRACE and InSAR satellite missions from January 2007 to December 2016 and from June 2016 to December 2016, respectively. GRACE-derived groundwater storage exhibits the depletion rate of -6.384 ± 0.409 mm/yr over 10 years of study period. In general, Qaryat al Ulya, Nairyah-Al Sarrar, Dammam-Qatif and Hasa experience subsidence during the short-term period. This study revealed that the urban area depicts smaller subsidence compared to agriculture area, particularly in Dammam and Hasa. This study highlights the cost effectiveness for assessing the limited fossil water storage variations that might lead to aquifer compaction.

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ملخص الرسالة

الاسم الكامل: آريا براديبتا براشيتو

عنوان الرسالة: تقدير معدل إستنزاف المياه الجوفية في المنطقة الشرقية بإستخدام البيانات المأخوذة من الأقمار الصناعية (GRACE-InSAR)

التخصص: جيولوجيا

تاريخ الدرجة العلمية: ديسمبر 2018

إن الاستغلال المفرط لموارد المياه العذبة قد لا يهدد استدامة طبقة المياه الجوفية الأحفورية فحسب ، بل قد يؤدي أيضًا إلى هبوط التربة. يمكن مراقبة هذه المشكلات في المناطق القاحلة ذات القياسات الأرضية القليلة من خلال دمج الاستشعار عن بعد بواسطة الأقمار الصناعية الحديثة . اجريت هذه الدراسة لمراقبة تغير مخزون المياه الجوفية وتطور هبوط الأراضي في المنطقة الشرقية من خلال استخدام الأقمار الصناعية GRACE و InSAR من يناير 2007 إلى ديسمبر 2016 ومن يونيو 2016 إلى ديسمبر 2016 ، على التوالي. أظهر GRACE أن معدل الاستنزاف للمياه الجوفية بلغ -6.384 ± 0.409 مم / سنة على مدار 10 سنوات من فترة الدراسة. بشكل عام ، شهدت قرية العليا, النعيرية - الصرار , الدمام - القطيف والأحساء هبوطًا خلال فترة قصيرة الأجل. كشفت هذه الدراسة أيضا أن المنطقة الحضرية لديها هبوطاً أقل مقارنةً بالمنطقة الزراعية ، وخاصة في الدمام والأحساء. كما سلطت هذه الدراسة الضوء على الإطار الفعال من حيث التكلفة لتقييم التباينات المحدودة في المياه الأحفورية التي قد تؤدي إلى انضغاط طبقة المياه الجوفية.

CHAPTER 1

INTRODUCTION

1.1. Background

Groundwater is the primary source for fresh water that supplies drinking water and agriculture demand for more than 50% of the global population (*UN Water*, 2015). Yet, currently the global fossil water aquifers are being heavily abstracted in inhabited areas and large irrigated zones, bringing it to high stressed aquifer with negative trend of storage (*Richey et al*, 2015). Hence, the fresh water aquifer depletion can be considered as a global problem that could have devastating effects on the availability of water supplies and related ecosystem. In arid countries with limited fossil water like the Middle Eastern countries, this issue become more critical due to population growth and increasing of water demand in agricultural zones to achieve food security.

The over exploitation of groundwater in water scarce regions not only can have negative effect on aquifer storage, but also might lead to subsidence (*Castellazzi et al*, 2016b; *Farr et al*, 2016; *Chen et al*, 2017; *Gong et al*, 2018; *Othman et al*, 2018). Land subsidence caused by excessive groundwater withdrawal has been reported damaging public vital infrastructure in California (*Farr et al*, 2016). Moreover, the aquifer storage also can be permanently reduced by long term subsidence (*Castellazzi et al*, 2016b). The effect of aquifer-related deformation issues must be well identified to prevent public infrastructure damage, flood mitigation, and – most importantly – to sustain the future fresh water resources.

Unfortunately, the groundwater abstractions and land subsidence development are often under-monitored. The utilization of recent multiple satellites missions such as GRACE (Gravity Recovery and Climate Experiment) and InSAR (Interferometry of Synthetic Aperture Radar) in data scarce regions would be helpful to evaluate long term groundwater storage variations and vertical ground deformation development (*Castellazzi et al*, 2016b*; Gong et al*, 2018; *Othman et al*, 2018). This remote sensing approach offers spatiotemporal resolution and cost-effective method that can be utilized in basin (GRACE) or local scale (InSAR). Interpreting these issues could properly assist decision-makers in developing water conservation and environmental protection plans.

1.2. Problem Statement and Objectives

Since the discovery of giant oil reserves in the 1930's, the Eastern Province of Saudi Arabia has experienced a rapid development in industrial, agricultural, and social sectors particularly in the last four decades. Its population has been increasing tremendously and the water demand rises continuously. The consumed fresh water in this region are mainly supplied from groundwater resources with the agricultural sector as the biggest user (Rasheeduddin et al, 2001). Former study conducted by Abderrahman et al (2007) reported that since 1967 to 2006, the groundwater withdrawal of UER and Dammam aquifers increased from 15.9 million m^3 to 149.2 million m^3 and from 118.5 million m^3 to 263.6 million m^3, respectively in Dammam Metropolitan Area (Figure 1.1). Considering the population growth, food security policies and the development of cultivated area, this rate

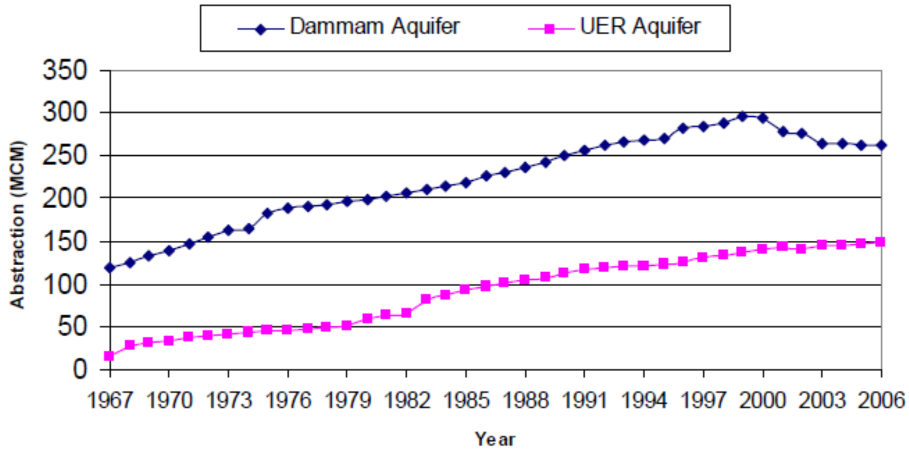


Figure 1.1 The history of groundwater pumping from UER – Dammam aquifer system in Eastern Province since 1967 until 2010 [Abderrahman et al, 2007].

of abstraction will threat the critical fossil water. Moreover, the high rate of groundwater extraction could lead to land subsidence. In the metropolitan area, this effect has the potential to damage public infrastructures.

Most physical groundwater studies in the Eastern Province have been conducted in local areas which depend on the availability of field measurement. Hence, it is difficult to evaluate this study at the basin scale where the insitu data are not well documented within the region. The contribution from another aquifer such as the Neogene aquifer is often negligible. Moreover, the study of fossil water aquifer-derived ground subsidence is of less concern due to lack of insitu data. To address these issues and fill the gap of the previous studies, this study has focused on the following objectives:

- Analyzing the spatiotemporal groundwater variations derived from GRACE satellite mission in the Eastern Province from January 2007 to December 2016.

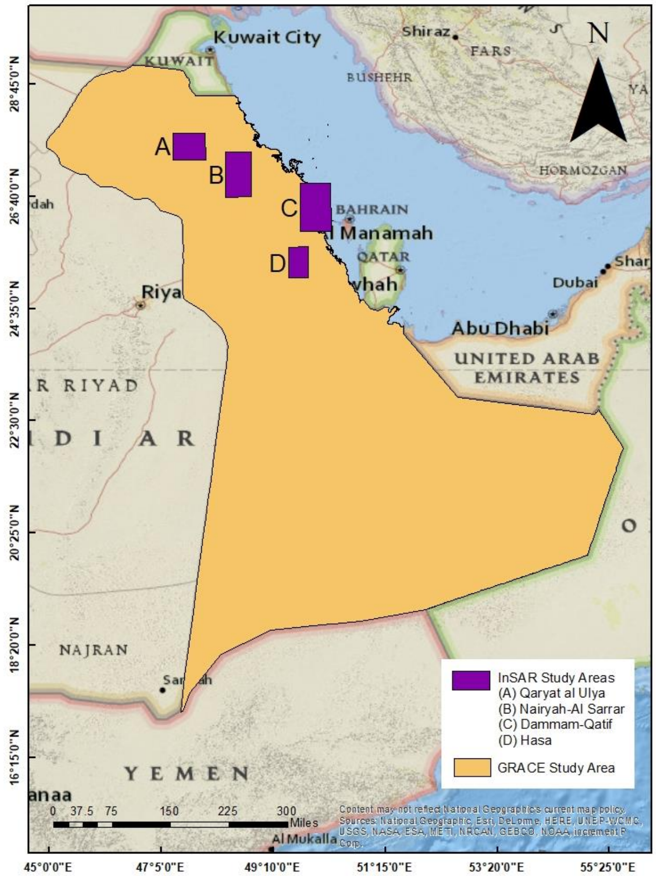


Figure 1.2 The selected location for GRACE study area and InSAR study areas

- Monitoring aquifer-related subsidence in municipality and large agriculture areas within the Eastern Province from June 2016 to December 2016 through SAR dataset derived from Sentinel-1A mission

1.3. Study Area

The Eastern Province of Saudi Arabia with an area of 672.522 km^2 was selected for this study. This province extends from the northern border to the southern border of Saudi Arabia along the Arabian Gulf and bounded by Iraq, Kuwait, Bahrain, Qatar, UAE, Oman and Yemen.

Some local municipalities and agriculture zones within the Eastern Province were chosen for subsidence development study based on the availability of SAR acquisition derived from Sentinel-1A mission: Qaryat al Ulya, Nairyah-Al Sarrar, Dammam-Qatif, and Hasa. These areas are classified as large agricultural and municipal zones in the Eastern Province (Rasheeduddin et al, 2001; Siebert et al, 2007). Figure 1.2 shows the selected location for GRACE and InSAR study.

1.4. Thesis Structure

The study of groundwater variations and land subsidence development in this thesis consists of six chapters. The first chapter exhibits general introduction regarding the global groundwater-related land subsidence issues, with the discussion of the problem in the study area, objective of this study, and overview of selected study area. The second chapter discusses the literature review based on previous studies including hydrogeology of the Eastern Province, the basic concepts of GRACE satellite and InSAR approach with its application in several areas. The third chapter elaborates on the data and methodology utilized in this study.

The fourth chapter presents the results of regional groundwater depletion trend and monitored local land subsidence over study period derived from GRACE and InSAR missions, respectively. The fifth chapter discusses the results with detailed explanation including its correlation with thesis objectives, the analyzed problem and challenges in the future. Finally, the last chapter concludes the finding and followed by recommendation for further study.

CHAPTER 2

LITERATURE REVIEW

2.1 Hydrogeological Setting

The aquifer systems in the Eastern Province range from Paleogene to Quaternary encompassing the Arabian Platform. The systems are comprised of UER, Rus, Dammam, Hadrukh, Dam and Hofuf Formations. UER, Rus and Dammam Formations are classified into Paleogene Sequence, while Hadrukh, Dam and Hofuf Formation are part of Neogene Sequence. According to its hydrogeological characteristics, the lithostratigraphic succession can be divided into aquifer and aquitard: UER aquifer, Rus aquitard, Dammam aquifer and Neogene aquifer (*Alsharhan et al*, 2001; *Rasheeduddin et al,* 2001; *Wagner,* 2011). The schematic stratigraphy and hydrogeological units of the aquifer system are depicted by figure 2.1

The UER Formation is mainly composed of limestone, dolomitic limestone and calcarenite and could not to be considered as fully interconnected aquifer due to the presence of shales, marls and argillaceous limestones. At the bottom, UER is comprised by marls overlying Aruma Formation, while at the top this aquifer is bounded by sulphatic base of Rus Formation (*Alsharhan et al,* 2001; *Wagner*, 2011; *UNESCWA & BGR*, 2013; *Dirks et al*, 2018). This aquifer is considered as the most productive aquifer in the eastern part of the Arabian Platform. Although UER is described as a confined aquifer, some parts of this aquifer can be categorized as an unconfined, especially at the outcrop and high areas like

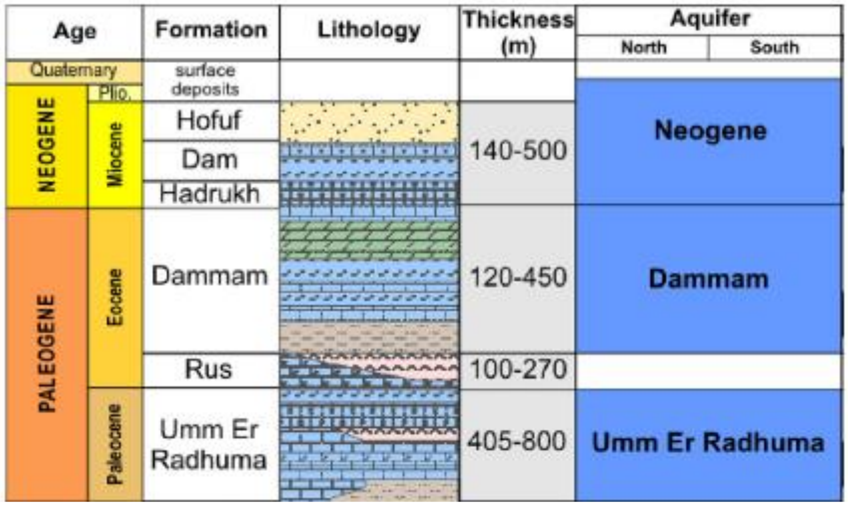


Figure 2.1 Lithostratigraphy and hydrogeological unit of the aquifer system in the study area (Dirks et al, 2018)

Dammam dome as showed by figure 2.2 (*UNESCWA & BGR*, 2013; *Dirks et al*, 2018). The depth and thickness of UER aquifer gradually increases from west to east. The average thickness of this aquifer is about 400 m where at the Gulf coast it reaches up to 700 m (*Wagner*, 2011; *Dirks et al*, 2018).

The total dissolved solid (TDS) of UER aquifer varies within the Eastern Province. These variations are affected by dissolution of thick Rus's evaporate overlying on the top of UER. *Alsharhan et al* (2001) reported that the observed TDS in Haradh is 600 mg/l while in Qatif the TDS increases up to 2,200 mg/l. Recent study by *Iwalewa et al* (2013) revealed that the average TDS of UER aquifer in Dhahran has increased from 2,800 mg/l to 4,200 mg/l since 1967 to 2010 due to excessive groundwater withdrawal. Overall, the TDS of this productive aquifer increases from the western part to the eastern part of the Eastern Province.

The Rus Formation is dominated by evaporates, marl, limestone and performs as an aquitard or aquiclude between the two confined aquifers: UER and Dammam aquifer

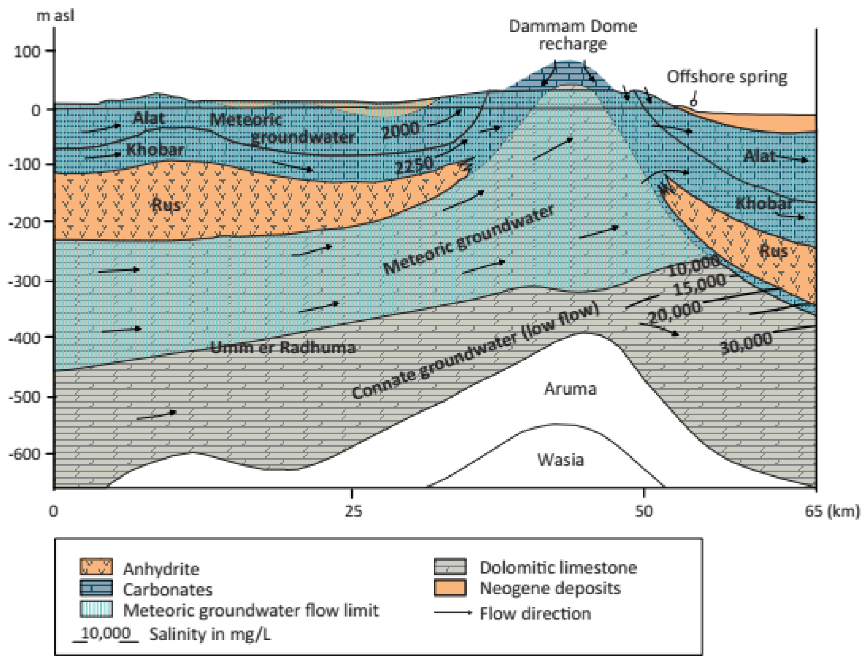


Figure 2.2 Hydrological section of Eastern Province's aquifer system near Dammam Dome area (UNESCWA and BGR, 2013)

(*Alsharhan et al*, 2001; *Wagner*, 2011; *UNESCWA and BGR*, 2013). In some places, this formation can be categorized as aquifer according to its thickness and the presence of non-anhydrites facies. For example, in Dammam Dome, Rus changes its facies into carbonates and serves as aquifer as reported by *Alsharhan et al (*2001) and *UNESCWA & BGR* (2013). In the coastal area, Rus Formation along with member of Dammam Formation (Midra, Saila and Alveolina Member) act as confined layer separating UER from Khobar aquifer (*Wagner*, 2011).

The Dammam Formation consists of five units: non aquiferous shale in the lower three units (Midra Member, Saila Member, Alveolina Member) and aquiferous carbonates in the upper two units: Khobar Member and Alat Member. Furthermore, those two upper members are referred to as Dammam aquifer. Generally, Dammam aquifer is composed by limestone and dolomitic limestone with intercalation of shale (*Alsharhan et al*, 2001;

UNESCWA and BGR, 2013). *Alsharhan et al* (2001) reported that Khobar Member is separated by Alat Member by the presence of marl layer, however, in some areas where this impermeable unit is absent, these two members act as one aquifer. The general aquifer thickness is around 70 m in Wadi al Miyah and 35-65 m in Hasa.

Previous study from *Abderrahman et al* (2007) mentioned that the hydraulic characteristic of Dammam aquifer is mainly controlled by lithology and structural features such as fractures, solution voids, anticline and syncline. Dammam aquifer is a confined aquifer in most of the Gulf region, especially in Saudi Arabia. However, in several places, the aquifer might act as an unconfined aquifer due to erosion, such as in the upper part of Abaruq member of Dammam Formation (*UNESCWA and BGR,* 2013).

The Neogene aquifer system is subdivided by three formations: Hadrukh, Dam and Hofuf Formations where Hadrukh and Dam perform as excellent aquifers. Hadrukh consists of sandstone, marly sand, siltstone and sandy limestone while Dam is composed by chalky and marly limestone with extensive fissure and karstification. The poor unconfined aquifer of Hofuf is predominantly comprised by marl and intercalated limestone-marl-sandstone in the upper part (*Alsharhan et al*, 2001; *Rasheeduddin et al*, 2001).

The Neogene aquifer system lies on the top of Dammam aquifer and mainly exploited in Hasa and Wadi Miyah areas (*Rasheeduddin et al*, 2001). *Al Thokais & Rausch* (2008) reported that Neogene performs as interconnected aquifer with Aruma, UER, and Dammam in Hasa due to the presence of fractures along Ghawar anticline. According to isotope study conducted by *Alsharhan et al* (2001), part of Neogene aquifer system in Hasa might come from UER aquifer. The same study also mentioned that TDS of Neogene aquifer decreases in area where this aquifer acts as unconfined aquifer due to recharge from rainwater.

The quartenary sand aquifers in the Eastern Province are located in Wadi al Batin which extend from Hafr Batin to Kuwait and southwestern part of Iraq. *Alsharhan et al* (2001) reported that this shallow aquifer is mainly composed by quartz sandstone, conglomerates, calcarenite and oolitic limestone. The quality of this aquifer is poor and mainly used for irrigation activities depend on the seasonal variations.

2.2 GRACE Satellite Mission

GRACE is a satellite mission launched by NASA in the United States and German Aerospace Center (Deutsche Forschungsanstalt für Luft und Raumfahrt/DLR) under the NASA Earth System Science Pathfinder Program (ESSP) to observe earth gravity field every thirty days (*Tapley et al*, 2004). GRACE is different from common satellites by its ability to provide gravity resolution in which sensitive to mass variations (*Castellazzi et al*, 2016a). GRACE consists of two twin satellites with a separation distance around 220 km in a polar orbit 500 km above the earth. The two satellites are linked by high precise inter-satellite, K-Band microwave ranging system and attached by the Global Positioning System receiver and attitude sensors in each satellite (Tapley et al, 2004). The accuracy of K-Band microwave ranging system is very precise, around some micron over a distance of 220 km and referred as the key instrument in GRACE satellite (*GFZ Postdam*, 2006; *Zlotnicky et al*, 2013).

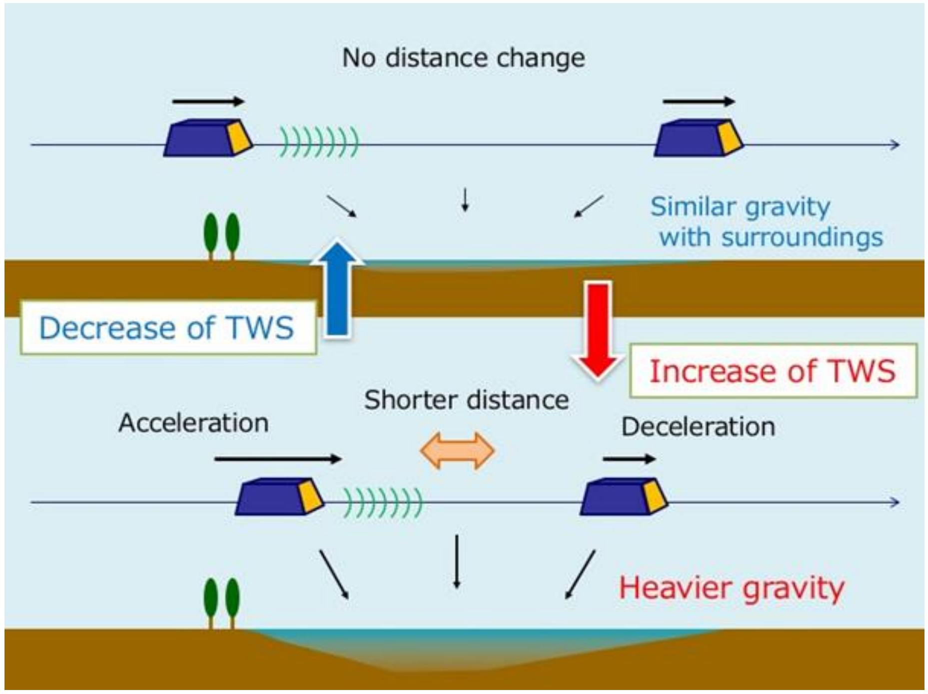


Figure 2.3 The mechanism of twin satellites measuring gravity variations (JAMSTEC, 2016)

The gravity variations for the most part of the earth remain constant over long-time interval. These variations particularly come from large features like a mountain. Long-term average mass distribution within the earth can be defined as static or mean gravity field. This concept will help to understand the structure of the solid earth. However, there are other gravity variations which are caused by mass distribution and mass transport processes much smaller time scales. These short-term mass variations are mainly caused by global hydrological cycle variations and defined as time variable gravity field (*Swenson & Wahr*, 2006).

The mass distribution and mass transport processes within the earth and its surface are not evenly distributed. The irregular mass distribution in the earth generates an inhomogeneous gravity field. The area with a little bit stronger gravity (greater mass concentration) will affect the first GRACE satellite, pulling it further away from the second satellite. Thus, by high precise inter-satellite system, a very small mass of gravity variations which is reflected by change in distance between the two identical satellites can be determined (*GFZ Postdam*, 2006). The calculation is so accurate that can observe the change of few microns in range around 0.1 µm/s. The mechanism of GRACE measuring the gravity variations is illustrated by figure 2.3

The time variable gravity derived from GRACE mission will be useful to observe large scale of terrestrial water storage variations, sea level rise and ice sheets (*Swenson & Wahr*, 2006). These twin satellites account vertically water storage above and below surface, including surface water, soil moisture, snow water and groundwater storage. The residual groundwater storage can be assessed by removing other water storage components from GRACE total measurement.

The utilization of GRACE in groundwater storage monitoring at basin scale has been widely applied by number of studies. *Famiglietti et al* (2011), *Scanlon et al* (2012), *Shamsudduha et al* (2012), and *Castle et al* (2014) successfully capture the groundwater variations calculated by GRACE which is consistent with historical ground observation. Prior studies conducted in the Middle East region by *Voss et al* (2013), *Richey et al* (2015), *Gonzalez et al* (2016) and *Fallatah et al* (2017) revealed that the limited fresh water resources have been heavily abstracted. *Castellazzi et al* (2016b), *Othman et al* (2018) and *Gong et al* (2018) show that GRACE can be integrated with InSAR method to describe the relationship between land subsidence with groundwater pumping. Assessment of climate variabilities and human influences to fresh water resources change also have been facilitated by these twin satellites (*Voss et al*, 2013; *Huang et al*, 2015; *Fallatah et al*, 2017). However, the hydrologic study by applying this gravity satellite is still limited to regional scale due to low resolution of GRACE. Hence, the upcoming mission called GRACE FO is expected has ability to provide better spatial resolution.

2.3 InSAR-Monitored Aquifer-Related Deformation

Many studies reveal that overexploited of groundwater resources has significant role in land subsidence development (*Galloway & Burbey*, 2011; *Reeves,* et al, 2011; *Castellazzi et al*, 2016b*; Othman et al*, 2018; *Gong et al*, 2018). This aquifer-related deformation issue typically brings significant effect in hydrogeologic setting composed by aquifer and aquitard (*Galloway & Burbey*, 2011). The concept of aquifer compaction generally based on effective stress principle as following equation:

$$\sigma_e = \sigma_t + p \qquad (1)$$

Where σ_e, σ_t and p represent effective stress, total stress and pore fluid pressure, respectively. The relationship between inside the aquifer system them is illustrated by figure 2.4

Total stress is mainly controlled by several factors like overburden load of deposited rock and tectonic activities (*Galloway & Burbey*, 2011). Change in effective stress and pore fluid pressure are opposite each other. Assuming total stress remain constant in time, pore fluid pressure change will affect the effective stress that lead to aquifer compaction or expansion (*Galloway et al, 1998; Galloway & Burbey*, 2011*).* Decreasing pore fluid pressure will increase effective stress causing aquifer compaction while increasing pore fluid pressure will decrease effective stress, subsequently, the aquifer undergoes expansion. The aquifer system undergoes permanent compaction if the effective stress

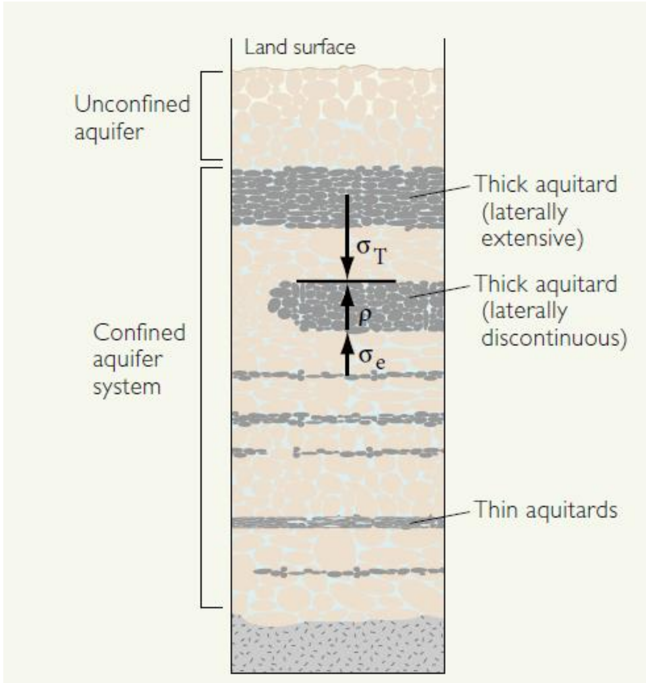


Figure 2.4 The relationship between effective stress, total stress and pore fluid pressure inside the aquifer system (USGS, 1999)

exceed the maximum former effective stress, while the aquifer system will be compressed elastically when the effective stress is below the maximum past effective stress (*Galloway et al*, *1998).*

Aquifer matrix compressibility will affect the response of lithological unit within aquifer system to effective stress (*Castellazzi et al*, 2016a). Since clay and silt are treated as the most compressible component, the increasing of effective stress could decrease porosity, specific storage and hydraulic conductivity of these facies (*Castellazzi et al*, 2016a). Subsequently, the compressed low permeability unit within the aquifer system will prevent vertical groundwater flow, depend on continuity and size of this layer (*Castellazzi et al*, 2016a).

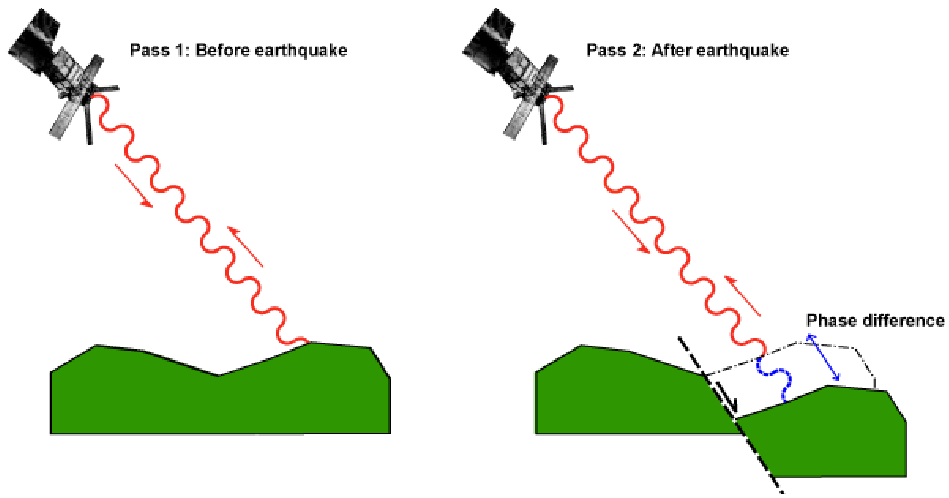


Figure 2.5 Illustration how interferogram is calculated between two SAR acquisitions (COMET, 2013)

Numerous methods have been used to assess and monitor ground vertical displacement including ground-based geodetic measurement and satellite remote sensing. Among those methods, the application of InSAR provides cost effective and efficient framework for subsidence monitoring caused by extensive groundwater withdrawal, particularly in data scarce region. Moreover, InSAR would support management of water resources and hazard mitigation at large and small scale as shown by previous studies (*Castellazzi et al*, 2016b; *Farr et al*, 2016; *Chen et al*, 2017; *Gong et al*, 2018; *Othman et al*, 2018).

SAR mission is a satellite-based microwave imaging system that utilizes two or more synthetic aperture radar images of certain area to measure ground deformation (*Ferretti et al*, 2007). This technique has ability to penetrate cloud since it uses microwaves and capable to operate day and night due to its active system with spatial coverage from 100 to 5000 km2 (*Ferretti et al*, 2007; *Castellazzi et al*, 2016a). Figure 2.5 depicts how interferogram representing ground deformation can be calculated through SAR acquisitions. Remote sensing satellites with SAR system will transmit radar pulses to the earth surface and record the amount of backscattered signal (*Ferretti et al*, 2007). SAR images record information of earth surface in the form of amplitude and phase. The recorded amplitude contains information about terrain slope and surface roughness while recorded phase measures the distance between satellite and earth surface (*Ferretti et al*, 2007). The difference in distance between satellite and earth surface along two acquisition at different time represents deformation of earth surface (*Ferretti et al*, 2007).

The main InSAR processing workflow for ground subsidence observation can be divided into three methods: Differential InSAR (DInSAR), Small Baseline Subset (SBAS), and Persistent Scatterers Interferometry (PSI) (*Galloway & Burbey*, 2011; *Castellazzi et al*, 2016a). D-InSAR method uses two or more SAR acquisition at same location and different time to create interferogram formation (*Ferrer et al*, 2007, *Castellazzi et al*, 2016a). The second method, SBAS, utilizes several acquisition images from SAR mission with all possible combinations and correcting by using SBAS logarithm to produce vertical deformation map (*Castellazzi et al*, 2016a). PSI uses acquisition object with stable scatter and high coherence, subsequently this technique provides better result in rural area, yet bring poor image in agriculture area (*Castellazzi et al*, 2016a).

One of challenges in utilizing InSAR is loss of interferometric coherence, particularly in high vegetated and agriculture area (*Ferrer et al*, 2007; *Castellazzi et al*, 2016a; *Farr et al*, 2016). This noise is caused by temporal decorrelation due to a small motion disturbing phase difference between two acquisitions (*Farr et al,* 2016). A short wavelength SAR could be not able to detect ground displacement in that particular area, hence a longer wavelength SAR could be applied to address the issue (*Castellazzi et al*, 2016a). Another challenge that considered as the most difficult error source to be solved is atmospheric effect caused by water vapor (*Castellazzi et al*, 2016a; *Farr et al*, 2016). This water vapor impedes signal transmitted from SAR mission and makes it look like surface deformation (*Farr et al*, 2016).

Nowadays, various missions with space borne SAR system including Radarsat-2 by Canadian Space Agency, ALOS-2 by Japan Aerospace eXploration Agency, TerraSAR by German Aerospace Center and Sentinel-1A and 1B by European Space Agency are currently operating (*Castellazzi et al*, 2016a). According to *Ferrer et al* (2007), these missions work in three microwave bands: C band (Sentinel-1A and 1B, Radarsat-2), L band (Alos-2), and X band (X-SAR). Recent mission with space borne SAR system has improved signal ratio to provide better spatial resolution of ground displacement and coverage (*Castellazzi et al*, 2016a).

CHAPTER 3

DATA & METHOD

3.1 Data

3.1.1. GRACE Data

This study used monthly GRACE Terrestrial Water Storage (TWS) spherical harmonic solution with the version of RL 05 provided by the University of Texas Center for Space Research (UT CSR) from January 2007 to December 2016[1]. GRACE TWS used in this study is expressed as anomaly of water thickness in cm with the baseline from 2004 to 2009. The GRACE TWS should be re-scaled back using provided scaling factor to recover the signal loss due to post processing steps, including smoothing, de-stripping and removing atmospheric effect. The GRACE TWS might contain uncertainty came from small wavelength that could generate long linear stripes affecting the spatial correlation of the gravity field coefficient. Hence, the smoothing technique is required to overcome this error through Gaussian post filter (*Swenson & Wahr*, 2006). However, the filter itself would influence geophysical signal particularly at high latitude and reducing the accuracy of spatial resolution. To solve this issue, *Landerer & Swenson* (2012) constructed the scaling factor based on independent TWS simulation which is not observed from GRACE.

GRACE quantifies amount of water storage above and below surface, such as surface water, soil moisture, snow water and groundwater storage. Hence, to estimate groundwater

[1] Downloaded at http://grace.jpl.nasa.gov/data/

storage, those three components should be subtracted from GRACE TWS. The Eastern Province is situated in arid region without parennial river and snow accumulation, therefore surface and snow water are considered negligible. The study area is also known as host for major oil field in Saudi Arabia. Subsequently, oil and liquid extraction caused by oil industry activities would affect the TWS variabilities and should be removed as well from GRACE TWS to isolate the groundwater storage as discussed by *Doll et al* (2013) and demonstrated by *Gonzales et al* (2016) in their study.

3.1.2. GLDAS Data

Land Surface Models (LSM) derived from Global Land Data Assimilation System (GLDAS) from 2007 to 2016 were utilized to calculate soil moisture in the Eastern Province. GLDAS is a joint program developed by scientists from the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP). GLDAS integrates satellite-based observation with ground data to simulate land surface states and hydrologic fluxes globally with a high resolution in near real time (*Rodell, et al.*, 2004).

Soil moisture is often referred as stored water in vadose zone and can be calculated from insitu data or LSM. Since insitu measurements are often unmonitored, the LSM might be regarded as the best approach to be applied in data scarce region. This study utilized three LSMs with spatial resolution of 1^{o} x 1^{o} and monthly temporal variations: National Centers for Environmental Prediction/Oregon State University/Air Force/Hydrologic Research Lab

(Noah) model, VIC (Variable Infitration Capacity) model and Mosaic[2] model. The three LSMs have different number and depth of soil layers in order to simulate soil moisture variances. For instance, Noah has four soil layers (0-10 cm, 10-40 cm, 40-100 cm, 100-200 cm), VIC has three soil layers (0–10 cm, 10–160 cm, 160–190 cm) while Mosaic includes three different soil layers (0–2 cm, 2–150 cm, 150–350 cm).

The simulated model is provided globally with high spatial (0.25^o x 0.25^o to 1^o x 1^o) and temporal resolution (3 hourly to monthly). Several studies have revealed the potential of LSM to estimate vadose zone in region where real observed data are not feasible. (*Fagmilietti et al*, 2011; *Scanlon et al*, 2012*; Shamsudduha et al*, 2012*; Voss et al*, 2013*; Gonzales et al*, 2016). LSM should be compared with in situ data to avoid unrealistic soil moisture model. However, since ground-based observation data are not available in the study area, this study applied the ensemble mean from three LSMs as demonstrated by *Shamsudduha et al* (2012) and *Fagmilietti et al* (2011). Soil moisture simulated by LSMs were calculated in unit of cm before estimate the monthly deviation from the mean.

3.1.3. InSAR Data

InSAR data were obtained from Sentinel-1A mission developed by European Satellite Agency (ESA) from June 2016 to December 2016. The data can be accessed and downloaded from the Alaska Satellite Facility with format of Single Look Complex (SLC)[3]. Several locations were chosen in this study, particularly agriculture and

[2] Downloaded from https://disc.sci.gsfc.nasa.gov/
[3] Downloaded from https://www.asf.alaska.edu/

municipality areas in the Eastern Province based on the availability and coverage of Sentinel-1A dataset.

Sentinel-1A provides interferometric swath mode in its acquisition with spatial resolution of 5m x 20m (*Veci*, 2016). This mission replaces the former ScanSAR mode with new technique called Terrain Observation with Progressive Scans SAR (TOPSAR). TOPSAR reduces azimuth resolution to minimize scalloping effect of the acquisition image. Compared to the ScanSAR mode, TOPSAR has lower ambiguity by optimizing burst length. In order to assure the alignment of interferometric, burst is adjusted from pass to pass. This makes TOPSAR useful for high resolution large swath application (*De Zan & Guarnieri*, 2006).

3.1.4. Field Data

Nineteen observed water level data distributed along the Eastern Province from 2005 through 2017 were used to validate GRACE and InSAR result. Due to the lack information of specific yield data, this study normalized each monitored well time series by its standard deviations following previous approach delivered by *Castle et al* (2014), *Fallatah et al* (2017) and *Sun et al* (2017). The followed approach calculated mean and standard deviation of each well time series and divided the mean-removed observed water level by standard deviation.

3.2 Laboratory Works

The method to obtain the objectives in this study is mainly based on laboratory work solely. Two different image processing and one network-flow algorithm software programs were utilized to generate spatiotemporal groundwater variations and land subsidence development in the selected study area. These software programs include SNAP, ArcGIS, and Snaphu. The general schematic workflow of this study can be summarized in figure 3.1.

Sentinel Application Platform (SNAP) is an open source software developed by ESA to process and analyze Sentinel-1A acquisition images. This study used Differential InSAR (DInSAR) technique to create subsidence map over the selected area. DinSAR is conventional SAR processing technique that relies on two acquired SAR images at different time in the same area to monitor land deformation. This technique has an advantage of observing subsidence at short term period. Twenty-eight collected images from InSAR acquisition with format of SLC were processed through SNAP to generate interferogram and coherence formations. After removing various noise and merging burst swath into single image, the ambiguous interferogram phase was unwrapped by running specific command line using Snaphu, an open source software developed by Stanford University.

Snaphu integrates topography, smooth generic and deformation data in statistical model and recovers unambiguous phase data through network flow technique. Time processing of unwrapping interferogram formation through snaphu depends on how big the study area. This step also consumes a lot of memories and sometime fails due to low memory. Bad coherence resolutions affected by noise were masked out to avoid inaccurate displacement measurement. The generated map will be converted into GeoTiff format to be processed furthermore using spatial analysis tool derived by ArcGIS. This tool will help to produce mean displacement time series and cumulative subsidence map. The detailed InSAR processing steps will be discussed in the following section.

GRACE RL05 datasets were provided in user friendly format, hence it can be processed immediately using spatial analysis tool. GRACE data have been processed from raw format by UT CSR, including de-stripping, smoothing and removing atmospheric effect as explained in previous section (*Swenson & Wahr*, 2006). The users still need to restore the signal loss due to processing steps by using scaling/gain factor depend on the hydrological characteristic of the study area. However, this study did not apply the scaling factor provided by JPL due to specific issue that will be explained in chapter 5.

GRACE derived TWS were isolated from the effect of averaged soil moisture generated from three LSMs. LSM dataset were provided with NetCDF format, hence it can be processed immediately using the same approach as GRACE RL05. The final result of spatiotemporal GRACE groundwater (GRACE GW) were compared with insitu data to check the reability after normalizing the value. In order to assess the influence of climate variabilities to freshwater change over study period, seasonal variations of GRACE GW also will be compared with ground-measurement rainfall data within the Eastern Province.

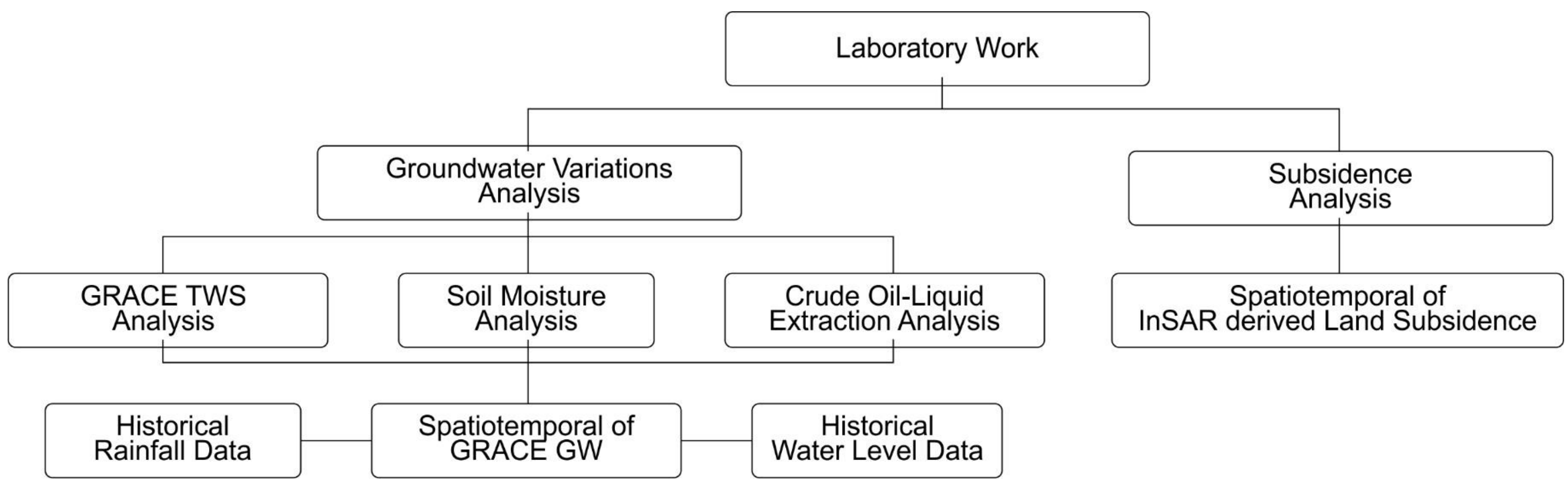


Figure 3.1 The general schematic workflow to observe groundwater variations and aquifer-related deformation in this study

3.3 Estimation of Groundwater Storage

Previous studies have demonstrated that groundwater component can be isolated from GRACE TWS (*Famiglietti*, et al., 2011; *Shamsudduha*, et al, 2012; *Scanlon et al*, 2012; *Voss, et al*., 2013; *Gonzalez, et al*., 2016). In this study, considering the climatologic and geomorphology of the study area, groundwater storage variations can be calculated by subtracting soil moisture and oil extraction. Following *Gonzales et al* (2016), the relationship between those variables can be expressed below:

$$GW = TWS - SM - So \qquad (2)$$

Where GW is groundwater storage variable, TWS is Terrestrial Water Storage derived by GRACE, SM represents soil moisture variations obtained from GLDAS and So is defined as crude oil-liquid extraction caused by oil industries.

The monthly crude oil-liquid extractions presented here were provided from the US Energy Information Administration (EIA). EIA is an agency established by the US Department of Energy to collects and analyzes the energy information production around the world. The provided data are free and can be accessed publicly through EIA portal[4]. The proposed data will be converted to equivalent of water height to be consistent with other terms in equation (2) before subtracting from GRACE TWS.

The trend error of GW is estimated using standard error propagation as expressed below:

$$\sigma_{GW} = \sqrt{\sigma_{TWS^2} - \sigma_{SM^2} - \sigma_{So^2}} \qquad (3)$$

[4] Downloaded at https://www.eia.gov

Where σ_{TWS}^2, σ_{SM}^2, and σ_{So}^2 are defined as trend error of GRACE TWS, LSM and Oil extraction, respectively. GRACE TWS trend error can be calculated by propagating GRACE monthly error onto least square estimated trend following *Fagmilietti et al*, 2011 and *Voss et al*, 2015. The monthly error was analyzed by using leakage and measurement error provided by Jet Propulsion Laboratory (JPL) as defined below.

$$\sigma_g = \sqrt{\sigma_{l^2} + \sigma_{m^2}} \qquad (4)$$

Where σ_l^2 is leakage error and σ_m^2 is measurement error. The trend error in soil moisture and crude oil-liquid extraction are calculated based on standard deviations of soil moisture trend computed from three different GLDAS simulations and oil extraction trend as calculated from previous study (*Fagmilietti et al, 2011*; *Voss et al, 2013*; and *Huang et al*, 2015)

3.4 Land Subsidence Monitoring

InSAR works by estimating the subsidence occurred in an area relative to the first acquisition image date and location (*Farr et al*, 2016). The schematic workflow of InSAR processing steps is summarized by figure 3.2. InSAR's first acquisition is often referred as master image, while the second acquisition represents slave image. Coregistration of two acquisition images into stack will ensure that both of them have ground target with the same range and azimuth (*Ferretti et al*; 2007; *Veci*, 2016).

After applying coregistration between two complexes observed SAR images over the same area and different acquisition time, the interferogram formation and coherence estimation can be generated. Creating interferogram will eliminate one of errors that contribute to

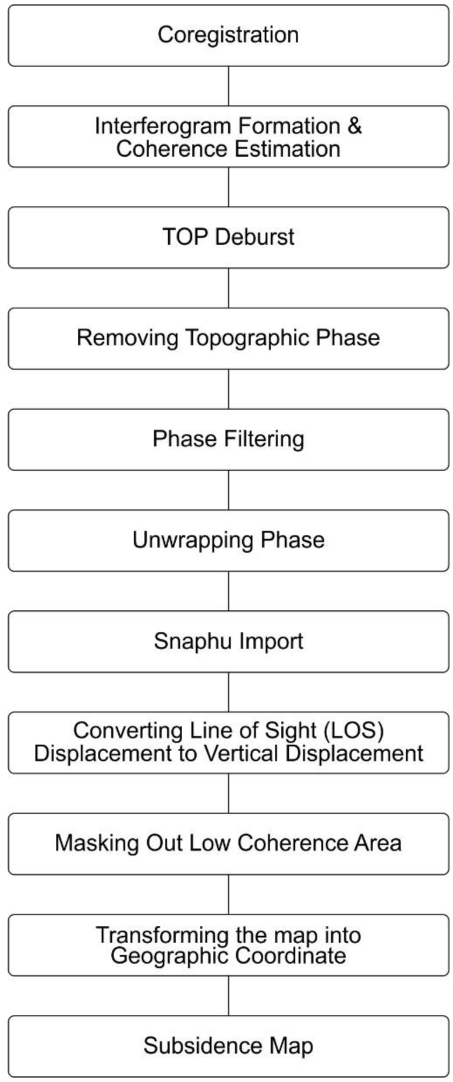


Figure 3.2 The schematic workflow of InSAR processing

phase difference due to earth curvature (*Veci*, 2016). In order to merge all burst data from swath into one single image, TOPS Deburst should be applied (*Veci*, 2016). The effect of topographic also will be eliminated based on referenced Digital Elevation Model (DEM) to produce flattened interferogram (*Veci*, 2016). Technically, InSAR processing steps can be classified into two stages: pre-unwrapping phase and unwrapping phase. The procedures that have been discussed before are referred as pre-unwrapping phase. Before unwrapping the interferometric phase, signal-to-noise ratio should be improved by performing

Goldstein filtering (*Veci*, 2016). Noise in InSAR acquisition could be affected from various source: temporal decorrelation, geometric, vegetation, and processing error (*Veci*, 2016). Hence, in order to generate maximum unwrapping result, this step must be conducted.

The interferometric phase derived from pre-unwrapping steps is often ambiguous, therefore it can be solved by applying unwrapping step. This unwrapping step is performed by using statistical cost and network flow algorithm called Snaphu which developed by Curtis Chen and Howard Zebker from Stanford University.[5] This step provides unwrapping phase product with Line-of-Sight (LOS) displacement. Transforming LOS displacement to vertical displacement is performing by using below equation (*SAR-EDU*, 2018)

$$Vertical\ Displacement = \frac{\phi\ unw * \lambda}{-4\pi * cos\theta_{inc}} \quad (5)$$

Where ϕ unw is unwrapping phase product, λ is wavelength of satellite, and $\cos\theta_{inc}$ represents LOS to vertical factor. The wavelength of Sentinel-1A is around 5.6 cm (*Ferretti et al,* 2007*)*

The atmospheric effect and small motion from crop within agriculture area might produce noise during acquisition, producing low coherence that cause loss of information. Due to its inability to measure subsidence accurately, low coherence area in this study will be masked out at least 60% of the interferogram following *Farr, et al* (2016). In the final step, the vertical displacement map will be projected into common geographic coordinate system through geocoding step. This step will generate the subsidence map relative to first acquisition.

[5] Available at http://step.esa.int/main/third-party-plugins-2/snaphu/

CHAPTER 4

RESULTS

4.1 GRACE Terrestrial Water Storage

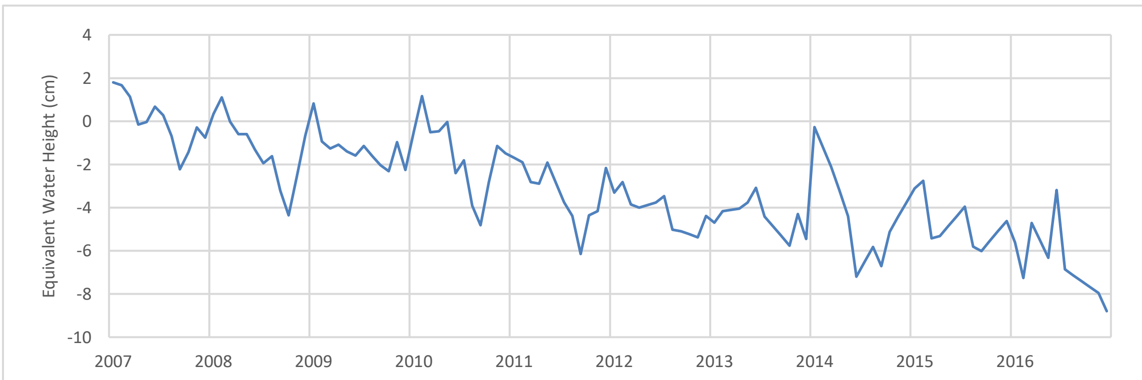


Figure 4.1 Monthly GRACE TWS anomalies for the study area from January 2007 to December 2016

GRACE is widely known having a problem regarding its battery started from 2011. Consequently, it contributed for missing TWS anomaly values for several months. Hence, to fill the missing records, simply interpolation was performed by using two adjacent months as demonstrated by numerous studies.

Monthly time series anomalies derived from GRACE TWS (figure 4.1) clearly show the declining trend from 2007 to 2016 in the Eastern Province. Since 2007, the magnitude shown by GRACE started to decrease and reached its lowest peak on December 2016. The decreasing trend of GRACE TWS is -6.72 ± 0.416 mm/yr which is equivalent with -4.52 ± 0.28 km^3 volume loss every year. During 10-years study period, the total volume loss in

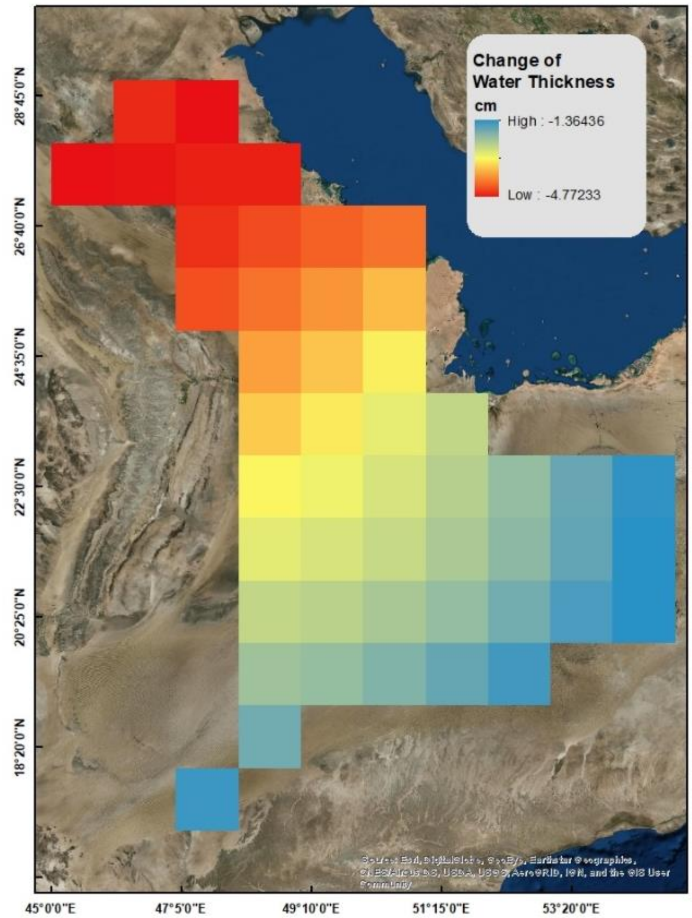


Figure 4.2 The averaged distribution of GRACE TWS spatial resolution in the Eastern Province over the study period

the Eastern Province is approximately 45.2 ± 0.885 km^3. However, this value could underestimate the TWS change since the study area involves uninhabited region like the Rub al Khali desert. This assumption is supported as well by the fact that scaling factor cannot be applied in this area, make the gravity signal representing TWS anomaly is smaller than the original one.

The GRACE TWS spatial variation showing the area with extensive abstraction over 10-years study period is depicted by figure 4.2. The GRACE TWS started to decrease from the southeast to the northwest, revealing the areas with high TWS depletion in the Eastern Province are situated in the northern and central part.

The Eastern Province is a host for several oilfields in Saudi Arabia, hence the change of GRACE magnitudes in this study might be influenced by both TWS and variations of oil extraction. In order to calculate groundwater storage in oil-rich region, the effect of oil extraction need to be removed from GRACE TWS along with soil moisture as shown by equation (2) in the previous section.

4.2 Simulated Soil Moisture

Three monthly anomalies of soil moisture from three different LSMs (Noah, VIC and Mosaic) were applied in this study to avoid any bias gained from one model solely. Noah provides four layers of vertical soil moisture including 0-10 cm, 10-40 cm, 40-100 cm, and 100-200 cm. The total layer of soil moisture simulated by Noah is simply estimated by summing the whole layer. The anomaly time series of Noah soil moisture is depicted by figure 4.3.

The magnitude from the first layer of soil moisture (0-10 cm) varies significantly compared to the other three layers as shown from the figure 4.3a. The soil moisture variances increased and reached its peak during wet seasons before decreasing along dry seasons. The high soil moisture variabilities displayed in the first layer were clearly controlled by precipitation as demonstrated from various studies as well *(Gonzalez, et al; 2016*; *Cai et al*; 2017)

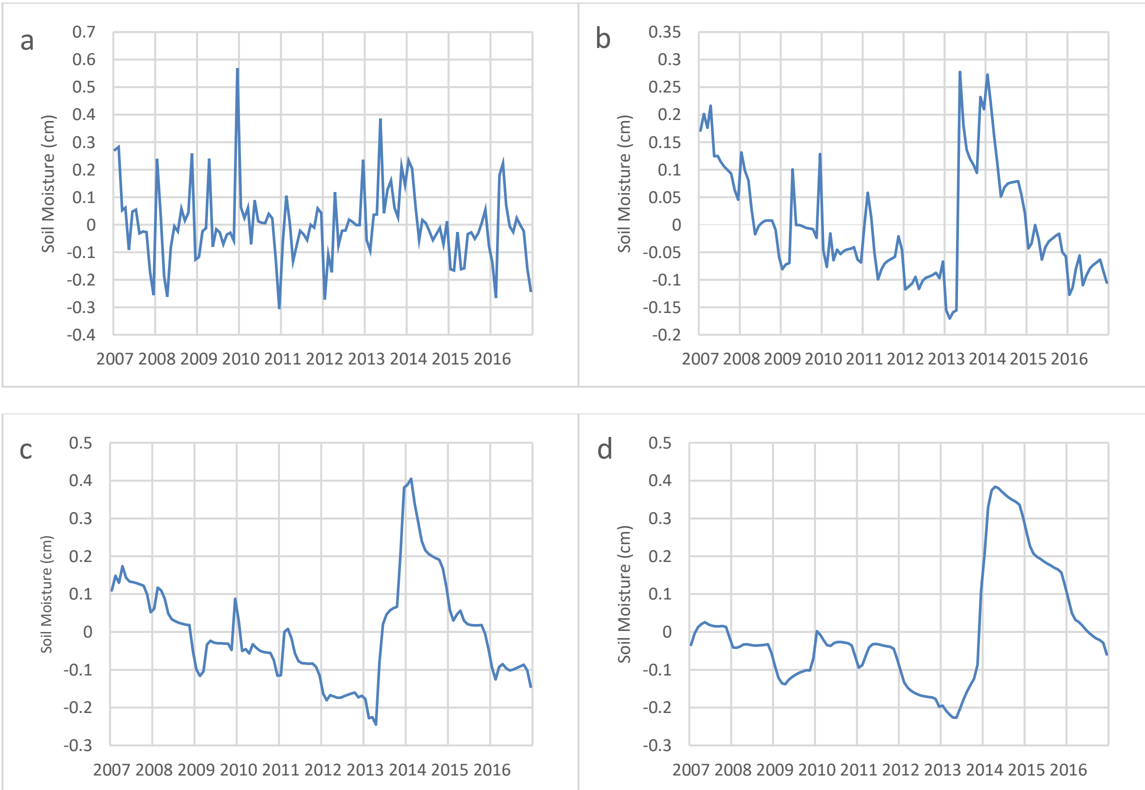


Figure 4.3 Monthly time series anomalies of simulated soil moisture derived from Noah over study period. (a) First layer (0-10 cm). (b) Second layer (10-40 cm). (c) Third layer (40-100 cm). (d) Forth layer (100-200 cm).

Figure 4.4 shows monthly time series of simulated soil moisture from three different LSMs and their average for the period of 2007 to 2016 in the Eastern Province. It is clearly observed that the magnitudes vary among LSMs and lead to uncertainty situation for recovering groundwater storage from GRACE TWS. In order to address this issue, the ensemble mean from three LSMs is assumed representing a realistic model. According to the figure, both Noah and VIC show slightly similar positive trend, meanwhile Mosaic exhibits negative trend. The averaged LSM depicts general depletion trend with rate of -0.396 ± 0.048 mm/yr. According to the depletion rate, the magnitude of averaged LSM is

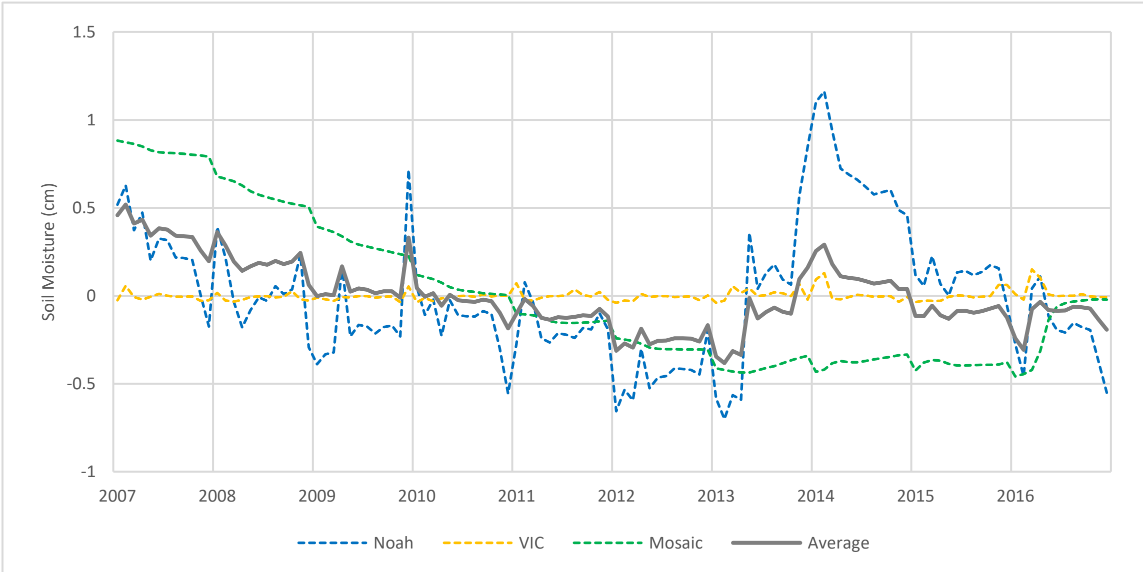
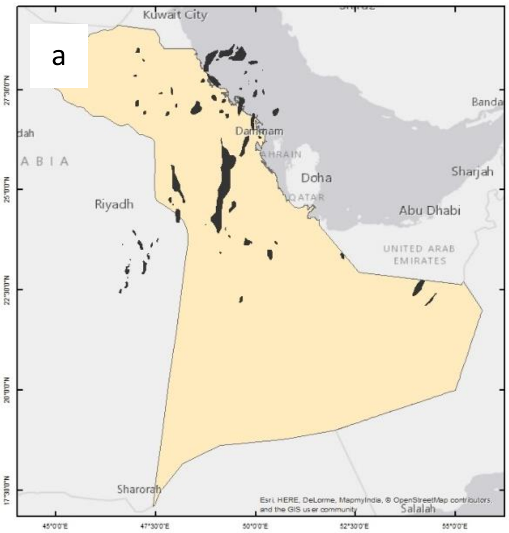


Figure 4.4 Comparison of simulated soil moisture from three different LSM and their average over the study period

relatively small compared to GRACE TWS. Hence, this study concludes that soil moisture component did not significantly affect TWS variations in the Eastern Province over the study period.

4.3 Crude Oil-Liquid Extraction

Figure 4.5 shows monthly anomalies of crude oil-liquid extraction derived by industrial activities in term of equivalent water height. The anomaly time series is constructed with the baseline from 2004 to 2009 in order to make it consistent with GRACE TWS and soil moisture variances. The uncertainties and difficulties in trend estimation discussed here are the data itself. The crude oil-liquid production obtained from EIA covers the whole Saudi Arabia, including both onshore and offshore fields. Unfortunately, those are the only data that can be accessed in this study. Hence, some assumptions are used in this section.



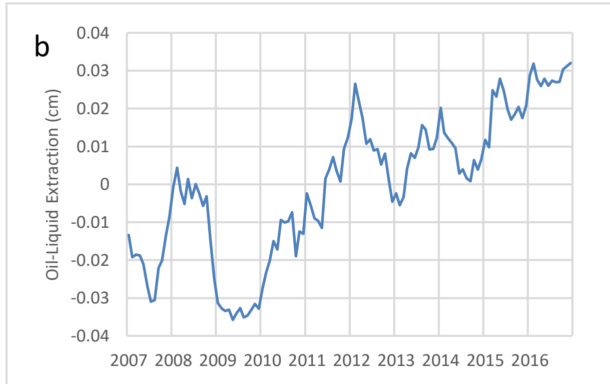


Figure 4.5 (a) The distribution of oil field in Saudi Arabia (b) Time series anomalies of crude oil-liquid extraction in Saudi Arabia over 10 years periodl

First, crude oil-liquid extraction mostly come from oil fields located in the Eastern Province. This assumption is supported by distribution map of total oil field in Saudi Arabia as depicted by figure 4.5a, showing that majority oil fields are situated in the study area. According to previous report published by EIA (2013), giant oil fields located in the Eastern Province such as Ghawar, Khurais, Shaybah, Qatif, Khursaniyah and Abqaiq have big contribution to total crude oil production. Secondly, the most oil production in Saudi Arabia was contributed by onshore fields. As reported by EIA based on Rystard Energy, oil production came from offshore fields were approximately 35% from total crude oil productions.

The increasing trend as observed from time series (figure 4.5b) is approximately 0.048 mm/yr over the study period. As stated before, the data explained in time series accounts total crude oil and liquid production in Saudi Arabia. Even with this rate, crude oil-liquid extraction in the Eastern Province remains small compared with other variables like the soil moisture parameter and does not affect GRACE TWS significantly. Therefore, the effect coming from oil industry activities can be neglected. This result is consistent with previous study conducted by *Doll et al* (2014), revealing that oil production fluxes in Saudi Arabia are much smaller than consumptive water for agriculture purpose.

4.4 GRACE-Derived Groundwater Storage

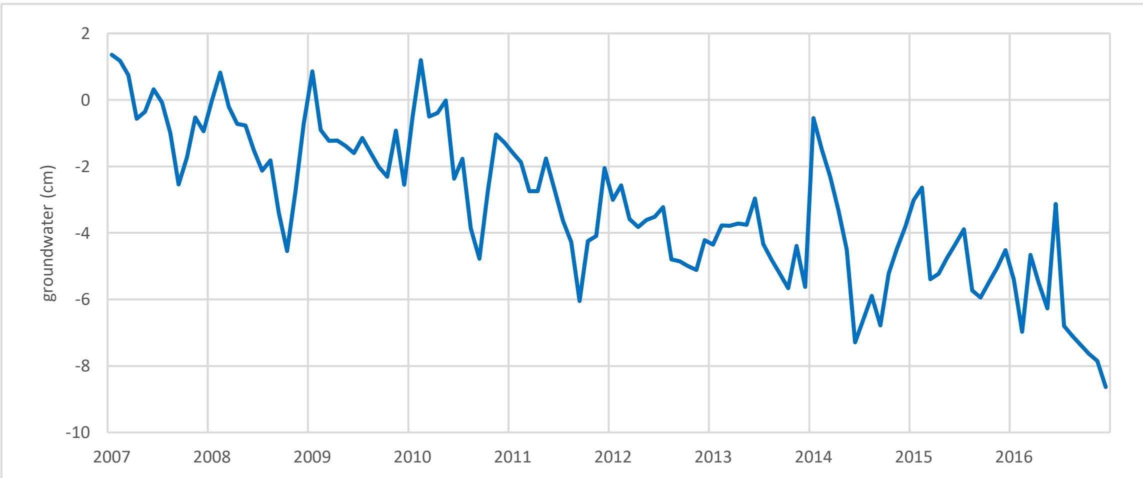


Figure 4.6 Groundwater storage (GRACE GW) anomalies in the Eastern Province over study period after removing soil moisture effect

The groundwater storage anomaly variations after removing soil moisture and crude oil-liquid extraction effect from GRACE TWS is showed by figure 4.6. As seen, GRACE GW relatively rise during wet season and decreased during summer. However, according to the time series, the groundwater storage over 10-years of study period shows trend of depletion with rate of -6.384 ± 0.409 mm/yr or equivalent with -4.293 ± 0.275 km^3 groundwater loss. The trend of groundwater storage depletion presented here is consistent with previous estimation conducted in the Middle East countries by *Voss et al* [2013], *Richey et al* [2015], *Gonzales et al* [2016], *Fallatah et al* (2017) and *Othman et al* (2018).

Figure 4.7a illustrates the 2007-2016 mean seasonal time series of GRACE GW in the study area. As seen from the figure, GRACE GW remains high during winter season

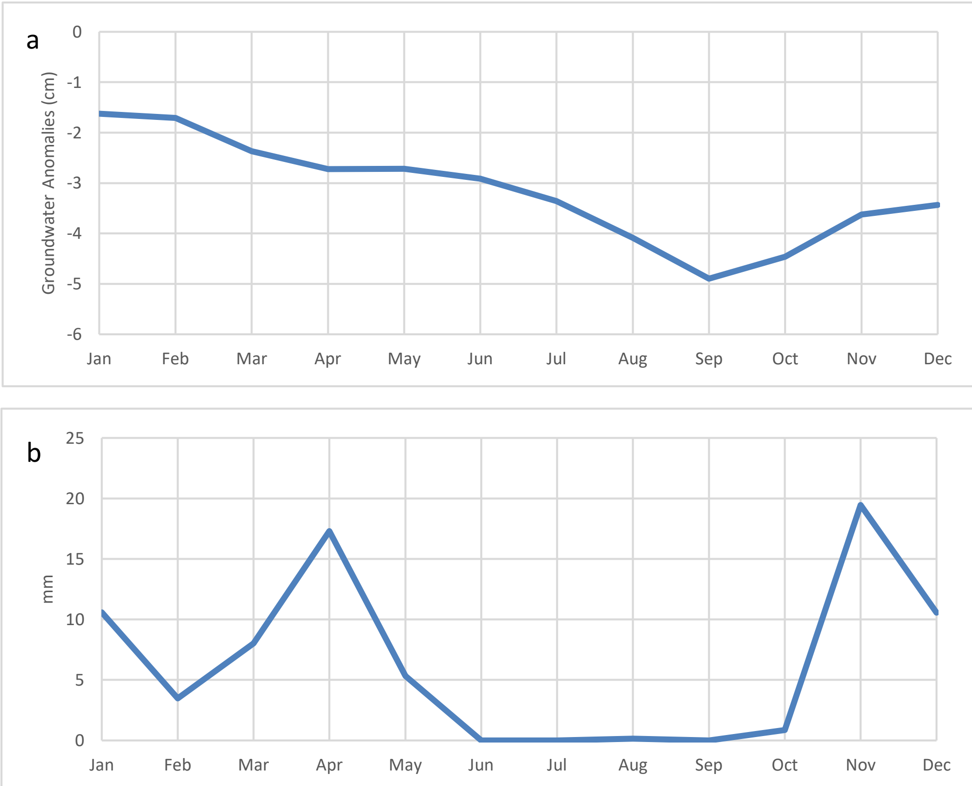


Figure 4.7 Mean annual cycle of (a) GRACE GW and (b) insitu measurement of rainfall rate. The data are collected over 10 years of period

(January-February), then start to decrease until its annual low on September before increasing again throughout the rest of year. Figure 4.7b exhibits the mean seasonal of ground observed rainfall data collected from three different stations within the Eastern Province from January 2007 to December 2016: Dammam, Hasa and Hafr Batin[6]. It is clearly observed that the largest monthly precipitation occurred during period of November and April. However, the precipitation variabilities are not reflected in GRACE GW variations in term of magnitude and amplitude, indicating that the storage is not affected by rainfall. This result is consistent with previous study conducted in central Saudi Arabia revealing that climate fluctuation is not the primary factor of groundwater deficit trend

[6] Available at https://www.stats.gov.sa/en

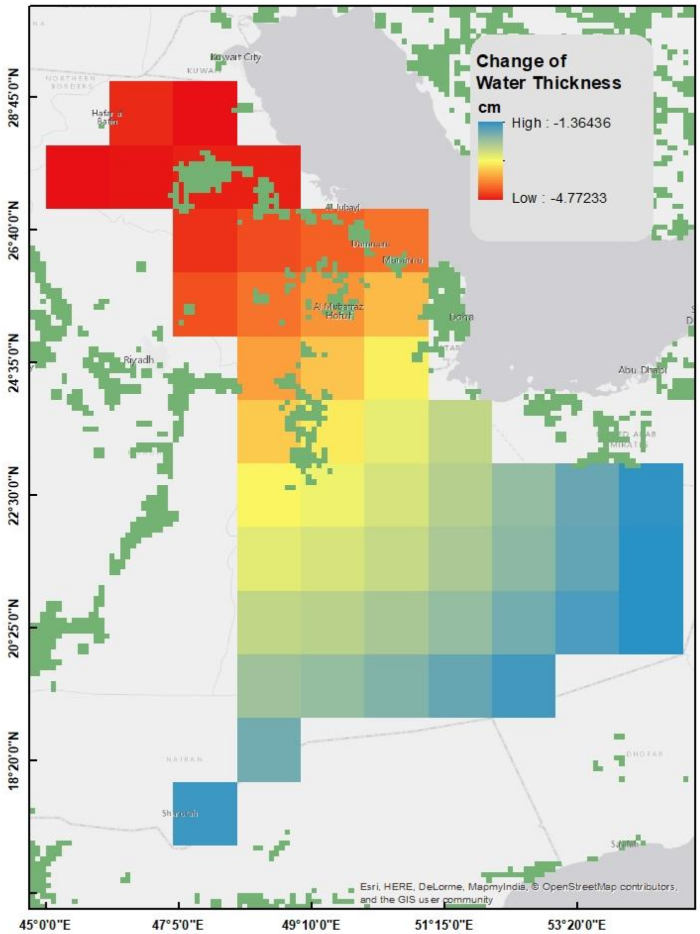


Figure 4.8 The relationship between averaged spatial variation of GRACE TWS change with distributed agriculture area within the Eastern Province

(*Fallatah et al*, 2017). Generally, in the arid area, precipitation could affect soil moisture variations instead of groundwater storage. Moreover, in the mid latitude areas, evapotranspiration plays significant role in influencing TWS storage than precipitation (Syed et al, 2008).

Figure 4.8 illustrates the relationship between distributions of cultivated area with averaged GRACE TWS change over the study period. It is noticed that the distribution of the highest groundwater depletions is located around cultivated land in the northern and middle part of the Eastern Province. However, generally the entire Eastern province is witnessing

Table 1 Water resources trend in the Eastern Province from January 2007 to December 2016

Component of Water Storage	Trend (mm/yr)	Volume lost (km^3/yr)
GRACE TWS	-6.72 ± 0.416	-4.519 ± 0.28
Soil Moisture	-0.396 ± 0.048	-0.266 ± 0.027
Groundwater	-6.384 ± 0.409	-4.293 ± 0.275

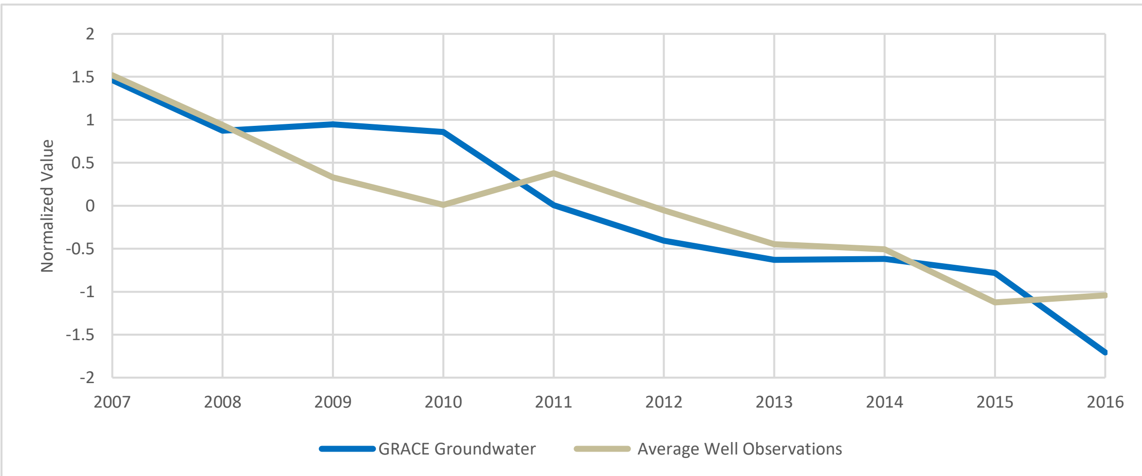


Figure 4.9 Validation of GRACE GW against yearly observed water level data

groundwater depletion since 2007 to 2016. The agriculture map derived from *Siebert et al* (2015) as showed from the figure shows that most agriculture zone in the Eastern Province are situated in the northern and the middle part. Considering the magnitude of soil moisture anomaly that is relatively low compared with TWS as showed by water storage components in Table 1, this study assumes that the utilization of groundwater for irrigation was the main contributor of TWS depletion since 2007 to 2016.

GRACE GW is compared with groundwater level observation from nineteen wells throughout the study area to validate the result. These wells monitored major and minor aquifers maintained in the Eastern Province such as UER, Dammam Wasiya and Neogen aquifers. This comparison shows that GRACE GW generally matched with the observed field data (figure 4.9). Hence, the groundwater depletion estimated in this study can be considered as realistic data. The discrepancy between them can be explained by using the fact that the ground-based observations are limited and not equally distributed in the study area

4.5 InSAR-Derived Ground Deformation

Relative land subsidence is identified in the selected study locations since June 2016 to December 2016. The ground subsidence is processed from Sentinel-1A acquisitions using DInSAR technique. These ground deformation variations reflecting the aquifer compaction and expansion are related to pore fluid pressure and effective stress change. Overall, the deformation occurred in four different agriculture areas show general subsidence. The observed subsidence explained in this study reflects relative displacement instead of actual deformation due to the limitation of insitu dataset. Another thing that should be considered is the potential atmospheric effect cannot be neglected using conventional DInSAR method, hence it could affect the measured vertical displacement. The deformation maps produced in this study also exhibit large bad spatial resolution area caused by temporal decorrelation. Furthermore, these large blank areas are mostly located within the agriculture areas. Detailed explanation dealing with this issue will be discussed in the next chapter.

Map of cumulative deformation in Dammam-Qatif areas is generated for the period August 14 to November 6, 2016. This map includes both rural and agriculture zone. As expected, the higher negative vertical displacement is mainly occurred in the center-north part along

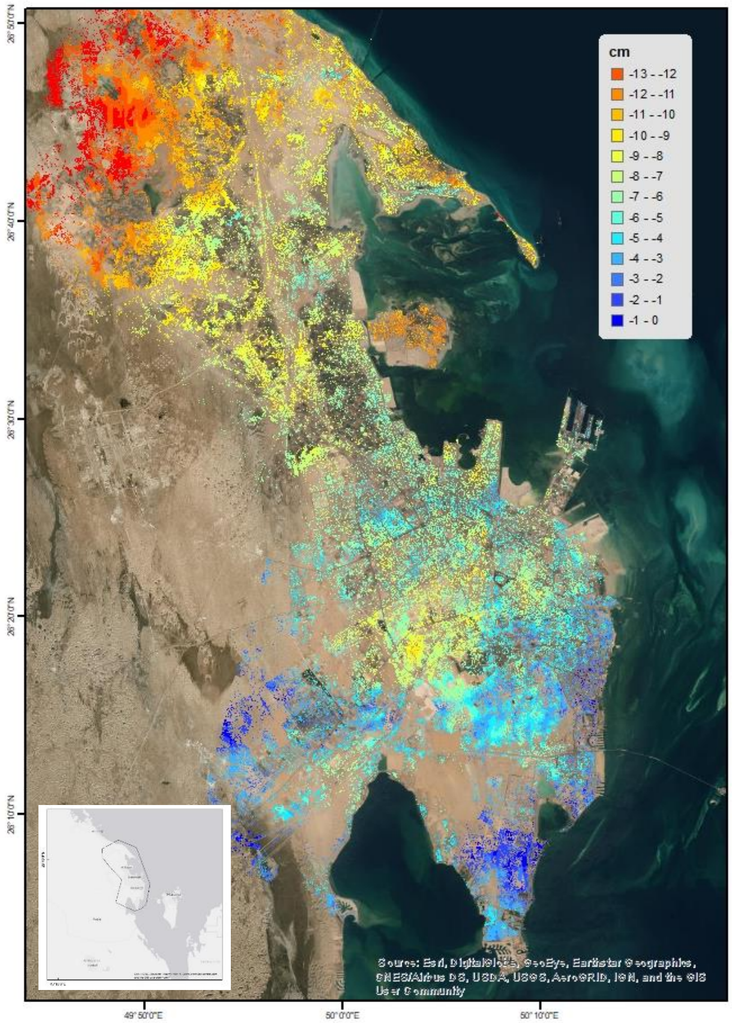


Figure 4.10 Cumulative vertical deformation map in Dammam-Qatif area over the study period

the agriculture zone near Qatif (figure 4.10a). The relative cumulative subsidence observed in the agriculture area varies from -8 cm to -13 cm. Subsidence occurred in that area might be attributed by groundwater pumping for irrigation consumption. According to ground-based observation data, head level in this area is getting lower since 2009 due to compaction of the compressible aquitard layer within the aquifer system.

Overall, the urban area in the southern part has experienced smaller subsidence than the agriculture area in the northern part with a range from 0 to -6 cm. However, the higher

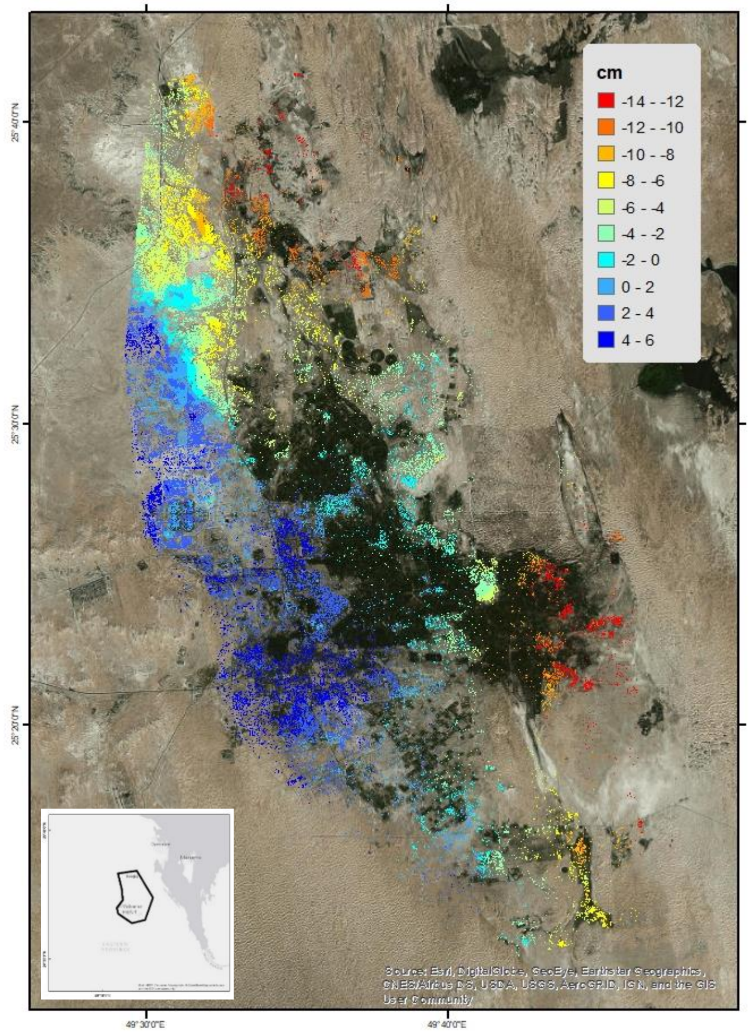


Figure 4.11 Cumulative vertical deformation map in Hasa area over the study period

subsidence compared to surrounded area is observed within the municipality area. Due to the limitation of insitu data, the negative displacement occurred in this area is assumed due to groundwater pumping for urban consumption. Even though having smaller deformation, subsidence occurred in this area might expose higher threat than agriculture area as it could affect the vital public infrastructure like road, building and pipeline network. It is observed from the figure as well that DInSAR method generates better spatial resolution in the urban areas compared to the agriculture areas that exhibit temporal decorrelation error due to geometric change of the object between two acquisitions.

Figure 4.11 depicts the total deformation map in Hasa area from June 8 to November 11. The highest cumulative subsidence observed from the figure located in south-western part near agriculture area has range from -12 to -14 cm. While the western part exhibits relative uplift deformation up to 6 cm over the study period. Large blank zone is monitored in dense vegetated area, providing no information regarding the deformation in this area. This kind of issue could be handled by utilizing other SAR missions with longer wavelength to be able penetrating high vegetated area. Ground uplift and subsidence occurred in this area might reflect reversible elastic deformation. This elastic deformation is probably caused by the presence of compressible layers like siltstone and intercalation of shale in UER, Dammam and Neogen aquifer. According to insitu data, water demand in Hasa is mainly supplied from those aquifers. Another factor that might affect deformation in Hasa is oil field activities situated in the western part of the study area. Several studies revealed that fluid injection into oil reservoir could attribute to uplift deformation due to increasing of pore fluid (*Zhou et al*, 2009; *Pearse et al*, 2014). Further investigation should be performed to define whether relative positive vertical displacement observed in the western part is associated with oil industry activities or due to post-pumping stage of groundwater withdrawal.

Qaryat al Ulya exhibits much less deformation in the southern part compared to the northern part from June 8 to December 29, 2016 (figure 4.12). The subsidence observed in the northern part varies from -6 cm to -12 cm, while in the southern part the range of negative vertical displacement is from 0 to -3 cm. The relative uplift deformation is

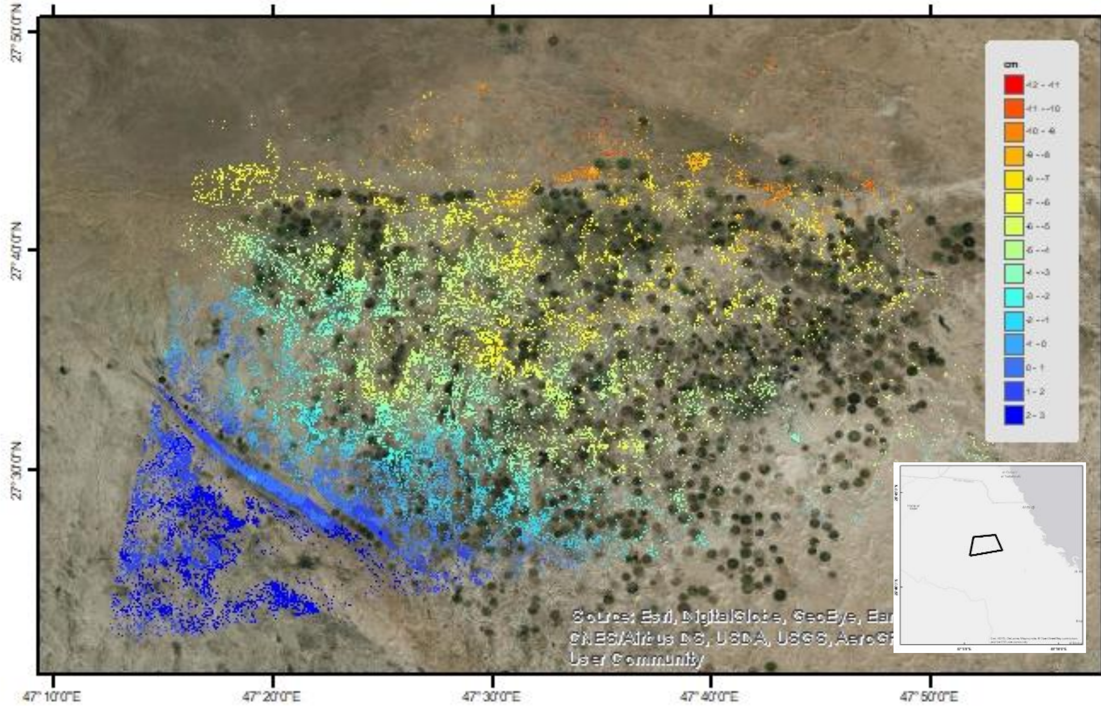


Figure 4.12 Cumulative vertical deformation map in Qaryat al Ulya area over the study period

monitored in the south-western part of the study area. Since the land use of this area is mostly dominated by cultivated zone, the relative uplift and subsidence occurred in Qaryat al Ulya are assumed attributed by groundwater pumping for irrigation purpose. Similar with what happened in Hasa, the uplift deformation over the study period is probably caused by the increasing of pore fluid during post-pumping event. The positive and negative vertical displacement variations here are regarded as reversible elastic deformation due to the presence of compressible layer within the aquifer system.

As shown from the figure, this area has the same issue as other agriculture areas where the coherence is low. However, since the agriculture zone in Qaryat al Ulya is less dense than Hasa, the spatial resolution in this area is better compared to the previous one. In order to achieve best result, longer wavelength derived from other SAR missions can be utilized in the further study.

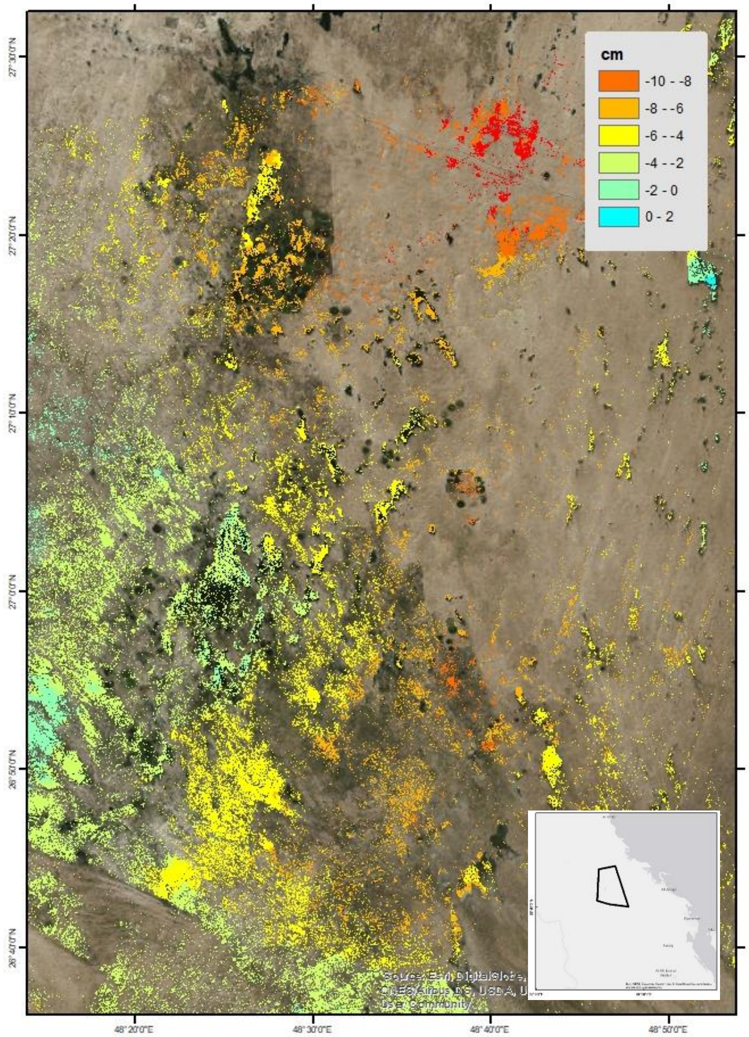


Figure 4.13 Cumulative vertical deformation map in Nairyah-Al Sarrar area over the study period

The cumulative deformation map of observed area in Nairyah-Al Sarrar area since June 8 to November 23, 2016 shows less spatial information compared to other acquisition from different areas due to loss of coherence (figure 4.13). The selected study area is characterized by the presence of both agriculture zone and Jaladi oil field. Oil industry activities also might contribute to the poor coherence resulted in this area. DInSAR technique applied in this study commonly generates poor result in area with fast movement of terrain surface. Therefore, utilization of advanced InSAR processing method like SBAS and PSI should be used to overcome this issue. Overall, the subsidence monitored in Nairyah-Al Sarrar varies from 0 to -8 cm with the highest negative vertical displacement occurred in the north-eastern part. The variations of subsidence in this area are considered not affected by groundwater withdrawal for irrigation purpose solely, but also by crude oil extraction.

CHAPTER 5

DISCUSSION

5.1. Long Term Declining Trend of Groundwater Resources

GRACE-derived groundwater indicates that the study area has experienced a groundwater volume loss of approximately - 4.52 km^3 with rate of depletion of - 6.72 mm/yr over the 10 years study period. It is indicated that the high consumed fresh water abstractions were exacerbated by low replenishment from precipitation. The rainfall rate in Saudi Arabia is relatively low as reported from various studies. The monitored groundwater depletion in the study area will exaggerate the long-term aquifer stress started from few decades ago. *Abderrahman, et al* (2007) reported that since 1967 until 2006, Dammam and UER aquifer have been abstracted around 222% and 917%, respectively. This situation could be alarming for the Eastern Province, a water scarce region with rapid development and mainly rely on groundwater storage to fulfill the daily water demand.

GRACE has ability to calculate vertically the stored water, including surface water, soil moisture, and groundwater. It can be said that the twin satellites measure all aquifers in the study area, including UER and Dammam as the main aquifers and few secondary aquifers. GRACE will not be able to calculate separated aquifer, therefore the depletion rate and volume loss given in this study represent the total productive aquifers in the Eastern Province.

Two other components contributing to GRACE TWS that were included to be analyzed in this study are soil moisture and crude oil-liquid extraction derived from oil company's activities. Soil moisture is stored in vadose zone and might be regarded as one of significant components in the hydrological processes. According to its trend and magnitude, the simulated soil moisture from three different LSMs did not have significant contribution for TWS variabilities in the study area. The different cases occurred in the warm and temperate regions, where soil moisture has high impact to TWS change [*Shamsudduha et al*, 2012]. This condition occurs due the fact that soil moisture variations are highly influenced by climate, particularly temperature and rate of precipitation. In the agriculture area, soil moisture changes are also affected by pumped water for irrigation purpose [*Liesch & Ohmer*, 2016]. However, since LSM has been proven to be able for estimating natural variabilities solely, those effects might not contribute in the soil moistures variabilities discussed here. Although LSM might has high uncertainty, since the field observed data are scarce, most recent studies still rely on this product due to its capability to provide spatiotemporally soil moisture global dataset in near real time. To minimize the uncertainty, this study applied the ensemble average from three different LSMs.

The crude oil-liquid extraction has small contribution as well to TWS variations. Even with total oil-liquid abstraction from both onshore and offshore field, its magnitudes is much smaller than GRACE TWS and soil moisture component. It is important to note, that the crude oil variable discussed here should be isolated from offshore and onshore field productions located outside of the Eastern Province. The offshore fields production is estimated to has contribution of around 35% from the total crude oil productions. However, since the available data are not available and cannot be easily accessed, by considering its magnitude, neglecting this component from GRACE TWS can be justified, following surface water and snow water. This result is consistent with *Gonzalez et al* (2016) revealing the oil extraction variabilities are very small compared with GRACE TWS in United Arab of Emirates (UAE), one of oil production countries in the Arabian Peninsula. Moreover, Doll et al (2014) stated that among oil production countries in the Middle East region, only small countries like Qatar and Kuwait who have similar fluxes in term of magnitude and amplitude from both GRACE TWS and oil-liquid extraction.

Understanding the dominant factor influencing groundwater depletion is important to avoid potential conflict in the future. Given the fact that agriculture zones in Saudi Arabia consume most the groundwater supplies, it can be concluded that major groundwater depletion in the study area is driven by the irrigation demand. This assumption is supported by the result of this study, revealing that majority of the biggest groundwater depletion consistent with distribution of cultivated area. Previous researches conducted in northern and central Saudi Arabia also addressed the same issue, stating that the freshwater depletion in this country is vulnerable to anthropogenic activities (*Fallatah et al,* 2017; *Othman et al*, 2018). *Richey et al* (2015) revealed that groundwater use practice for irrigation purpose is the main factor contributing to GRACE TWS depletion in the Arabian aquifer. Hence, better water resources management strategies in irrigation sector should be implied to avoid future conflict that might arise due to growth of population and food demand. Improvisation of conservative irrigation water scheme could potentially reduce the groundwater withdrawal in the Eastern Province up to 25% as simulated by *Abderrahman et al* (2007).

It has been reported that proper irrigation scheme has been implied by several countries in the Middle East region lately to sustain their limited freshwater resources. Jordan, Oman, Egypt and UAE have tried to conserve their water resources by utilizing treated wastewater for irrigation, injecting re-use wastewater into coastal aquifer to encounter seawater intrusion, pumping flash flood water into aquifer to increase groundwater storage, and recharging artificial aquifer through engineering approaches, respectively (*WWAP*, 2015).

Another issue that need to be considered in the application of GRACE spherical harmonic version in this study is scaling factor. As discussed in chapter 3, GRACE data should be recovered using provided scaling factor to retrieve possible signal loss due to post processing. This scaling factor was estimated from signal attenuation by comparing GRACE with GLDAS. However, in a region where groundwater abstraction is the biggest factor affecting TWS like the Eastern Province, the scale factor might not be accurate. The utilization of latest GRACE data provided by JPL and UT-CSR called mascon solution could handle this issue. This product offers higher spatial resolution with a grid of 0.5^o x 0.5^o. Moreover, mascon solution reduces various error and restore the possible signal loss by implementing different technique during the processing steps. Previous study showed that the comparison between this product with spherical harmonic version exhibits that mascon solution has better accuracy and smaller error (*Fallatah et al*, 2017).

5.2. Land Subsidence caused by Anthropogenic Factor

Numerous studies have reported that extensive groundwater abstraction attributed to aquifer compaction and land subsidence due to the effective stresses (*Zhou et al*, 2009; *Castellazzi et al*, 2016b; *Farr et al*, 2016; *Chen et al*, 2017; *Smith et al*, 2017; *Gong et al*, 2018; *Othman et al*, 2018). The land sinking deformation commonly occurs in hydrogeological setting composed by aquifer and aquitard (*Galloway & Burbey*, 2011).

Since the effect of subsidence could threat the public infrastructure and environment, therefore it should be anticipated. This phenomenon can be monitored by utilizing InSAR approach. InSAR calculates phase difference between two SAR satellite acquisitions that related to ground deformation. This study demonstrated the ability of Sentinel-1A acquisitions by using DInSAR technique to monitor the spatiotemporal deformation in the Eastern Province's agriculture area over short period (June to December 2016).

During the study period, several uplift and subsidence area have been able to be observed using DInSAR technique. The uplift and subsidence variations throughout the short period of InSAR's study were correlated with groundwater withdrawal and post-pumping stage. These ground deformation variations might reflect elastic or inelastic deformation caused by effective stress within the aquifer system. The presence of low permeability of finer-grained lithological unit (aquitard) in the Eastern Province aquifer system such as shale and siltstone in UER, Dammam and Neogene aquifers are regarded as important factors for generating vertical displacement variations. The sediment compaction that leads to ground subsidence is mainly occurred in compressible and less permeable layer referred as an aquitard.

The ground subsidence occurred during the study period was caused by the increasing of effective stress and decreasing of pore fluid pressure due to groundwater withdrawal. This condition would generate aquitard drainage that lead to aquifer compaction. Meanwhile, the increasing of pore fluid pressure will attribute to the decreasing of effective stress, resulting the ground uplift. The aquifer system undergoes inelastic deformation if the effective stress exceeds the maximum effective stress. It might decrease the groundwater storage, permeability and pore space permanently. This permanent deformation can be estimated by integrating InSAR, skeletal-specific storage, hydraulic parameter, and in situ hydraulic head level as illustrated by *Smith et al* (2017) in San Joaquin Valley. The aquifer system will be compressed elastically when the effective stress is still below the maximum effective stress (*Galloway et al, 1998).* This study reveals that the ground deformation occurred in the urban area could pose a potential hazard for public infrastructure.

Over-exploited fossil water aquifer in the agriculture zone is assumed responsible for the land subsidence observed in Qaryat al Ulya, Hasa, Nairyah-Al Sarrar and agriculture area near Qatif. Previous study conducted in Central and Northern Saudi Arabia also suggested the same factor for land subsidence development in cultivated area (*Othman et al*, 2018). According to results from GRACE, the temporal variation of uplift and subsidence monitored in the selected study area might affected by irrigation pattern instead of climate variabilities. However, the effect of climate cannot be fully neglected to aquifer-related deformation particularly during wet season when the water level rises due to recharge. In Nairyah-Al Sarrar region, the ground displacement development is not only triggered by agriculture activities, but also affected by the presence of Jaladi oil field. Crude oil extraction in oil industry activities might attribute to observed ground subsidence in that area.

It should be noted that validation against temporal vertical displacement derived from Sentinel-1A cannot be performed due to the unavailability of monthly water level observations as the hydraulic head level is attributed by aquifer compaction. Field experiment by distributing GPS over the study area also need to be performed not only to monitor the observed vertical displacement at InSAR scale, but also to select specific location that experience less deformation as a reference point in order to generate absolute subsidence map. Moreover, GPS will help to validate the InSAR result. Monthly or daily water level data are also required in InSAR's study. These in situ data are not only useful for validating the result, but also to bring better understanding about the relationship between groundwater storage change and land subsidence.

Among the selected study area, the urban area of Dammam and Hasa provided better spatial resolution compared to other monitored area, revealing that DInSAR technique provides better result in the urban area. The loss of coherence in the agriculture areas are mainly due to the short wavelength derived from C-band Sentinel-1A, hence, it cannot penetrate vegetation. Longer wavelength from other space borne missions like L-band Advanced Land Observation Satellite-2 (ALOS-2) should be used to address these common issues in high vegetated area. This solution can be applied as well in other agriculture areas like Hofuf and Qatif, where temporal decorrelation generally resulting loss of coherence. Several agriculture activities such as harvesting and crop growing could change the scattering characteristic of the object, causing decorrelation.

Despite generating good result in urban area, DInSAR technique has several limitations, for example, its accuracy is limited by temporal decorrelation and atmospheric effect. The temporal decorrelations due to change in physical and geometric properties were monitored in Dammam-Qatif, Hasa and Nairyah-Al Sarrar. In order to overcome these issues, the advanced InSAR processing technique such as PSI and SBAS could be utilized. The use of PSI technique could address the issue with longer L-band InSAR data which is less sensitive to small deformation than C-band InSAR data. *Chen et al* (2017) demonstrated that the shorter wavelength C-band can be applied in dense vegetation area using PSI technique in San Luis Valley agriculture zone. L-band InSAR data could be utilized in area that expected undergoes bigger deformation like mining industry. Higher temporal resolution (6-12 days repeat cycle) should be considered to gain good coherence. The quality of coherence is influenced as well by local climate like rainfall and strong wind, hence SAR acquisition data during those events should be avoided (*Ferretti et al*, 2007)

CHAPTER 6

CONCLUSION & RECOMMENDATION

Conclusions

This study has discussed the TWS issue in the Eastern Province by utilizing the gravity satellite data. The results show that TWS variations were largely controlled by the groundwater component instead of soil moisture and oil-liquid extraction. The aquifer systems in the study area depleted from 2007 to 2016 with rate of -6.384 ± 0.409 mm/yr. The high rate of groundwater depletion was driven by anthropogenic activities like groundwater pumping for irrigation consumption rather than climate variabilities. Climate components like precipitation and evapotranspiration have minimum effect in influencing the groundwater variations in the study area. The negative trend of groundwater storage agreed well with the observed well data.

The over extraction of natural fresh water resources led to land subsidence especially within the agriculture area. This phenomenon can be observed by using SAR satellite. Hasa, Nairyah-Al Sarrar, Dammam-Qatif and Qaryat al Ulya exhibited relative ground subsidence and uplift during the study period. The agriculture area in Hasa and Dammam-Qatif showed higher subsidence compared to the urban area. This indicates that the groundwater abstraction in the agriculture area is higher than the urban area. Possible various sources of errors derived from SAR acquisition were observed in this study, such as the temporal decorrelation.

This study exposes the advantage of cost-effective spatiotemporal remote sensing application (GRACE and InSAR) to monitor the physical groundwater issues that might lead to ground deformation, particularly in regions where freshwater extractions are high and not frequently monitored. Integration between satellite and real data might assist the decision maker to construct more effective management of water resources. Moreover, it will give better understanding of land deformation influenced by groundwater pumping that could damage any public infrastructures. The improved water resources management in the Middle East is not only to maintain the quality and quantity of productive aquifer, but also to achieve food security due to rise of populations.

Recommendations

For further study, the last released GRACE product derived from CSR and JPL called mascon solution can be utilized to achieve good accuracy, particularly at smaller area. This product offers better spatial resolution than spherical harmonic solution (the data used in this study) with a grid of 0.5^o x 0.5^o. Moreover, Mascon solution has ability to minimize error and restore possible signal loss by improving its processing technique.

Other different InSAR missions with longer wavelength and better temporal resolution should be performed to generate better coherence especially in high vegetated area in Hasa, Qatif and Qaryat al Ulya. The advanced InSAR processing technique such as PSI and SBAS could be performed to reduce the atmospheric effect and achieving better result.

Field data measurement by collecting monthly water level and GPS observation in the study area are required to validate InSAR result. The GPS measurement is useful to select reference point for generating absolute vertical displacement as well. Since GRACE has low resolutions, field work could support InSAR approach for groundwater storage monitoring at a local scale where GRACE cannot be applied.

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