An Integrated Approach (Remote Sensing, Hydrogeology, Geotechnical, and Geoinformatics) to Assess and Monitor Fossil Aquifers and Associated Land Deformation Over the Arabian Peninsula

Abdullah Ghurmullah Saeed Othman
Western Michigan University, abdullah3035@gmail.com

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AN INTEGRATED APPROACH (REMOTE SENSING, HYDRO GEOLOGY, GEOTECHNICAL, AND GEOINFORMATICS) TO ASSESS AND MONITOR FOSSIL AQUIFERS AND ASSOCIATED LAND DEFORMATION OVER THE ARABIAN PENINSULA

by

Abdullah Ghurmullah Saeed Othman

A dissertation submitted to the Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy Geosciences
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Doctoral Committee:

Mohamed Sultan, Ph.D., Chair
Alan Kehew, Ph.D.
William Sauck, Ph.D.
Richard Becker, Ph.D.
Deformational features such as subsidence, sinkholes, fissures, settling and cracks in buildings and structures, and earthquakes are being reported from many of the world’s arid lands, in areas where fossil aquifers are being excessively exploited. Using the Lower Mega Aquifer System (LMAS) in Arabia as a test site, I applied an integrated approach (remote sensing, geodesy, GIS, geology, hydrogeology, and geotechnical) to identify nature, intensity, spatial distribution, and factors controlling the observed deformation in the central (Al-Qassim and Ha'il regions; area: $16 \times 10^4$ km²) and the northern (Wadi As-Sirhan Basin; area: $\sim 10.9 \times 10^4$ km²) Arabia. A four-fold approach was adopted to accomplish the following: (1) assess the spatial distribution of land deformation and quantify deformation rates using field and Interferometric Synthetic Aperture Radar (InSAR) and Persistent Scatterer Interferometry (PSI) methods (period: 2003 to 2012); (2) estimate aquifer depletion rates using temporal (04/2002-06/2016) Gravity Recovery and Climate Experiment (GRACE) solutions; (3) generate a GIS database to host all relevant data and derived
products (e.g., remote sensing, geology, geotechnical, GPS, groundwater extraction rates, and water levels, etc.) and to conduct spatial correlations of these spatial and temporal datasets in search of causal effects; and (4) identify extraction scenarios to attain sustainable utilization and to minimize land deformation. The following observations are consistent with deformational features being caused by excessive groundwater extraction: (1) distribution of deformational features correlated spatially and temporally with increased agricultural development and groundwater extraction, decline in water levels and in groundwater storage; (2) earthquake events (1.5 - 5.5 M) increased from a single event at the onset of the agricultural development program in 1980 (extraction: 1 km³/yr), up to 13 events per year in the nineties, the decade that witnessed the largest expansion in groundwater extraction (average annual extraction: >6.4 km³) and land reclamation; and (3) earthquake epicenters and the deformation sites are found largely within areas bound by the Kahf fault system suggesting that faults play a role in localizing deformation. Findings from the PSI investigation revealed high, yet irregularly distributed, subsidence rates (-4 to -15 mm/yr) along a NW-SE trending graben within the Wadi As-Sirhan with the highest subsidence rates being localized within elongated bowls, that are proximal to, or bound by, the major faults and that areas to the east and west of the bounding faults show no, or minimal subsidence. Findings from the analysis of GRACE data indicate that sustainable extraction from the LMAS could be attained by reducing groundwater extraction by 3.5 to 4 km³/yr and provide replicable and cost-effective methodologies for optimum
utilization of fossil aquifers and for minimizing the deformational effects associated with their utilization.
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CHAPTER 1
INTRODUCTION

1.1 Background

Subsidence is triggered by natural and/or anthropogenic causes and is defined as the differential sinking of the Earth’s surface due to volume reduction of subsurface materials, or presence and collapse of subsurface voids (Ren et al., 1989). Subsidence due to volume reduction by natural and/or anthropogenic factors, is generally a slow phenomenon operating over relatively large areas. Subsidence rates were traditionally measured by ground-based geodetic surveys and techniques (e.g., precise differential levelling, global positioning systems, tripod lidar, extensometry) (Galloway and Burbey, 2011). The advent of InSAR technologies enabled cost-effective contiguous measurements of land deformation over large areas (Gabriel et al., 1989). These technologies have been successfully applied to the Antelope and Santa Clara Valleys in California, Las Vegas Valley of Nevada (Galloway and Hoffmann, 2007; Galloway et al., 1998; Fielding, et al., 1998), and the San Luis Valley of Colorado (Reeves, et al., 2011).

Recent (as early as the 1990s) applications of radar interferometric techniques enabled detection and measurement of slow land deformation over large areas (Hooper, 2006; Kampes, 2006) worldwide (e.g., central Mexico [Chaussard, et al., 2014], Nile Delta [Becker, and Sultan, 2009]; and San Francisco Bay Area [Bürgmann, et al., 2006]) and the correlation of radar-detected subsidence with
relevant temporal and spatial observations provide insights into the factors causing the observed subsidence (e.g. Higgins, et al., 2014; Chaussard, et al., 2013). These observations could include groundwater or oil/gas extraction rates, water levels, and rock and sediment type. For example, subsidence of up to 40 mm in 35 days over the Lost Hills and Belridge oil fields in the San Joaquin Valley in California was determined to have been caused by excessive oil extraction from a shallow depth (~700 m below the surface) (Fielding, et al., 1998).

Deltas worldwide are undergoing subsidence due to sediment compaction. Persistent Scatterer Interferometry (PSI) studies over large sections of the Nile Delta, the home for more than fifty million people, revealed sediment compaction-related subsidence of up to 8 mm/yr (Becker, and Sultan, 2009). Likewise, applications of Interferometric Synthetic Aperture Radar (InSAR) techniques over the Fraser River delta, western Canada, revealed an average subsidence of 1 to 2 mm/yr due to Holocene sediment compaction that is exemplified locally (up to 8 mm/yr) by sediment compaction related to large structural load (Mazzotti, et al., 2009).

Subsidence and other deformational features such as fissures, sink holes, and earthquakes, have been reported in many of the arid and semi-arid parts of the world where progressive groundwater extraction projects have been implemented over the years. Using InSAR and Global Positioning System (GPS) data, land subsidence of up to 6 cm/yr and fissures were detected (1992 to 1997) over the Las Vegas Valley
due to intensive groundwater extraction (93 hm³/yr; Bell, et al., 2002). Groundwater-extraction related deformation was reported for both confined and unconfined aquifers (Galloway et al., 1998; Poland, 1960). The deformation is either uniform over large areas or differential, causing damage to buildings and infrastructure and fissures (Burbey, 2002); and causing vertical and possibly horizontal displacement of land surface (Galloway and Burbey, 2011; Burbey, 2001).

The largest number of subsidence cases have been documented in arid lands where precipitation is minimal, limited or no surface water resources are available, intensive irrigation programs are implemented, and groundwater is the sole source for water supply (Maliva and Missimer, 2012). Examples of such areas include the Sahara of North Africa and the Arabian Peninsula. Aquifers within those areas were largely recharged in previous wet climatic conditions in the Pleistocene and are receiving only modest recharge locally; in these settings the increasing anthropogenic discharge is not compensated for by the modest recharge (Sultan et al., 2014). Examples of such systems are the Mega Aquifer System (MAS) in Arabian Peninsula (e.g. Sultan, et al., 2014; Jado and Zötl, 1984; Hoetzl and Zoetl, 1978), the Nubian Aquifer System in northeastern Africa (Mohamed et al., 2017), the Northwestern Sahara Aquifer System in northwestern Africa, and the Great Artesian Basin in eastern Australia (Taylor et al., 2013). In such areas, and for those fossil aquifers, one would expect that the excessive and prolonged extraction of non-renewable groundwater would cause sustained drawdown of artesian head, intergranular stresses
consistently higher than the maximum historical stress, compaction of highly compressible clay beds (aquitards) if present, and land subsidence, and possibly fissuring, reactivation of faults, and damage to structures and well casings, if differential vertical displacement occurs.

1.2 Objectives

In this study, I conduct an integrated investigation of one of the largest fossil aquifer systems in the arid world, the MAS of the Arabian Peninsula. The MAS (area: \( \sim 2.3 \times 10^6 \) km\(^2\)) extends across the Arabian Shelf of the Arabian Peninsula (Fig. 2a) in the Kingdom of Saudi Arabia, and the countries of Yemen, Oman, Emirates, Qatar, Kuwait, and Jordan. Within and surrounding the areas targeted for agricultural expansion (Fig. 1) which lie over the MAS, one or more types of deformational features (e.g., fissures, fractures, sink holes, subsidence) and/or structural damage has been reported. These areas include the Tabah village, Wadi Al-Yutamah in southern Medina city, and Wadi Najran (Fig. 1) (Youssef, et al., 2014; Vincent, 2008; Bankher and Al-Harthi, 1999; Amin and Bankher, 1997; Roobol et al., 1985).

In the mid-eighties, the Saudi government started the implementation of an aggressive agricultural development program in central Arabia (Al-Qassim and Ha'il regions; Fig. 1), that led to an increase in cultivated lands (1984: \( 213 \times 10^3 \) hectare; 2004: \( 316 \times 10^3 \) hectare) and groundwater extraction (\( 1.9 \times 10^9 \) m\(^3\)/yr in 1984 to \( 4.4 \times 10^9 \) m\(^3\)/yr in 2004). Similar extensive agricultural projects were implemented in northern Arabia (Wadi As-Sirhan in Al Jawf region; Fig. 1) where the cultivated areas
increased from $14 \times 10^3$ hectare in 1984 to $164 \times 10^3$ hectare in 2004 and the groundwater extraction increased from $0.095 \times 10^9$ m$^3$/yr to $2 \times 10^9$ m$^3$/yr (Abunayyan and BRGM, 2008; MOAW, 2004; MOAW, 1984).

My integrated study encompassed a regional study over the MAS in central and northern Arabia and a local study over the Wadi As-Sirhan Basin (WASB) (Fig 1, and 2. A). The regional study encompassed: (1) field investigations to examine land deformation features and to generate a “land deformation database”, and (2) spatial correlation (in a GIS environment) of field data with relevant data sets including lithologic and structural maps, seismic records (Al-Amri, 1998), and landuse maps in search of regional relationships and causal effects. Findings from the regional study were then further investigated and refined in a local study over the WASB in which integrated observations from radar interferometry and relevant data sets were utilized. These include geologic, structural, and land use maps, and temporal and spatial variations in Terrestrial Water Storage (TWS) from Gravity Recovery and Climate Experiment (GRACE) data, seismicity, water levels, and GPS measurements (Fig. 1). Two areas within the WASB were targeted for radar interferometric studies; the first is Issawiya, Tabarjal, and Busayta, and the second Dumat Aljandal and Sakakah (Fig. 1). Those two areas had the largest coverage with ENVISAT radar imagery. I suspect that findings from my investigation could be relevant to many of the fossil aquifer systems in the arid and semi-arid parts of the world.
Figure 1. Location map of the regional study area (northern and central Arabia) and local study area (WASB) showing distribution of the field-verified land deformation sites, LMAS outcrops (Saudi Geological Survey; MOPMR, 1980) and irrigated areas (extracted from Landsat thematic mapper data), areas covered by radar interferometric studies within the WASB, the investigated GRACE pixels, earthquake epicenters for years 1982 to 2014 (Al-Amri, 1998), GPS stations (MOMRA CORS network, Saudi Arabia, 2015; MAGNET GPS Network, Nevada Geodetic Laboratory, 2017).
CHAPTER 2
GEOLOGIC, HYDROGEOLOGIC AND CLIMATIC SETTING

2.1 Introduction

The basement complex of the Arabian Shield crops out along the margins of the Red Sea forming the mountain chain of the Red Sea Hills (Fig. 2). Successions of Phanerozoic sedimentary formations unconformably overly the basement complex and dip gently to the east reaching thicknesses of up to 10 km (Fig. 3) near the Arabian Gulf (Margat, 2007; Konert, et al., 2001; Lloyd and Pim, 1990; Powers, et al., 1966). The outcrops at the foothills of the Red Sea Mountains decrease in age eastwards towards the Gulf, the oldest being of Cambrian age and the youngest of Quaternary age (Fig. 2b). The uplift associated with the Red Sea opening exposed the basement complex and the overlying Phanerozoic cover providing opportunities to recharge aquifers within the Phanerozoic formations where they cropped out. The opening of the Red Sea reactivated many of the older NW-trending sinistral Najd fault systems that cross cut the Arabian Shield in outcrop and apparently dips under the sedimentary cover beneath the entire Peninsula (Fairer, 1983). The reactivation was dip-slip in response to the extensional events associated with rifting during Middle to Later Cenozoic time (Giannerini et al., 1988; Kellogg and Reynold, 1983) and these faults are mapped as the Kahf fault system in Figure 1. Similar observations pertaining to dip-slip movement on earlier Najd faults were reported in the Eastern Desert of Egypt (Sultan et al., 2011).
Figure 2. Geologic map for the Arabian Peninsula and cross section (modified after Chapman, 1978). (a) Generalized geologic map for the Arabian Peninsula. (b) cross section along line A-A’ in Figure 2a. Figures 2a and 2b show the distribution and stratigraphic relations of the Precambrian igneous and metamorphic complex of the Arabian Shield and the overlying Phanerozoic Arabian Shelf rock units and the multi-layered aquifers of the Phanerozoic Mega Aquifer System (MAS). Also shown are locations of the regional study in northern and central Arabia and the local study over Wadi As-Sirhan.
Figure 3. Depth to the basement in the Arabian Plate, showing a west to east increase in thickness of the sedimentary cover (modified after Konert et al., 2001)
2.2 Geology, Hydrogeology, and Climate of the Regional Study Area (Lower Mega Aquifer System)

Collectively the limestone and sandstone aquifers within the Phanerozoic sections from one of the largest multi-layered aquifers world-wide, the Mega Aquifer System (MAS) (Fig.2). The MAS was largely recharged under previous wet climatic conditions, yet at present it is still receiving modest local modern recharge, especially in southwest Arabia where the precipitation is up to 800 mm/yr in some places in the Faifa Mountain and its surroundings in the Jazan region (Alharbi, et al., 2014). Cl-36 dating of groundwater samples from the Empty Quarter yielded ages up to 1 million year. Those previous wet conditions contrast with the current arid climatic conditions with average annual rainfall of 100 mm/yr (Fig.4) over most of the Arabian Peninsula (Barthélemy, et al., 2007) and extremely limited surface-water resources.
Figure 4. Tropical Rainfall Measuring Mission (TRMM) average annual rainfall (from 2000 to 2013) showing the highest amount of precipitation over the Red Sea hills in the southwestern parts of the Arabian Peninsula. Also shown are the locations of the regional study area (northern and central Arabia) and the local study area (Wadi As-Sirhan).
The main aquifers within the MAS comprise (Fig. 2): (1) Paleozoic (sandstone accumulations); (2) Mesozoic (marine carbonates); (3) Cenozoic: (a) Paleogene (carbonate formations); (b) Neogene–Quaternary (sedimentary and volcanic formations) (Wagner, 2011). The MAS is divided into two main groups (Fig. 2b) separated by the Hith anhydrite formation: (a) the Upper Mega Aquifer System (UMAS), which includes Biyadh, Wasia, Aruma, Umm Er Radhuma, Rus, and Dammam formations, and (b) the Lower Mega Aquifer System (LMAS), which includes the Saq, Wajid, Tabuk, Tawil, Minjur, and Dhruma formations. The area occupied by the UMAS and LMAS is $180 \times 10^4$ km² and $56.3 \times 10^4$ km², respectively.

2.3 Main Productive Hydrological Units in the Lower Mega Aquifer System

2.3.1 Saq Sandstone Aquifer

The Saq sandstone aquifer is of Late Cambrian and Early Ordovician age and has extensive outcrop areas along the central and northern boundary of the Arabian Shield (Fig. 1) as well as a huge extension in the subsurface ($31\times10^4$ km²) with thicknesses ranging from 250 to 700m (UN-ESCWA and BGR, 2013). The Saq aquifer forms the major aquifer with 65% of the production over the regional study area (LMAS) and especially in the central part (Al-Qassim and Ha'il regions) of Saudi Arabia. In these areas, many wells reach near or below 1,000 m depth, but in the northern and northeastern part of LMAS the aquifer is too deep to be exploited (Abunayyan and BRGM, 2008). The reserves for the Saq aquifer are estimated at 290 km³ with modest
annual recharge of around 0.31 km³. Dating of groundwater from this aquifer yields ages ranging from 22,000 to 28,000 years old (Vincent, 2008). Groundwater extraction is often initially artesian with recorded pressures of up to 12.3 atmospheres (Vincent, 2008).

### 2.3.2 Tawil Sandstone Aquifer

The Tawil sandstone aquifer is of Silurian-Early Devonian age. It extends (4×10⁴ km²) in the northern part of the regional study area along Wadi As-Sirhan Basin (Fig. 5a) with thicknesses ranging from 200 to 300 m (Fig. 5b); the aquifer crops out in the western part of WASB between Tabuk and Busayta (UN-ESCWA and BGR, 2013). This aquifer is one of the most productive aquifers in the northern part of the regional study area, providing approximately 10% of the annual LMAS's production. The reserves are estimated at 22 km³, and the groundwater is largely fossil with negligible modern recharge (< 2 mm/yr) (Abunayyan and BRGM, 2008; UN-ESCWA and BGR, 2013). Groundwater from the aquifer is largely used for agricultural activities over WASB in the Busayta and Dumat Al-Jandal areas. The abstraction increased from 0.039 km³/yr in 1984 to 1 km³/yr in 2005 and the water table levels ranged from 570 to 600 m.a.s.l. (Abunayyan and BRGM, 2008).
2.3.3 STQ (Secondary-Tertiary-Quaternary) Aquifer System

The STQ (Secondary-Tertiary-Quaternary) aquifer is composed of sequenced rock units of Late Cretaceous to Quaternary ages with thicknesses reaching up to 1300 m (Fig. 5b). The system consists of a stack of geological units with varying aquifer properties that unconformably overlie Paleozoic sequences. The STQ is widespread, yet discontinuous, within the regional study area. Aquifers belonging to this unit include Cretaceous units (Wasia, Aruma) as well as Tertiary to Quaternary (Turayf, Sirhan) fill of the Wadi Sirhan Basin (UN-ESCWA and BGR, 2013; Abunayyan and BRGM, 2008). The groundwater flows towards the depression of WASB, where the water level is shallow (22 m to 65 m deep). The aquifer is mainly used for the agricultural activities as a second productive aquifer in the northern part of the regional study area (Abunayyan and BRGM, 2008). In the period from 1984 to 2005, the over exploitation for irrigation increased the groundwater extraction from 0.141 to 1.4 km³/yr (UN-ESCWA and BGR, 2013).

2.4 Geology and Hydrogeology of the Local Study Area (Wadi As-Sirhan Basin)

The UMAS is absent in northern and northwestern Arabia, the area including the WASB. In this area, the LMAS comprises the Saq (the primary aquifer, although it is deep and untapped) and the overlying Tabuk, Tawil, Jauf, Jubah, and STQ (Secondary, Tertiary, and Quaternary complex) as local productive aquifers (Fig. 5). The WASB is formed of Silurian-Early Devonian sandstone (Tawil Formation), Paleogene sedimentary rocks (Turayf Group), Neogene (Sirhan Formation) and
Quaternary basalt, alluvial deposits, gravels, Khabras (silt and clay cemented by evaporite minerals), and sabkhas within depressions in the northwestern section of the study area (Wallace, et al., 2000)(Fig. 5). The principal structure in this area is a graben complex (vertical displacement: up to 1,500 m; UN-ESCWA and BGR, 2013), bounded by major faults from the east and west that probably formed by tensional forces associated with Red Sea rifting (Meissner, et al., 1990). The faults apparently act as conduits for groundwater discharge as evidenced by the presence of mud flats, salt lakes, and Sabkha (e.g., Al Hazawza Sabkha) within the depression and proximal to the faults (UN-ESCWA, 1990; ACSAD, 1983).

Devonian productive aquifers that are part of the LMAS are found within the depression. Those include Tawil (Central WASB), Jauf, Jubah aquifers (southern WASB) and Cretaceous to Quaternary STQ complex aquifer (Secondary-Tertiary-Quaternary) in the central to Northern WASB. Since the nineties most of the production has been from the confined parts of the Tawil aquifer in the WASB (Abunayyan and BRGM, 2008).
Figure 5. Geologic map, cross section, and stratigraphy of WASB. (a) Geologic map for the WASB and surroundings showing the distribution of the northwest-southeast trending Wadi As-Sirhan graben (modified after Wallace, et al., 2000). (b) Cross section along line B-B'-B'' in Figure 5a showing the thickness of the lithologic units and aquifers and groundwater flow directions (modified after UN-ESCWA and BGR, 2013), (c) General stratigraphic classification of the WASB (modified after Halawani, 2001).
CHAPTER 3

METHODOLOGY

3.1 Introduction

The regional study encompassed: (1) field investigations to examine land deformation features and to generate a “land deformation database”, (2) spatial correlation (in a GIS environment) of field data with relevant data sets including lithologic and structural maps, seismic records (Al-Amri, 1998), Terrestrial Water Storage (TWS) and Ground Water Storage (GWS) from Gravity Recovery and Climate Experiment (GRACE) solutions, GPS measurements, water levels, and landuse maps (Fig. 1 and 6) in search of regional relationships and causal effects. Findings from the regional study were then further investigated and refined in a local study over Wadi As-Sirhan in which observations from the above-mentioned datasets were integrated with those extracted from radar interferometric measurements (Fig. 1). Two areas within the WASB were targeted for radar interferometric studies, the first of which is Busayta and Issawiya, and the second Sakakah (Fig. 1). These two areas are hereafter referred to as the Busayta and Sakakah regions. These two areas were selected because they had the largest coverage of ENVISAT radar imagery.
3.2 Field Observations

Over the past decade, there has been an increase in reported incidences of land deformation events that resulted in losses of life and property, especially from the northern and central parts of Arabia (Fig. 1 and 6). Members of my research team conducted field trips in 2004, 2010, and 2015 to investigate: (1) deformation events reported from central (Al-Qassim and Ha'il regions) and northern (Al Jawf region) Arabia, (2) deformational features (sink holes) extracted from temporal high resolution satellite images, and (3) locations where displacement was extracted from InSAR data. Throughout the field work, one or more of the following deformational styles were observed and documented in 37 locations (Fig. 6): subsidence, sinkholes, earth fissures, settling of buildings, and infrastructure/structure damages. Specifically, we documented six large sinkholes (Fig. 6; Photos. 6 and 7) (diameter: 15 to 40 m), five smaller sinkholes (diameter: 1 to 3 m), earth fissures in 14 sites (Fig. 6; Photos. 1, 2, 5, and 8) (fissure width: 18 cm to 2 m), and cracks in roads and buildings in 12 locations (Fig. 6; Photos. 3 and 4). In the search for causal effects, we collected relevant field data including proximity to agricultural developments and urban areas, agricultural practices (groundwater extraction, excessive watering, etc.), presence or absence of sewage systems, temporal variations in groundwater levels, types of soils and bedrock, and distribution of fractures/fault systems. Approximately 26 locations of these features were observed in and around agricultural lands, and the remaining 11 locations in urban areas lacking adequate organized sewage systems.
Figure 6. Location map of the regional study area (northern and central Arabia) (LMAS) and local study area (WASB), locations of field-verified land deformation sites, distribution of cultivated land over the regional study area, locations of borehole drilling sites for the swelling tests, and field shots of selected land deformation sites collected during our field trips.
3.3 Gravity Recovery and Climate Experiment (GRACE)

The Gravity Recovery and Climate Experiment (GRACE) is a joint satellite mission between the National Aeronautics and Space Administration (NASA) in the United States and the German Aerospace Center (DLR) in Germany. GRACE equipment comprises twin satellites (GRACE A and GRACE B) that rotate the Earth at close proximity to each other. The two satellites were launched in March 2002 from Plesetsk Cosmodrome in Russia, in an orbital voyage that was estimated to last for five years. Sixteen years later, the two satellites are still in operation. The two satellites orbit the Earth, one in front of the other, rotating in a polar orbit with an approximate separation of 200 km, and an inclination of 89.5° and altitude of 500 km (Fig. 7) (Bettadpur, 2006; Flechtner, 2005; Bruinsma, 2006).

The two satellites maintain the same distance, speed, and height until a gravity anomaly is detected. Mass anomalies are captured as disturbances in the distance between the two satellites that are used to measure temporal variations in the global earth gravity field (Tapley et al., 2004). These temporal variations in the gravity field within the investigated short time periods (months, years) are largely related to mass variations in hydrologic systems including groundwater, surface water, glaciers, and oceans. GRACE measures the spatiotemporal variations in TWS (Mohamed et al., 2017; Ahmed et al., 2016, 2014; Wouters et al., 2014; Sultan et al., 2014, 2013; Wahr et al., 1998), where the term “TWS” refers to the vertically integrated
measurement of water storage that includes groundwater, soil moisture, surface water, snow water, and vegetation water (Strassberg et al., 2007).

GRACE Mission

Science Goals
High resolution, mean & time variable gravity field mapping for Earth System Science

Mission Systems
Instruments
- KBR (JPL/SSL)
- ACC (ONERA)
- SCA (DTU)
- GPS (JPL)
Satellite (JPL/DDS)
Launcher (DLR/Eurockot)
Science (CSR/JPL/GFZ)

Orbit
Launch: March 2002
Altitude: 500 km
Inclination: 89 deg
Eccentricity: ~0.001
Lifetime: (Plan: 5 years) (Until 2016)
Non-Repeat Ground Track
Earth Pointed, 3-Axis Stable

Figure 7. Sketch diagram showing the flight configuration for the Gravity Recovery and Climate Experiment (GRACE); source: http://www.csr.utexas.edu/grace/.
I analyzed the recently released (release 05; RL05), high resolution (grid size: 0.5° x 0.5°), monthly mass concentrations (mascon) solutions throughout the investigated period (April 2002 to June 2016) to estimate the temporal variations in TWS over the lower MAS (regional study) and over the WASB (local study). The data was obtained from the Center for Space Research (CSR) at the University of Texas (http://www.csr.utexas.edu/grace) (Save et al., 2016) and was used without any previous processing, filtering and without applying any empirical scaling factors (Save et al., 2016). The secular trend in GRACE-derived TWS data was extracted by simultaneously fitting a trend and a seasonal term to each TWS time series and errors were estimated using procedures described in Scanlon et al. (2016). The change in groundwater storage was estimated using the following equation:

\[
\Delta GWS = \Delta TWS - \Delta SMS \quad \cdots \cdots \cdots \cdots \cdots \cdots (3.1)
\]

Where, \(\Delta GWS\) and \(\Delta SMS\) represent the change in groundwater and soil moisture storage, respectively. The soil moisture was extracted from the Global Land Data Assimilation System (GLDAS) model, a NASA-developed land surface modeling system which simulates climatic and hydrologic variables (Rodell et al., 2004). GLDAS simulates multiple offline land surface models, integrates observation-based data, and executes globally at 2.5° to 1° resolutions, enabled by the Land Information System (LIS) (Kumar et al., 2006). GLDAS developed four land surface models: the Variable Infiltration Capacity (VIC), the Community Land Model
(CLM), Noah, and Mosaic. GLDAS models include the parameters of the land surface and the environment situations such as soil moisture and surface temperature, evaporation and sensible heat fluctuation (Fang et al., 2009).

The soil moisture time series, over the investigated areas, were calculated by averaging the soil moisture estimates from the four GLDAS model versions (Variable Infiltration Capacity [VIC], Community Land Model [CLM], Noah, and MOSAIC [Rodell et al., 2004; Dai et al., 2003] and the errors ($\sigma_{SM}$) from the standard deviation of the trends computed from the four GLDAS simulations. The trend error in GWS ($\sigma_{GWS}$) was calculated using standard error propagation equations:

$$\sigma_{GWS} = \sqrt{(\sigma_{TWS})^2 + (\sigma_{SM})^2}$$

(3.2)

where;

$\sigma_{GWS}$ = Error estimates in the trend of GWS anomaly.

$\sigma_{TWS}$ = Error in the GRACE TWS anomaly estimates.

$\sigma_{SM}$ = Errors associated with soil moisture anomaly.
3.4 Interferometric Synthetic Aperture Radar (InSAR)

Since the 80s, there have been several launches for geodetic synthetic aperture radar (SAR) satellites including Seasat, RADARSAT-1, ERS-1/2, ALOS PALSAR, JERS-1, ENVISAT, Sentinel-1, and others. The launches were conducted by one of the following agencies or as a joint operation between two of those agencies: NASA, European Space Agency (ESA), and Japan Aerospace Exploration Agency (JAXA). The Interferometric Synthetic Aperture Radar (InSAR) satellite technique uses electromagnetic waves of specific wavelengths to measure with accuracy (Submillimeter to millimeter) the distances from the satellite to objects of interest. Temporal measurements to individual objects are then used to generate maps of surface deformation and to monitor and map the intensity (magnitude) of earth movements. Standard radar wavelengths in space imaging systems include C-band, L-band, and X-band (Massonnet and Feigl, 1998). The ENVISAT satellite C-band, which is used for the purposes of this study, transmits a wavelength of 5.6 centimeters (Funning et al., 2003).

This method has been successfully applied to map small displacements (> 0.1 mm/yr) associated with fault slip from earthquakes, and subsidence related to landslides, aquifer compaction, and seasonal deformation caused by fluctuations in groundwater storage (Massonnet and Feigl, 1998; Hoffmann et al., 2001; Burbey, 2002).
Interferometric synthetic aperture radar (InSAR) processing involves estimation of the difference in phase between at least two radar scenes to extract differences in range to a land surface point and to identify subtle changes in topography (Fig. 8). In normal three-pass InSAR interferometry, the displacement is calculated from the difference between the unwrapped phase of a reference interferogram and a pair spanning deformation (Becker and Sultan, 2009). Figure 8 shows the basic configuration of a pair of images used in repeat-pass interferometry. The first pass measures the reference range phase \( \phi_o \) for each pixel for time \( t_o \) to a target from and to the satellite position, and the second pass measures the range to the same target. The difference in phase is calculated with special consideration to the baseline which is a physical distance between the location of the satellite in the first and second pass, the look angle, and the angle between the baseline vector and the tangent plane (Becker, 2008).

The factors which contribute to phase differences between two or more radar scenes include topography, deformation, and atmospheric effects.

\[
\phi = \phi \text{topo} + \phi \text{def} + \phi \text{atm} + \phi \text{noise} \ldots (3.3)
\]

The phase \( \phi \) is recorded cyclically from \(-\pi < \phi < \pi\), so there is by default an ambiguity in determining the range to a target from the satellite reference position from \( \phi \). The radar interferometric analysis involves the removal of the atmospheric, topographic, and noise contributions. This process is described extensively by Gabriel and Massonnet elsewhere (Massonnet and Feigl, 1998; Gabriel et al., 1989).
Figure 8. Sketch diagram demonstrating the Interferometric Synthetic Aperture Radar (InSAR) applications involving the use of phase change between successive images to measure land level changes throughout the scenes acquisition period; source: http://www.asprs.org.
In this study, twenty-nine descending Synthetic Aperture Radar (SAR) scenes (Table 1) were acquired from the European Remote Sensing ENVISAT satellite. Twenty-one of those scenes were acquired over the Tabarjal and Busayta area (tracks: 221, 351 and 493) and the remaining eight scenes over the Sakakah and Dumat Aljandal area (Track: 178) (Fig. 9). The investigated period for Busayta is from Aug 2003 to Jan 2012, and for the Sakakah area, it is from December 2003 to July 2008. The spatial baseline ranged from 17 to 835 m with respect to the master scene (acquisition date: May 17, 2004, August 01, 2007, and March 21, 2011) for the Busaytah area, and from 38 to 750 m in Sakakah area (master scene acquisition date: November 11, 2007). The maximum temporal baseline is 1434 days for both areas. For the majority of the investigated areas, the density of permanent scatterers ranged from 10 to 20 permanent scatterers/km² with a coherence threshold value of 0.7.

I applied PSI techniques (Hooper et al., 2007; Hooper et al., 2004) to investigate the spatial variations in subsidence rates across the WASB in two sites (Tabarjal, Busayta, Sakakah and Dumat Aljandal areas) (Figs. 1 and 17), the two areas where the largest stack of usable ENVISAT radar scenes were acquired. The PSI method restricts the phase unwrapping and analysis to coherent pixels, pixels containing individual scatterers which remain stable over the investigated time period. In the study area, these scatterers represent buildings, outcrops, rocks, dwellings, utility poles, and well foundations that were identified using the Stanford Method for Persistent Scatterers (StAMPS) algorithm (Hooper et al., 2007). Precise
orbit information was obtained from Delft Institute for Earth-Oriented Space Research (Scharroo and Visser, 1998); the interferometric processing was performed using the Delft object-oriented radar interferometric software (DORIS) (Kampes et al., 2003), the Repeat Orbit Interferometry Package (ROI_PAC), and the StAMPS (Hooper et al., 2004).
Table 1. ENVISAT scenes used in permanent scatterers investigation. Temporal and perpendicular baselines are shown relative to the scenes acquired on May 17, 2004, August 01, 2007, and March 21, 2011 for area “d” (Tabarjal and Busayta) and November 11, 2007 for area “e” (Sakakah).

<table>
<thead>
<tr>
<th>Area</th>
<th>Satellite</th>
<th>Acquisition date</th>
<th>Perpendicular baseline (m)</th>
<th>Temporal baseline (days)</th>
<th>Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tabarjal</td>
<td>ENVISAT</td>
<td>20030811</td>
<td>-646</td>
<td>-279</td>
<td>493</td>
</tr>
<tr>
<td>Tabarjal</td>
<td>ENVISAT</td>
<td>20031124</td>
<td>-262</td>
<td>-174</td>
<td>493</td>
</tr>
<tr>
<td>Tabarjal</td>
<td>ENVISAT</td>
<td>20040202</td>
<td>835</td>
<td>-104</td>
<td>493</td>
</tr>
<tr>
<td>Tabarjal</td>
<td>ENVISAT</td>
<td>20040308</td>
<td>338</td>
<td>-70</td>
<td>493</td>
</tr>
<tr>
<td>Tabarjal</td>
<td>ENVISAT</td>
<td>20040517</td>
<td>0</td>
<td>0</td>
<td>493</td>
</tr>
<tr>
<td>Tabarjal</td>
<td>ENVISAT</td>
<td>20040621</td>
<td>-17</td>
<td>35</td>
<td>493</td>
</tr>
<tr>
<td>Tabarjal</td>
<td>ENVISAT</td>
<td>20071203</td>
<td>409</td>
<td>1295</td>
<td>493</td>
</tr>
<tr>
<td>Tabarjal</td>
<td>ENVISAT</td>
<td>20080421</td>
<td>420</td>
<td>1434</td>
<td>493</td>
</tr>
<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20031210</td>
<td>-421</td>
<td>-1101</td>
<td>221</td>
</tr>
<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20040602</td>
<td>660</td>
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<td>221</td>
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<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20060329</td>
<td>-756</td>
<td>-350</td>
<td>221</td>
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<tr>
<td>Busayta</td>
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<td>20070314</td>
<td>404</td>
<td>-140</td>
<td>221</td>
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<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20070801</td>
<td>0</td>
<td>0</td>
<td>221</td>
</tr>
<tr>
<td>Busayta</td>
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<td>20090527</td>
<td>233</td>
<td>664</td>
<td>221</td>
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<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20101121</td>
<td>651</td>
<td>-120</td>
<td>351</td>
</tr>
<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20101221</td>
<td>588</td>
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<td>351</td>
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<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20110120</td>
<td>478</td>
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<td>351</td>
</tr>
<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20110321</td>
<td>0</td>
<td>0</td>
<td>351</td>
</tr>
<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20110520</td>
<td>316</td>
<td>60</td>
<td>351</td>
</tr>
<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20110619</td>
<td>-190</td>
<td>90</td>
<td>351</td>
</tr>
<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20111017</td>
<td>-394</td>
<td>210</td>
<td>351</td>
</tr>
<tr>
<td>Busayta</td>
<td>ENVISAT</td>
<td>20120115</td>
<td>-705</td>
<td>300</td>
<td>351</td>
</tr>
<tr>
<td>Sakakah</td>
<td>ENVISAT</td>
<td>20031207</td>
<td>-471</td>
<td>-1410</td>
<td>178</td>
</tr>
<tr>
<td>Sakakah</td>
<td>ENVISAT</td>
<td>20040425</td>
<td>-101</td>
<td>-1295</td>
<td>178</td>
</tr>
<tr>
<td>Sakakah</td>
<td>ENVISAT</td>
<td>20040530</td>
<td>379</td>
<td>-1260</td>
<td>178</td>
</tr>
<tr>
<td>Sakakah</td>
<td>ENVISAT</td>
<td>20040704</td>
<td>-691</td>
<td>-1225</td>
<td>178</td>
</tr>
<tr>
<td>Sakakah</td>
<td>ENVISAT</td>
<td>20040808</td>
<td>-284</td>
<td>-1190</td>
<td>178</td>
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<tr>
<td>Sakakah</td>
<td>ENVISAT</td>
<td>20060813</td>
<td>750</td>
<td>-455</td>
<td>178</td>
</tr>
<tr>
<td>Sakakah</td>
<td>ENVISAT</td>
<td>20071111</td>
<td>0</td>
<td>0</td>
<td>178</td>
</tr>
<tr>
<td>Sakakah</td>
<td>ENVISAT</td>
<td>20080713</td>
<td>38</td>
<td>275</td>
<td>178</td>
</tr>
</tbody>
</table>
Figure 9. Location map of the local study area (Wadi As-Sirhan Basin), the areas covered by radar interferometric studies within the Wadi As-Sirhan Basin in Busayta and Tabarjal, Sakakah and Dumat Aljandal, and field-verified land deformation sites.
3.5 Global Positioning System (GPS)

Three dimensional global positioning system data from JOUF Continuously Operating Reference Station (CORS) of MOMRA Real Time Network (MRTN) network station (Sakakah city; lat: 29.962°N; long: 40.199°E) (Fig. 1) was used to detect and quantify the horizontal motion of the Arabian plate as well as the vertical land deformation in the study area. The CORS network provides detailed and accurate real-time position output without the need for a reference base station unlike the traditional Global Navigation Satellite System (GNSS) surveying observation techniques (Al Omar et al., 2015). The JOUF station data was analyzed using the Orbit Analysis Simulation Software (GIPSY) developed by the Jet Propulsion Laboratory (JPL) at NASA (Zumberge et al., 1997) to extract the deformation rate (averaged for every minute) and pattern in the year 2015 for the southern part of WASB. To compute the temporal change in deformation rate of the southern part of the regional study area (LMAS), I used daily GPS vertical displacement data (July 2012 to Oct 2015 interval) from the SOLA (lat: 24.9105°N; long: 46.4003°E) (Fig. 1) GNSS station provided by the MAGNET GPS Network from Nevada Geodetic Laboratory (2017).
3.6 Satellite Imagery Data Analysis

Temporal Landsat (5, 7, and 8) imagery (path 172 and row 39) acquired (acquisition date: February 1987, 1991, 2000, March 2003, January 2014, and February 2017) over WASB were processed to track the development of agricultural activities throughout the past three decades (1987 to 2017). The Landsat 5, 7, and 8 missions were launched in March 1984, April 1999, and February 2013, respectively, as collaborative efforts between the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS). Temporal variations in the areas occupied by agricultural developments were assessed using the Normalized Difference Vegetation Index (NDVI) images. Using the reflection from the red band and the near infrared band, the NDVI was extracted using standard calculations (Rouse et al., 1974):

\[
\text{NDVI} = \frac{\text{near infrared} - \text{red}}{\text{near infrared} + \text{red}} \tag{3.4}
\]

The higher the NDVI values, the greater the density of vegetation, and vice versa. The areas occupied by cultivated land were extracted from the Landsat imagery using a threshold NDVI value of 0.3; the threshold value was validated by visual comparisons with Google Earth images.
3.7 Geotechnical Investigation (Expansive soil)

Geotechnical studies were performed on surface and subsurface samples that were collected from sites where land deformation was observed/reported to investigate the physical properties of soils in these locations. Specifically, the samples were collected to investigate the presence of expansive soils in these areas. Those soils swell upon absorption of water and shrink as they lose it, causing cracks, earth fissures, and damage to buildings and infrastructure. These kinds of soils are characterized by the presence of active clay minerals (e.g. montmorillonite group) which is responsible for the pronounced volume change capability of the soils. Expansive soils were reported from eastern and western Saudi Arabia, areas that witnessed an increase in a number of constructional activities.

The geotechnical analyses were conducted to investigate whether the observed deformation could be related to the presence of expansive soils in the investigated sites. Nineteen boreholes were drilled in the summer of 2015 (Fig. 6) with depths ranging from 13 to 60 meters within the regional study area (Al Jawf, Ha'il and Al Qassim regions). The borehole locations were selected proximal to (< 500 m) the deformation sites, samples were collected from the intercepted clay layers, and the free swell ratios for these layers were measured.
The free swell ratio refers to the ratio of the sediment volume of soil (passing from 425-µm sieve) in distilled water (Vd) to that in carbon tetrachloride or kerosene (Vk) (Prakash and Sridharan, 2004).

FSR = (Vd/Vk)……………………………………(3.4)

Finally, the free swell ratio was used to classify the soil expansivity of the collected samples and to identify the clay type for the collected samples (Table 2):

<table>
<thead>
<tr>
<th>Soil Expansivity</th>
<th>Clay Type</th>
<th>Free Swell Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negligible</td>
<td>Non-swelling</td>
<td>≤ 1.0</td>
</tr>
<tr>
<td>Low</td>
<td>Mixture of swelling and non-swelling</td>
<td>1.0-1.5</td>
</tr>
<tr>
<td>Moderate</td>
<td>Swelling</td>
<td>1.5-2.0</td>
</tr>
<tr>
<td>High</td>
<td>Swelling</td>
<td>2.0-4.0</td>
</tr>
<tr>
<td>Very high</td>
<td>Swelling</td>
<td>&gt; 4.0</td>
</tr>
</tbody>
</table>

Table 2. Expansive soil classification based on free swell ratio (Sridharan and Prakash, 2000).
3.8 Arabian Peninsula Seismographic Database

Until 2003, there were three independent analog seismic telemetry networks with seventy-five seismograph stations in Saudi Arabia: (1) the King Saud University (KSU) network that was established in 1985, (2) the King Abdulaziz City for Science and Technology (KACST) network that was established in 1993 (Al-Amri, 1998), and (3) the Saudi Geological Survey (SGS).

Starting in 2005, all of the three networks were integrated under the National Centre for Earthquakes and Volcanoes (NCEV) that is part of the SGS. This network monitors earthquakes across the Arabian Peninsula and the Middle East with a good signal-to-noise (> 0.5; Al-Amri, 2008). Archival (starting at 1965) seismic data compiled from the International Seismological Center (ISC) and from the Preliminary Determination of Epicenters (PDE) (Ambraseys, 1988) are available upon request for educational and research purposes from King Saud University (Al-Amri, 1998) and from the National Centre for Earthquakes and Volcanoes (NCEV).
3.9 Construction of Geospatial Information System (GIS)

The adopted approach entails the following steps: (1) compilation of relevant spatial (rock and soil types, structures, etc.) and temporal (groundwater extraction, landuse/landcover, distribution and magnitude of earthquakes, etc.) datasets; (2) construction of a GIS database to host, organize, manage, and analyze the data sets, and (3) implementation of spatial correlations of the reported land deformation locations and extracted InSAR deformation with the generated digital products (soil types, groundwater extraction, TWS, and GWS, etc.) in search for causal effects.

The generated database incorporates co-registered digital mosaics with a unified projection (type: UTM Zone 37, datum: WGS-1984) including: (1) regional (scale: 1:4,000,000) and detailed (scale: 1:250,000) geologic maps; (2) digital elevation models (DEM; spatial resolution: 30 m), generated from Level 1A Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes; (3) Landsat 5, 7, and 8 Thematic Mapper (TM) scenes (spatial resolution: 30 to 60 m); (4) distribution of fractures/fault systems extracted from geologic maps and subsurface data; (5) distribution of the reported land deformation locations; (6) water well locations; (7) temporal groundwater levels; (8) distribution of the irrigated areas; (9) GRACE-derived TWS and GWS trend (mm/yr) maps over the Arabian Peninsula; (10) temporal three-dimensional GPS measurements, and (11) PSI results over Busayta and Sakakah areas in WASB.
CHAPTER 4

DATA ANALYSIS

4.1 Introduction

In this section, spatial and temporal correlations for the above mentioned datasets (Chapter 3) are provided in support of the hypothesis that excessive extraction from the LMAS in central and northern Arabia is largely responsible for the observed land deformation (fissures, reactivation on pre-existing faults, sink holes), the detected subsidence from PSI analysis, and the recent seismic activity.

4.2 Lower Mega Aquifer System (LMAS)

The findings from the geotechnical analyses revealed that the majority of the investigated samples (17 of 21 samples) in the regional study area had negligible soil expansivity (FSR: < 1) and the remaining 4 samples had low expansivity (FSR: 1.0-1.5) (Table.3; Fig.6). These results indicate that the observed deformation over the study area is not caused by the presence of expansive clays.

Most (70%) of the identified land deformation sites were located in and around cultivated lands (Figs. 1 and 10a) and a few sites (24%) were identified within urban areas (small village) that are proximal (< 20 km) to the cultivated areas. Moreover, the overwhelming majority of the identified earth fissures (14 sites) trend in a northwest-southeast direction, and are proximal and sub-parallel to, the widely-distributed northwest trending Kahf fault system in central and northern Arabia including the WASB study area (Figs. 1, 6 and 10a).
Table 3. Summary of expansive soil results based on free swell ratio.

<table>
<thead>
<tr>
<th>Boreholes No.</th>
<th>Total Depth (m)</th>
<th>Water Depth (m)</th>
<th>Sample Depth (m)</th>
<th>Free Swell Ratio</th>
<th>Soil Expansivity</th>
<th>Clay Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH-1</td>
<td>15</td>
<td>8.2</td>
<td>4 to 5.5</td>
<td>1.2</td>
<td>Low</td>
<td>Mixture of swelling and non-swelling</td>
</tr>
<tr>
<td>BH-2</td>
<td>15</td>
<td>6.8</td>
<td>13 to 15</td>
<td>0.12</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-3</td>
<td>15</td>
<td>12.8</td>
<td>6.90 to 12</td>
<td>0.09</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-4</td>
<td>15</td>
<td>11.5</td>
<td>3.0 to 5.5</td>
<td>0.31</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-5</td>
<td>15</td>
<td>8.7</td>
<td>8.5 to 11</td>
<td>1.2</td>
<td>Low</td>
<td>Mixture of swelling and non-swelling</td>
</tr>
<tr>
<td>BH-6</td>
<td>15</td>
<td>9.7</td>
<td>8.0 to 9.0</td>
<td>0.04</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-7</td>
<td>60</td>
<td>NA</td>
<td>42 to 45.5</td>
<td>1.4</td>
<td>Low</td>
<td>Mixture of swelling and non-swelling</td>
</tr>
<tr>
<td>BH-8</td>
<td>20</td>
<td>15</td>
<td>9.0 to 10.30</td>
<td>0.14</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-9</td>
<td>15</td>
<td>12.5</td>
<td>10.0 to 12.0</td>
<td>0.68</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-10</td>
<td>15</td>
<td>6.7</td>
<td>10.0 to 15</td>
<td>0.82</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-11</td>
<td>15</td>
<td>7.8</td>
<td>9.0 to 11.0</td>
<td>0.023</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-12</td>
<td>15</td>
<td>9.4</td>
<td>3.80 to 5.50</td>
<td>0.12</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-13</td>
<td>13</td>
<td>6.8</td>
<td>5.50 to 7.0</td>
<td>0.2</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-14</td>
<td>13</td>
<td>9.6</td>
<td>5.0 to 6.10</td>
<td>0.31</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-15</td>
<td>13</td>
<td>7.8</td>
<td>6.0 to 8.50</td>
<td>0.25</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-16</td>
<td>13</td>
<td>10.9</td>
<td>9.0 to 11.5</td>
<td>0.8</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-17</td>
<td>13</td>
<td>5.6</td>
<td>8.50 to 10</td>
<td>0.2</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-18</td>
<td>55</td>
<td>40.8</td>
<td>11 to 12.5</td>
<td>0.82</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
<tr>
<td>BH-19</td>
<td>56</td>
<td>35.7</td>
<td>8.50 to 9.50</td>
<td>0.07</td>
<td>Negligible</td>
<td>Non-swelling</td>
</tr>
</tbody>
</table>
The distribution of the identified deformation sites correlated spatially with the distribution of seismically active areas (Fig. 10b), areas witnessing excessive extraction (Fig. 10c), and areas showing TWS depletion (Fig. 10d). Inspection of Figures 10a and 10c show that the epicenters are close to the cultivated lands. Figure 11 shows that the onset of seismic activity in the study area apparently started in the early 1980s, the time during which the intensive groundwater extraction program was launched, peaked in the 1990s and early 2000s, the period that witnessed the highest groundwater extraction rates. Up to year 1980, extraction in the study area was minimal (< 1 km³/yr), continued to increase until the nineties, and levelled off at around 7 to 8 km³/yr by year 2007, then declined to about 5.5 km³/yr by year 2015 (Fig. 11). The reported groundwater extraction amounts in Figure 11 represent the cumulative extraction amounts from Al-Qassim, Ha'il and Al Jawf regions (Fig. 1).
Figure 10. Correlation maps including the distribution of land deformation over LMAS for the comparison of the outputs over LMAS. (a) The distribution and the direction of Kahf faults system modified after (Khalil, 2016) and the cultivated land. (b) earthquake epicenters reported in years (1982 to 2014) provided by Seismographic Network Datasets (Al-Amri, 1998). (c) Groundwater drawdown for the major aquifers (SAQ and Tawil) in the regional study area (LMAS) modified after (Abunayyan and BRGM, 2008). (d) Secular trend (mm/yr) for GRACE-derived TWS for the regional study area (LMAS) temporal (04/2002-03/2016, Mascon 1° X 1°).
Figure 11. Correlation between groundwater extraction (1971 to 2015) and earthquake (>1 Magnitude) events (1982 to 2014) (Al-Amri, 1998) over the regional study area (LMAS), and Wadi As-Sirhan Basin (WASB); data provided by the Ministry of Water and Electricity (Database of Water Resources Development Department, 2016).
Between the time the earlier trip was conducted in 2004 and the later trip in 2010, a significant increase in the cultivated lands was observed (Fig. 12), shallow (depth range: < 75 m) wells (e.g., SW1, SW2, and SW4; Fig. 1) dried up, sinkholes (e.g., Fig. 2: SH1, SH2, and SH3; Fig. 1) enlarged in size (diameter increased by more than 5m) and the shallow water (few meters deep) in the sinkholes dried up. The decline in groundwater levels that I observed during our field trips is consistent with observations from monitoring wells provided by the Ministry of Water and Electricity (Database of Water Resources Development Department) in Saudi Arabia. The selected monitoring wells are located over LMAS outcrops and are distant (20 to 100 km) from cultivated lands, where excessive groundwater extraction occurs. The excessive extraction is apparently unsustainable as evidenced by the decline in water levels. A 50 m drop in water levels has occurred in the WASB depression (Figs. 1 and 13: wells 2 and 3), 18 m in the northern sections of the regional study area (Figs. 1 and 13: wells 1, 4 and 8), and 9 to 17 m in the central and southern sections (Figs. 1 and 13: wells 9, 10, 11, and 12).
Figure 12. Time series for Landsat 5, 7, and 8 scenes acquired (February 1987, February 1991, February 2000, March 2003, January 2014, and February 2017) over the Busayta area in WASB.
Figure 13. Water levels (2002 to 2015) from twelve monitoring wells drilled in the recharge areas of the LMAS provided by the Ministry of Water and Electricity (Database of Water Resources Development Department, 2016).
The excessive extraction and unsustainable utilization of the LMAS is reflected in both GRACE solutions and the GPS measurements. A depletion in GRACE-derived TWS and GWS over LMAS and WASB is observed. The spatial distribution of the secular trends in GRACE-derived TWS data over the Arabian Peninsula are shown in Figure 14. Positive trends indicate an increase in TWS with time and negative trends indicate the opposite. Inspection of Figure 14 shows that the areas occupied by the LMAS and the WASB are experiencing significant negative TWS trends (shades of yellow, orange, and red), compared to areas to the south that range from lower depletion (shades of cyan) to near-steady conditions (shades of blue) along the Red Sea coastal plain. Figure 14 shows the temporal variations in GRACE-derived TWS and the secular trend over the LMAS (-9.1 ± 1.3 mm/yr; -4.6 ± 0.5 km³/yr) and the WASB (-9.4 ± 1.4 mm/yr; -1.0 ± 0.1 km³/yr). Using GRACE-derived TWS data together with GLDAS-derived soil moisture data and applying equation 1, GWS time series for each of the LMAS and the WASB were extracted (Fig. 15; Table 4).
Figure 14. Secular trend (mm/yr) for GRACE-derived TWS for the Arabian Peninsula extracted from temporal (04/2002-03/2016) CSR 1°X1° Mascon solutions showing high TWS depletion rates over the study areas. Also shown are the outlines of the two areas for which time series were derived and plotted in Fig. 15.

Figure 15. Time series and secular trends for TWS and GWS over the regional study area (LMAS) and Wadi As-Sirhan Basin (WASB) outlined in Fig. 14.
Table 4. Partitioning of terrestrial water storage (TWS) over the Lower Mega Aquifer System (LMAS) and Wadi As-Sirhan Basin (WASB).

<table>
<thead>
<tr>
<th>Area</th>
<th>Area</th>
<th>ΔTWS†</th>
<th>ΔSMS#</th>
<th>ΔGWS§</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>km²</td>
<td>mm/yr</td>
<td>km³/yr</td>
<td>mm/yr</td>
</tr>
<tr>
<td>Regional study area (LMAS)</td>
<td>0.44×10^6</td>
<td>-9.1±1.3</td>
<td>-4.6±0.5</td>
<td>-1.3±0.2</td>
</tr>
<tr>
<td>Wadi As-Sirhan Basin (WASB)</td>
<td>0.1×10^6</td>
<td>-9.4±1.4</td>
<td>-1.0±0.1</td>
<td>-1.2±0.2</td>
</tr>
</tbody>
</table>

Note: GRACE observations, LSMS outputs, and field data were used to estimate the partitioning of TWS in SMS, and GWS over areas occupied by the LMAS and WASB.

†ΔTWS: Change in terrestrial water storage.

‡ΔSMS: Change in soil moisture storage.

§ΔGWS: Change in groundwater storage.
The observed TWS and GWS annual cycle are apparently largely controlled by groundwater extraction. Temperatures in summers (June - August) are high (range: 28° to 37° C and frequently exceed 48° C), compared to winter temperatures (range: 5° to 20° C); evaporation rates are as high as 28 mm/day in the summers and as low as 0.4 mm/day in the winters (Alsharhan et al., 2001). For these reasons, agricultural activities and groundwater extraction increases in the winter season (December-February) and decline in the summers. This suggestion is supported by the correspondence between the GRACE solutions and the vertical displacements extracted from the SOLA (July 2012 to Oct 2015) and the JOUF (Jan 2015 to Dec 2015) GPS stations (Fig. 16). Excessive extraction in the winter causes decline in water levels and land subsidence in the winter and the replenishment of the extracted groundwater by groundwater flow causes a rebound in the summer season. Given that I observe a depletion rate of -3.7 ± 0.6 km³/yr in GWS over the study area and a subsidence rate of 2.3 mm/yr from the SOLA station, I suspect that the replenishment does not fully compensate for the extracted groundwater.
Figure 16. Vertical displacement rate from GPS stations versus GWS mascon solutions over a single 1°×1° pixel. (A) Vertical displacement rate from the GPS SOLA station versus GWS solution. (B) Vertical displacement rate at the JOUF station versus GWS solutions. Locations of SOLA and JOUF stations and GRACE pixels are shown in Fig. 1.
4.3 Wadi As-Sirhan Basin (WASB)

The Wadi As-Sirhan area is a part of the regional study area and displays all the previously described correlations between the locations of deformation sites and the distribution of agricultural areas, areas affected by the Kahf faults and seismic activity, areas witnessing drawdown in water levels and depletion in GRACE-derived TWS and GWS (Figs. 1, 10, 14, 17). To achieve a better understanding of the distribution, nature, and the factors controlling the ongoing land deformation in the study area, I applied PS radar interferometric techniques (Hooper et al., 2004, 2007) using stacks of ENVISAT ASAR scenes that were acquired throughout the period 2003 to 2012 over two locations (Busayta and Sakakah) regions within the Wadi As-Sirhan area (Table 1). Both regions contain cultivated lands; the Busayta is heavily cultivated (87% of investigated area) and is considered to be the food basket of Saudi Arabia, whereas the Sakakah region has far fewer cultivated lands (13% of investigated area) and as a result less groundwater is extracted. The applied PS technique enables successful interferometric applications over a wide range of physiographic and atmospheric conditions including highly vegetated lands (Becker and Sultan, 2009) similar to the ones being investigated in Wadi As-Sirhan.

Figure 17c shows the averaged velocity along line of sight and displays land deformation pattern over the two investigated regions. On this figure points that are moving away from the satellite (subsiding) appear in shades of red and orange and those that are stable (0 to 1 mm/yr) appear in shades of green and yellow. Inspection of Figure 17c shows that for the Busayta region, subsiding areas (-2 to -15 mm/yr)
cover extensive domains (41% of InSAR investigated area) and are located along of the NW-SE-trending fault zone that bounds Wadi As-Sirhan graben. Specifically, the subsiding areas within the graben are bound by two major faults, the Wadi As-Sirhan fault in the north and Al Busayata fault in the south (Figs. 17a, c). Subsiding areas are found within or proximal to cultivated areas (NDVI > 0.3) and those regions experiencing large drops in groundwater levels (Figs. 17a, b, c). In general subsidence is high (-2 to -15 mm/yr), yet irregularly distributed, within the graben compared to areas to the east and west of the bounding faults which show no, or minimal subsidence. The highest subsidence rates are localized within elongated bowls, many of which are proximal to, or bound by, the major faults in the area. A number of the observed fissures are found along the peripheries of the subsiding bowls (Fig. 17c).

For the Sakakah region, the subsiding areas (5% of InSAR investigated area) and the subsidence rates (-3 to -8 mm/yr) are small compared to the Busayta region. This is to be expected since: (1) the cultivated area is small (13% of InSAR investigated area) compared to the Busayta region (36% of investigated area), (2) the groundwater extraction (0.17 km³) and drop in water levels are modest (up to 1.5 m/yr) compared to Busayta (2.3 km³; up to 4 m/yr), (3) The aquifer thickness is small (range from 260 to 300 m) compared to Busayta region that lies within a fault bounded graben with thickness exceeding 600 to 980 m in center of the depression (Fig. 5b).
Figure 17. Correlation maps for the distribution of land deformation over the Wadi As-Sirhan with density of irrigated lands, groundwater drawdown, and PSI results. (a) Correlation of the distribution of land deformation with that of irrigated lands (modified after Wallace et al., 2000). (b) Correlation of the distribution of land deformation with groundwater drawdown (1960 to 2005) (modified after Abunayyan and BRGM, 2008). (c) Correlation of the distribution of land deformation with PSI results. Also shown are the distribution of the major faults (modified after Wallace, et al., 2000).
CHAPTER 5
DISCUSSION AND IMPLICATIONS

5.1 Introduction

In the previous sections I demonstrated that the identified land deformation-related features (sink holes, fissures, subsidence, and earthquakes) are correlated spatially with features associated with agricultural development and groundwater extraction in central and northern Arabia suggesting a causal effect (Figs 1; 10a, b, c; 11, and 13). The increase in cultivated land (Fig. 12) was associated with decline in water levels and depletion in GWS and TWS (Fig. 15). Not only were those correlations observed spatially, but temporally as well. For example, earthquake events (1.5 - 5.5 M) increased from one event/yr in 1980, the year that witnessed the onset of the agricultural development program in central and northern Arabia (extraction: 1 km³/yr), up to thirteen events/yr in the 1990s, the decade that witnessed the largest expansion in groundwater extraction (average annual: >6.4 km³) and land reclamation (Fig. 11). These observations support the suggestion that excessive groundwater extraction is responsible for the observed subsidence, fissures, sinkholes, and shallow earthquakes.
5.2 Regional Study Area over the Lower Mega Aquifer System (LMAS)

The findings are consistent with those reported from many of the aquifers world-wide (e.g., Poland, 1960; Galloway et al., 1998; Hoffmann et al., 2001; Bell et al., 2002; Burbey, 2002; Galloway and Burbey, 2011). The detected subsidence in these areas has been attributed to an increase in effective stress that causes compaction and land subsidence (Donaldson et al., 1995). The downward stress from the weight of the overlying rock and water is balanced by the effective stress and pore pressure. Pumping decreases pore pressure causing an increase in the effective stress which in turn will cause compaction and land subsidence (Donaldson et al., 1995) (Fig. 18). I adopt a similar conceptual model to explain the observed subsidence over the LMAS.

Figure 18. Sketch diagram showing land subsidence due to loss of support resulting from excessive groundwater extraction (modified after Khattak, 2015).
Pumping from limestone aquifers such as the Aruma and Sirhan could result in the loss of buoyant support in the roof of pre-existing cavities, collapse of the roof, and development of sink holes (Yousef et al., 2016). Moreover, infiltration of irrigation water in the agricultural areas promotes dissolution of carbonates, enlargement of preexisting cavities and finally sinkhole development (Urich, 2002). Figure 1 shows that earthquake epicenters and the deformation sites are found largely within areas affected by the Kahf fault system suggesting that the presence of faults plays a role in the development of deformation.

5.3 Local Study Area over Wadi As-Sirhan Basin (WASB)

My PS results are similar to those reported from Las Vegas and surroundings (Bell et al., 2002) that suggest that the bounding faults (Figs. 5a and 17; Wadi-As-Sirhan and Al Busayta faults) are acting as subsidence barriers. My results also indicate that the observed patterns of subsidence persisted throughout the investigated period (year 2003 to 2012). The fact that the high subsidence areas (bowls) within the graben do not always coincide with the areas of the highest extraction could indicate that the subsidence could be affected by the distribution of low-yield, compressible fine-grained sediments. This suggestion is supported by well data from Wadi As-Sirhan that shows the presence of significant compressible clay layers (e.g., Mira Formation; Wallace, et al., 2000).
The fissures around the margins of the subsidence bowls (1, 2, 3, and 4) in Tabarjal and Busayta (Fig. 17c; area “d”) are probably caused by bending beam movements around the subsiding bowl, the area where horizontal extension is high (Bell et al., 2002). Examples include fissures at the margins of the four outlined bowls in area “d”. Fissures could also result from horizontal forces that are associated with compacting sediment or from horizontal seepage pressures caused by pumping; both mechanisms produce horizontal strain that is localized along planes of weakness (Helm, 1994). Fissures that are located proximal to the faults could have been developed with this mechanism. One example is the fissure in the lower left corner of area “e” that is proximal to Wadi As-Sirhan fault (Fig. 17).

5.4 Research Implications

Many of the aquifers world-wide are in near-steady conditions where the natural and anthropogenic discharge is compensated for by recharge. For such aquifers, one would expect to observe near-steady GWS secular trends. Examples include: Northern Great Plains Aquifer, Cambrian-Ordovician Aquifer System, and Great Artesian Basin (Richey et al., 2015). Where data is available, such aquifers are expected to show near-steady secular GPS elevations and zero radar averaged velocity (Chew and Small, 2014). That is not the case with the LMAS, a fossil aquifer that was largely recharged in previous wet climatic periods, yet is still receiving modest recharge at present (Sultan et al., 2008). Three observations indicate that the LMAS is not at near-steady state conditions and that extraction from the LMAS is not
compensated for by replenishment: (1) the observed depletion in TWS (-4.1 ± 0.6 km³/yr) and GWS (-3.5 ± 0.6 km³/yr) over the investigated period (Figs. 14, 15), (2) the radar interferometric studies over Busayta region yield subsidence rates of -4 to -15 mm/yr (Figs. 17c, d), and (3) the limited GPS measurements show subsidence rates of up to -2.3 mm/yr in SOLA station southern LMAS (Figs. 1, 16a).

My findings suggest that if the excessive extraction of groundwater continues, one would expect that subsidence, seismicity, and structural damage to engineering structures will continue, existing sinkholes and fissures will enlarge, and newer ones will form. To minimize those hazards, the groundwater extraction has to be reduced by 3.5 to 4 km³/yr to about 50% of its value in the nineties, and consideration should be given to the implementation of groundwater recharge projects over LMAS, a technique that was found to be successful in reducing water-level declines and land deformation as well in Santa Clara Valley, California (Reichard and Bredehoeft, 1984). Finally, the GRACE applications presented in this study could provide cost-effective and replicable methodologies for optimum utilization of fossil aquifers and for minimizing the deformational effects associated with their utilization.
CHAPTER 6
SUMMARY AND CONCLUSION

This study applies an integrated approach for the assessment and monitoring of the Lower Mega Aquifer System (LMAS) and the associated land deformation (i.e., subsidence, earth fissures, and sinkholes) in central and northern areas of the Arabian Peninsula. The adopted approach correlates the spatial distribution of observed and recorded field deformation sites with relevant remote sensing, geodesy, geology, hydrogeology, and geotechnical datasets/observations in a GIS environment in search for causal relationships.

The spatial and temporal analysis of the investigated datasets revealed that the spatial distribution of the observed deformation correlates with the distribution of: (1) cultivated lands, (2) areas of high groundwater extraction and severe decline in water levels, and (3) earthquake epicenters. Moreover, the onset of the intensive agricultural program in the study area in the early eighties was accompanied by an increase in the number of earthquakes. These observations are consistent with the deformational features being caused by excessive groundwater extraction. My findings are consistent with others reported from similar fossil aquifers worldwide.

Findings from the Interferometric Synthetic Aperture Radar (InSAR) investigation revealed high, yet irregularly distributed, subsidence along a NW-SE
trending zone within the Wadi As-Sirhan graben with the highest subsidence rates being located along elongated bowls proximal to, or bound by, the major faults and surrounded by earth fissures.

GRACE data analysis indicates that the current extraction rates in the study area are unsustainable, yet sustainable extraction could be attained if the extraction is reduced by 3.5 to 4 km³/yr. This will also reduce the deformational effects associated with the high groundwater extraction.

The regional study in northern and central Arabia provides a general understanding of the causes of, and remedies for, the ongoing land deformation. It is recommended that the detailed radar interferometric studies that were conducted in Wadi As-Sirhan be extended to cover the entire length and width of the Kahf fault zone, the area that is experiencing land deformation and earthquake activities. These studies should take advantage of the new generations of the European Space Agency Sentinel SAR satellites. Moreover, deep seismic surveys are also recommended over the Kahf fault zone to map its distribution, orientation, and displacement together with additional GPS stations to monitor the vertical displacement throughout the Kahf fault zone over extended time periods.

Finally, special attention should be paid to the development of a national plan for the sustainable utilization of the fossil groundwater in the kingdom, a plan that
will meet the required water resources, ration the use of existing water resources, and at the same time minimize the hazards associated with excessive use of this valuable resource.
REFERENCES


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APPENDIX I.

A. Interferograms: Output of StaMPS PS analysis (Track 493)
B- Interferograms: Output of StaMPS PS analysis (Track 221)
C- Interferograms: Output of StaMPS PS analysis (Track 351)
D- Interferograms: Output of StaMPS PS analysis (Track 178)
APPENDIX II.

A- Lithostratigraphic Column of Rocks Units in Wadi As-Sirhan Basin (WASB)
(modified after Wallace, et al., 2000)
B- Lithostratigraphic Column of Rocks Units in Ha’il (modified after Ekren, et al., 1987)
C- Lithostratigraphic Column of Rocks Units in Al-Qassim (modified after Manivit, et al., 1986)