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Utilization of Remote Sensing Data for Estimation of the Groundwater Storage Variation

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UTILIZATION OF REMOTE SENSING DATA FOR ESTIMATION OF THE GROUNDWATER STORAGE VARIATION

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ABSTRACT

Groundwater is the most extracted raw material, with an average withdrawal rate of 982 km^3 per year, where 70 percent of the total groundwater withdrawn is used for agriculture globally (Margat & van der Gun, 2013). With climate change and increased water demands in recent years, monitoring the changes in the groundwater storage is of the utmost importance. This thesis presents an analysis that determines the rates, trends, and directions where groundwater storage is going in Pakistan. It also correlates fluctuations in groundwater storage with variations in precipitation and agricultural productivity in the country. The overall objectives of this thesis are to identify the long-term variations in groundwater storage, and examine the impact of precipitation and crop production on the groundwater reserves in Pakistan.

In this thesis, The Gravity Recovery and Climate Experiment (GRACE) satellite data are used to estimate changes in groundwater storage for the study period of April 2002 – June 2017. By subtracting the different water subcomponents, i.e. soil moisture and snow water equivalent, derived from the Global Land Data Assimilation System (GLDAS) Noah from the GRACE data products, variations in groundwater storage are estimated. Precipitation data for this study is obtained from the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) CDR system. Agricultural information, which includes the crop water requirement, is derived from CROPWAT, and yield data are obtained from the Bureau of Statistics, Punjab.

The results reveal that groundwater storage in Pakistan is declining at a high rate. Over a period of 183 months, Punjab province has observed the highest loss in total volume of groundwater storage (28.2 km^3), followed by Balochistan (19.57 km^3), Khyber Pakhtunkhwa (9.84

km^3), and lastly, Sindh (5.46 km^3). The results also show that precipitation has a weak positive impact on groundwater storage and soil moisture, depending on the region. Lastly, crop cultivation has had a significant impact on the groundwater withdrawal rates, with amounts varying on a district by district basis.

The contributions of this study include a better understanding of variations in the groundwater storage across different provinces in Pakistan, and an analysis of the effect of groundwater changes in relation to crop water demand and precipitation. GRACE data can be used to assess groundwater depletion in areas where groundwater monitoring is not available, as it can help with the evaluation of decreasing trends in groundwater levels. It can also provide policy makers information needed to conserve groundwater resources for future use.

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LIST OF ABBREVIATIONS

GRACE - The Gravity Recovery and Climate Experiment

GLDAS - Global Land Data Assimilation System

PERSIANN - Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks

ΔTWS - Terrestrial Water Storage Anomalies

SM - Soil Moisture

SWE - Snow Water Equivalent

P - Precipitation

ΔGWS - Groundwater Storage Anomalies

NOAA - National Oceanic and Atmospheric

CSR - Center for Space Research

GPCP - Global Precipitation Climatology Project

BCM - Billion Cubic Meters

MCM - Million Cubic Meters

CWR - Crop Water Requirement

MLC - Maximum Likelihood Classifier

INTRODUCTION

1.1 Research Background

Sylvia Green once said, "No water, no life. No blue, no green". This statement emphasizes the fact that water is essential for the survival of the global ecological system. With abundant water resources globally, only four percent of the total water is available as fresh water. From the total freshwater on our planet, groundwater constitutes 95 percent. Currently, groundwater is the most extracted raw material, with an average withdrawal rate of 982 km^3 per year globally (Margat & Van der Gun, 2013). Around 70 percent of the total groundwater withdrawn is used for agriculture globally (Margat & Van der Gun, 2013). Thus, with climate change and increased water demands (Zhang et al., 2014,2016; Kalra et al., 2017; Carrier et al., 2013; Thakali et al., 2016, 2018; Pathak et al., 2016a,b, 2017; Sagarika et al., 2014, 2015, 2016), monitoring the changes in groundwater storage is of the utmost importance. Over time, and the exploitation of ground water, there may be a crisis of groundwater overuse and contamination in the coming years.

Traditionally, to analyze the changes in groundwater storage, authorities follow a simple principle, which is the measurement of the water level on a daily basis from observational wells. In the United States, the changes in water levels are tracked through collective efforts between the U.S. Geological Survey (USGS) and local agencies. Most of the wells that are being analyzed are located by unconfined aquifers, which are minimally affected by anthropogenic stress. The undisturbed locations of the wells make them good for long term monitoring of groundwater variations (Xiao et. al, 2015). However, this is not the case everywhere. Many countries have no access or resources to install monitoring wells for long term monitoring. Such problems are very common in underdeveloped and developing countries, and this has resulted in the overexploitation of groundwater resources, due to the lack of any regulations. Overexploitation of groundwater contributes to overall poor management of water resources exacerbating the climate extremes such as droughts and floods (Ahmad 2016; Dawadi et al., 2012; Chen et al., 2017; Wu et al., 2013; Qaiser et al., 2011, 2013; Choubin et al., 2014; Tamaddun et al., 2016, 2017,2018,2019; Shrestha et al., 2011,2012; Ahmad and Simonovic 2000, 2005; Rusuli et al., 2015, Ahmad and Prashar 2010; Dawadi et al., 2013, Bukhary et al., 2017, Venkatesan et al., 2011a,b; Amoueyan et al., 2017; Forsee and Ahmad, 2011; Mosquera-Machado and Ahmad, 2007; Nyaupane et al., 2018).

As one of the world's agricultural capitals, Pakistan has seen variations in groundwater, which are perceptible over a yearly period. The groundwater use in Pakistan is difficult to monitor with traditional methods. However, with a range of remotely sensed data, it is much easier to interpret the components individually (Puri et al., 2011a, b; Stephen et al., 2010a, b). In the recent years, the monitoring of the hydrological cycle using remote sensing and GIS has proved to be efficient and popular. According to Patra et al. (2016) remotely sensed data has helped in groundwater study by providing information on the following factors:

1. Identification of geological structures and hydro-physical properties;
2. Areas of recharge and discharge;
3. Depth and conditions for occurrence of groundwater;
4. Direction of movement and degree of salinity of groundwater.

Systematic long-term monitoring of groundwater is crucial, as it provides solutions to many complex water resources issues. As drilling wells at intervals cannot show the direct changes in groundwater storage, there needs to be an evaluation with monitoring programs, in order for the data being collected to represent a viable source of information (Hicks, 2018). Moreover, factors such as properties of aquifer composition and soil subsurface are needed, in addition to the daily water level, to determine the groundwater storage for a particular area (Hicks, 2018). Thus, the traditional method can be limited to only the local scale, instead of regional, basin, or country levels for analyzing the long-term variations in groundwater storage.

1.2 Research Motivation

A considerable amount of research has been done globally on the estimation of and long-term variations of groundwater storage using remotely sensed data. While much attention has been paid to the influence of the Gravity Recovery and Climate Experiment (GRACE) to estimate the variations in groundwater storage at a country or a basin level, the factors impacting these variations have been studied less. GRACE is a unique and a valuable remote sensing platform to monitor the groundwater storage variation under all types of terrestrial conditions (Tapley et al., 2004). GRACE uses GPS and a microwave ranging system to map the earth's gravity field variations caused by the variations in the earth's mass surface (Skaskevych, 2014). Along with the Global Land Data Assimilation System (GLDAS), a land surface modeling system, GRACE can provide monthly groundwater storage variations for a particular region. Several studies, across multiple sites and at various spatial scales, have used GRACE to remotely monitor groundwater storage, and have shown the potential of using GRACE in the estimation of groundwater storage variations globally. For example, in the United States (Rodell et al., 2007.; Strassberg et al., 2009; Yeh, et al., 2006, Skaskevych, 2014), India (Chinnasamy et al., 2015; Rodell et al., 2009; A. K. Singh et al., 2017; Van Der Velde et al., 2014), China (Cao et al., 2015; Feng et al., 2013; Yang et al., 2017; Yin et al., 2017), and Pakistan (Iqbal et al., 2016) researchers have all used GRACE and have found accurate results.

Pakistan being dependent on its water resources has made the agriculture division a critical part of the country's economy. The agricultural sector is contributing to around 20 percent of the total GDP (Pakistan Economic Survey, IRIS Punjab). Due to limited supply and excessive losses in the irrigation system, surface water cannot meet all the irrigation needs (Ghumman et al., 2018a; Ateeq-ur-Rauf et al., 2018; Ghumman et al., 2018b; Ghumman et al., 2014). Also, the scarcity of good quality surface water has required Pakistan to rely on irrigation using tube wells (Saleem et al., 2017). Aamer and Sabir (2014) stated that more than 50 percent of the total irrigated lands in Pakistan are being served through groundwater wells, which has resulted in the deterioration of the groundwater quantity and quality. The groundwater contribution to irrigation in the country has increased to 55 percent in 2010 from eight percent in 1960 (Watto, 2018). Additionally, half of its overall irrigation water requirements, and 70 percent of its drinking water consumption, is obtained from groundwater abstractions (Watto, 2018). The groundwater usage contributes around 1.3 billion USD to the national economy per year (Bhutta & Alam, 2006), and has played an important role in reducing poverty, especially in rural areas, where groundwater access provides for agricultural production (Bhutta & Alam, 2006).

In the Punjab province alone, the number of private tube wells has increased, from about ten thousand in 1960 to about five hundred thousand in 2000 (Saleem et al., 2017), and is continuing to grow at an increasing rate. Groundwater monitoring in Pakistan presents number of challenges. It is difficult to monitor the groundwater variations in Pakistan, due to an increasing number of unaccounted wells as well as lack of measurement tools. Numerous studies have been done on the quality aspect of the groundwater on country, regional, and district scales in Pakistan. However, only a few have studied the quantity aspect using GRACE (Iqbal et al., 2016; 2017). With this research motivation, this thesis uses GRACE to obtain and estimate the groundwater information in Pakistan. In particular, this thesis is focused on identifying the long-term variations in groundwater storage, and analyzing the impact of precipitation and crop production on the groundwater reserves in the country.

1.3 Research Objectives

The overarching goal of this research is to analyze the fluctuations in groundwater storage and correlate them to variations in precipitation and agricultural productivity in Pakistan. In order to achieve this, the thesis is divided into two objectives. The first objective estimates groundwater storage change and analyzes trends at a provincial level in Pakistan using GRACE. Furthermore, it evaluates the impact of precipitation on groundwater storage in each of the provinces in Pakistan. The second objective focuses on the active agricultural districts in Punjab. It first identifies the long-term variations in groundwater storage and then examines the impact of precipitation and crop production on groundwater reserves in Rahim Yar Khan, Bahawalpur, Vehari, and Khanewal districts. The results achieved from these objectives are expected to provide greater insight in understating abrupt changes in groundwater storage. Water managers and policy makers may also find the outcomes of this thesis useful in understanding the effect of precipitation variability and agricultural activity on groundwater storage at a regional scale. To formulate the objectives and conduct the research, the following set of questions and their respective rationale were developed.

Objective 1: Estimation of groundwater storage variations and trends at a provincial level in Pakistan using GRACE.

Research Questions:

1. What is the overall extent of groundwater depletion and at what rate has it been depleted in Pakistan for the period for which GRACE data is available (April 2002 – June 2017)?
2. What regions are experiencing severe depletion?
3. Does the variation in the groundwater storage has a correlation with precipitation?

Rationale:

The trends observed in groundwater storage can be attributed to precipitation variability, as a high amount of precipitation can help with an increased rate of recharge. However, the rate of recharge can vary within the country, as some regions receive higher precipitation compared to others. In addition, change in climate can also lead to increased water demand (Sharabian et al., 2018).

Objective 2: Groundwater storage changes and crop area mapping using remotely sensed data in Punjab, Pakistan.

Research Questions:

1. By how much has groundwater been depleted in the Rahim Yar Khan, Bahawalpur, Vehari, and Khanewal districts for the period for which GRACE data is available (April 2002 – June2017)?
2. Does the variation in the groundwater storage has correlation with precipitation?
3. Do variations in groundwater storage relate to changes in agricultural productivity?

Rationale:

The growing concerns of population growth and climate change have resulted in an increase in water demand. This has ultimately impacted accessibility to groundwater resources and lead to a water stress situation. Incorporating precipitation variability and agriculture productivity of a region with the variations in groundwater storage can help to provide better insight on groundwater changes in relation to crop water demand and precipitation (Ahmad et. al, 2005).

The objectives researched are presented in a manuscript format. The current chapter contains the introduction and background of the problem. It also formulates the research questions for the research. Chapter 2 is a manuscript titled "Estimation of groundwater storage variations and trends at a provincial level in Pakistan using GRACE," which addresses the first set of research questions. This chapter analyzes the trends present in the GRACE derived groundwater storage and estimates the volumetric loss of the groundwater storage in Pakistan at a provincial level. Chapter 3 is a manuscript titled "Groundwater storage changes and crop area mapping using remotely sensed data in Punjab, Pakistan," which addresses the second set of research questions. Chapter 3 is focused on identifying the long-term variations in groundwater storage and examining the impact of precipitation and crop production on the groundwater reserves for the selected agricultural districts. Increased abstraction of groundwater reserves for agriculture and anthropogenic use has resulted in the reserves turning saline, along with decreasing the depth of the water table. Therefore, this chapter combines the remote sensing, land surface model, and survey data to understand the variations in groundwater storage in relation to precipitation and crop cultivation. Chapter 4 summarizes and concludes the thesis with the major contributions and limitations. It also provides recommendations for future work.

ESTIMATION OF GROUNDWATER STORAGE VARIATIONS AND TRENDS AT A PROVINCIAL LEVEL IN PAKISTAN USING GRACE

2.1 Introduction

Groundwater is considered as the largest source of usable fresh water in the world and an active part of the hydrological cycle. Being less vulnerable to quality degradation and droughts than surface water, it is widely demanded globally (Aeschbach-Hertig & Gleeson, 2012). It is estimated that 982 km^3 of groundwater is withdrawn every year globally (NGWA, 2016). The five countries with the highest groundwater extraction are India, China, the United States, Pakistan, and Iran, extracting a total of 61 percent annually (NGWA, 2016). This heavy dependence on groundwater around the world has resulted in various issues including groundwater depletion, contamination, and salinization (Yin et al., 2017).

Pakistan is among the world's largest producers and suppliers of food and crops. Ranking eighth worldwide in agricultural output, Pakistan heavily relies on groundwater for human and agricultural use (Iqbal et al., 2017). Groundwater usage contributes to approximately 1.3 billion USD to the national economy per year (Bhutta & Alam, 2006) and has played an important role in reducing poverty, especially in rural areas. This boon in the economy has resulted in being a bane for the national groundwater reserves in the form of depletion. This depletion has also affected many provinces in Pakistan, and the growing dependence of unsustainable groundwater use for irrigation is ultimately threatening future crop production (Scanlon et al., 2012). As groundwater extraction is not regulated or protected under legislation in Pakistan, anyone with enough financial capital and land can install a tube well and abstract groundwater, without consideration of safe yields (Bhutta & Alam, 2006). A study performed by Wada et al. (2010), reported on the groundwater depletion around the major regions of the world and identified that Northeastern

Pakistan and Northwestern India had the highest depletion rates. Studies have also shown that the current net groundwater abstraction in Pakistan is comparatively higher than recharge, which has resulted in the lowering of the water table (Bhutta & Alam, 2006). At this rate, the annual per capita water-availability in Pakistan, presently 1,100 m^3, is expected to decrease to 837 m^3 by the year 2025, resulting in a food shortage of 70 million tons (Kahlown & Majeed, 2003). Pakistan, being once a water surplus country with an extensive amount of water resources, is now a water deficit country (Kahlown & Majeed, 2007). Therefore, without any legislative action, reduction in the available groundwater is inevitable.

Groundwater study can be tedious, as it requires a vast amount of data about lithological units, and surface water, as well as structural, climatic, and, geological conditions. Moreover, with the increasing number of wells, and lack of measurement tools, unfortunately, it is difficult to monitor groundwater on a large scale. In recent years, the monitoring of the hydrological cycle using remote sensing has proved to be an efficient way. With a range of remotely sensed data (aerial photographs and satellite images), it is much easier to interpret the lithological units individually. Apart from being time and resource-efficient, remote sensing data can also aid in the decision-making process. For example, if the variability in the groundwater in an aquifer is known over a period, the authorities can make better decisions in terms of long-term sustainability by making suitable policy choices.

The Gravity Recovery and Climate Experiment (GRACE) mission has been considered as a unique and valuable way to monitor groundwater storage variations under all types of terrestrial conditions (Tapley et al., 2004). GRACE is a pair of sister satellites which use GPS and a microwave ranging system to map the earth's gravity field variations caused by the variations in the earth’s mass distribution. The GRACE mission has given pioneering breakthroughs in the disciplines of hydrology, geology, oceanography, and glaciology (GRACE-FO) over time. GRACE was the first mission that provided an opportunity to estimate the variations in groundwater from space. Combining GRACE with a land simulation model, estimation of groundwater storage has been a great success. With increasing interest over time, several studies across multiple regions have used GRACE and the Global Land Data Assimilation System (GLDAS) to remotely monitor groundwater, and have shown the potential of using GRACE in the estimation of groundwater storage.

Rodell and Famiglietti (2001) analyzed the GRACE derived Terrestrial Water Storage in Illinois to check for uncertainty using different in situ observations. This was the first study to check for variations in the GRACE products. Yeh et al. (2006) continued this research and studied the changes in groundwater storage on a monthly basis from 2002 – 2005. The results of the study concluded that a GRACE-based method was favorable to estimate monthly to seasonal groundwater storage on a 200,000 km^2 scale. The results also matched with the in situ observations of soil moisture storage and groundwater storage. It was the first study to compare the GRACE derived groundwater storage with actual in situ well data. The following year, Rodell and Famiglietti (2002) studied changes in groundwater in the High Plain aquifer using GRACE. Being one of the most productive agricultural regions in the world with a semi-arid climate, GRACE predicted a total uncertainty of about 8.7 mm in groundwater storage arising from the removal of soil moisture effects from land surface modelling (GLDAS). A year later, Rodell et al. (2007), computed variations in groundwater storage over the Mississippi River basin (900,000 km^2) for the period of 2002–2005 using GRACE. The computed GRACE derived groundwater storage was compared against 58 wells set in an unconfined aquifer. The results showed a high correlation for the sub-basins, which had areas higher than 900,000 km^2, whereas, the results performed poorly for the two sub-basins with areas less than 500,000 km^2.

Apart from the studies in the United States, Rodell et al., (2009) have used GRACE observations to estimate the variations in groundwater resources in Northwestern India (Rajasthan, Punjab, Haryana, and Delhi). To compute groundwater storage variations, the study subtracted soil moisture variations estimated using GLDAS from GRACE products for the period of August 2002 – October 2008. The results showed that groundwater was being depleted at a mean rate of 4.0 ± 1.0 cm per year equivalent height of water, which was the highest depletion rate globally in terms of groundwater storage. The results estimated a loss of about 109 km^3 of groundwater, which was almost double the capacity of the Nagarjuna Sagar Reservoir, India's largest surface water reservoir. Available evidence suggested that the major decline in groundwater storage was due to over-consumption of water for irrigation and other anthropogenic uses.

In Pakistan, Iqbal et al., (2016) conducted the first study in Pakistan to evaluate the changes in groundwater resources in the Indus Basin using GRACE for the period of 2003 – 2010. The study used a variable infiltration capacity (VIC) hydrological model to generate the monthly values for the soil moisture and surface runoff. Once derived, these monthly values were subtracted from the GRACE product to get the variations in the groundwater storage. The results showed a similar declining trend between the GRACE - derived groundwater storage and in situ piezo-metric well data. It was estimated that groundwater storage was declining at a mean rate of about 13.5 mm per year in equivalent height of water during 2003-2010 in the Upper Indus Basin, which was about 11.82 km^3 per year of fresh groundwater stock. Iqbal et al. (2017) continued their study to evaluate the effectiveness of GRACE with a different groundwater model simulation (Visual MODFLOW).

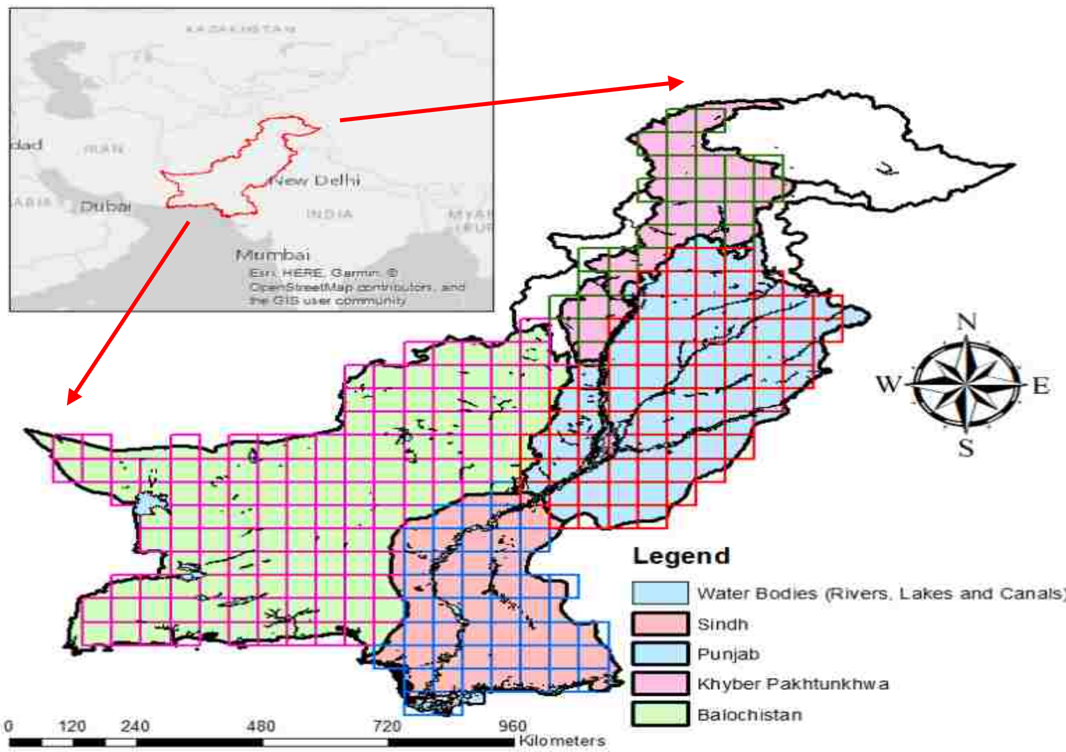
The results were also in favor of showing a declining trend in the groundwater storage derived from GRACE, MODFLOW, and the in situ data.

While much attention has been paid to the influence of GRACE to estimate the variations in groundwater storage at a country or basin level, impacts within a province in a country has been studied less. Therefore, this research uses GRACE to derive groundwater storage in Pakistan and reports the relation between groundwater storage and precipitation. The primary objective of the study is to estimate the groundwater storage in Pakistan on a provincial basis from the April 2002 – June 2017 period, and relate the changes in groundwater storage to precipitation trends. This chapter analyzes the trends present in the GRACE derived groundwater storage and estimates the volumetric loss of groundwater storage in Pakistan at a provincial level. This research highlights the factors impacting the fluctuations in the groundwater in Pakistan.

2.2 Groundwater Issues in Pakistan

Pakistan lies in southern Asia, bordered to the east by India and the west by Iran and Afghanistan. It has an area of 796,100 km^2, where 97.1 percent is land and 2.9 percent is water (AQUASTAT FAO, 2011). Figure 2-1 is the representation of the provincial map, with major water bodies of Pakistan overlaid by a $0.5° \times 0.5°$ grid size. The grid represents the cells covered by GRACE satellites. The area for each of the provinces is estimated by counting the pixels within the provincial boundary completely. Pakistan consists of four provinces: Punjab (243, 000 km^2), Sindh (157, 000 km^2), Balochistan (382, 000 km^2), and Khyber Pakhtunkhwa (96, 000 km^2), as well as bordering territories controlled by the Pakistan Federal government. Additionally, being a subtropical arid region, with high mountains in the north and low plains in the south, Pakistan experiences three major seasons including monsoon, summer, and winter. The national average annual precipitation is around 500 mm, but varies from less than 100 mm in Balochistan to more than 1500 mm in Punjab and Khyber Pakhtunkhwa (AQUASTAT FAO, 2011). This variability in the seasonal rainfall affects the river flows and the surface water levels in the country, ultimately affecting the groundwater storage levels. During the months of June in the plains and July in the mountainous areas, Pakistan experiences an average temperature of over 38°C (AQUASTAT FAO, 2011). The winter season is considered as the driest season due to minimal precipitation. However, the northernmost regions of the country are home to huge glaciers and high peaks and receive a moderate amounts of snowfall during winters (AQUASTAT FAO, 2011).

Figure 2-1 depicts that Punjab has the highest amount of water bodies (rivers, lakes, and canals) and is home to one of the most extensive irrigation networks (Indus Basin Irrigation System). To produce large yields of crops, locals have over-exploited the groundwater reserves in the area. In addition, being the second largest and most populous province in Pakistan, Punjab uses the Indus River as a primary source for water. With established canal systems, Punjab has one of the most fertile regions for agricultural production. Around 60 percent of the total population of Pakistan lives in Punjab and the economy is dominated by service in the agriculture sector. Punjab is dominant in the agricultural sector due to its rich and fertile soil and contributes to approximately 76 percent of the total annual food grain production in Pakistan, with cotton and wheat being the largest crops produced. This heavy dependency on groundwater for agricultural activity has caused a great amount of depletion of groundwater reserves in Punjab. Iqbal et al., (2017), estimated an average total loss in the groundwater reserves for the Punjab province to be around 6.3 km^3 for the period of 2003 - 2010. With one of the highest depletion rates in groundwater storage in the country, Punjab is at the verge of facing a water crisis if the government does not employ policies to conserve its groundwater reserves.



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Balochistan is the largest province of Pakistan in terms of land. A large part of the province is underdeveloped, but the economy is based upon the production of natural gas and minerals. Located in an arid zone, Balochistan does not receive a large amount of precipitation, and a large part of the population depends on tube wells for water access and irrigation. Currently, there are over 6000 tube wells in the province with no regulation against their use or installation (Kahlown & Majeed, 2003). With groundwater being the only source for agricultural production, locals have been exploiting the groundwater reserves for a long time, which has affected water quantity as well as quality aspects. From a survey carried out in 2009, it is reported that the groundwater levels in the Balochistan basin are declining at a rate of three meters annually. Kahlown and Majeed (2003) also reported that water demand in Balochistan has increased to 500 million cubic meter (MCM) in 2010 from 25 MCM in 1950 and has been growing significantly. This aggravated increase in the use of groundwater has affected the overall quantity of the groundwater reserves.

Sindh, with the second largest economy in Pakistan, is also heavily dependent on the agriculture sector. Sindh is responsible for extensively producing cotton, rice, wheat, and mangoes. With the increasing population, Sindh is dependent on surface water and some groundwater wells for everyday use. According to Guriro (2016), a majority of the residents in Sindh do not have access to clean drinking water, as the water is contaminated and poses health hazards. The water is drawn from the Indus River for agricultural and human use, where around 89 percent of the cropped areas are irrigated through a canal system (Khan Tagar, 2013). Due to high groundwater salinity, Sindh survives on surface water from the Indus River instead of the groundwater reserves.

Khyber Pakhtunkhwa is a province with minimal agricultural practices. It is located in the northern part of Pakistan and is dominated by forests. A man-made aquifer has been built in the western part of the province, which recharges from the natural hydrological process (precipitation, river flow, and seepage between canals). Also, with abundant surface water resources and the highest amount of precipitation in the country, Khyber Pakhtunkhwa has a lower dependence on the groundwater reserves compared to the other provinces. According to Van Steenbergen and Oliemans (2013) the agricultural sector in Khyber Pakhtunkhwa only accounts for 11 percent of the groundwater use.

2.3 Data Sources and Descriptions

This section provides descriptions of the sources and the types of data used for the study period of April 2002 – June 2017 (183 months). The monthly terrestrial water storage for Pakistan is obtained from GRACE, whereas, the monthly soil moisture and snow water equivalent are derived using GLDAS Noah, and the monthly precipitation is derived from the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) CDR system.

Table 2-1. Summary of the datasets used in the study

Type	**Source**	**Variable**	**Spatial and Temporal Resolution**
Satellite	CSR GRACE RL05 Mascon Solutions	Δ Terrestrial Water Storage (ΔTWS)	0.5° x 0.5°, monthly
Model	GLDAS Noah Land Surface Model L4	Soil Moisture (SM)	1° x 1°, monthly
Model	GLDAS Noah Land Surface Model L4	Snow Water Equivalent (SWE)	1° x 1°, monthly
Network	PERSIANN CDR	Precipitation (P)	0.25° x 0.25°, monthly

2.3.1 Terrestrial Water Storage (ΔTWS) from GRACE

The monthly estimates of Terrestrial Water Storage anomalies (ΔTWS) in this study are obtained from GRACE RL05 Mascon solutions, provided by the Center for Space Research (CSR) at the University of Texas, Austin (Save et al., 2016). TWS can be defined as all forms of water stored above and underneath the surface in form of vegetation water content, snow, ice, soil moisture, and groundwater, as well as surface water in rivers, lakes, wetlands, and manmade reservoirs (Syed et al. 2008). The processed GRACE gravity field solutions have the same processing standards as the CSR RL05 spherical harmonics solutions on GRACE Level-1 observations. The processed data is represented on a $0.5° \times 0.5°$ grid but has the equal area geodic grid of $1° \times 1°$, which was the original resolution of the CSR RL05 mascon solution. The processed data also has c_{20} replacement, Degree 1 Corrections, GIA Correction, and no additional smoothing or empirical de-stripping applied, in order to be consistent with all other GRACE solutions (Save et al., 2016). According to Zhong et al. (2018), "mascon solutions can still provide comparable ΔTWS estimates as traditional spherical harmonic products"(p. 4). The GRACE anomalies derived from the mascon solution have a relative mean anomaly baseline from 2004 to 2009, with a few missing months (January 2011, June 2011, May 2012, October 2012, March 2013, August 2013, September 2013, February 2014, July 2014, December 2014). The ΔTWS monthly anomalies are expressed in terms of equivalent water height (cm) with respect to the relative mean anomaly baseline (2004 – 2009).

2.3.2 Soil Moisture (ΔSM) and Snow Water Equivalent (ΔSWE) from GLDAS NOAH

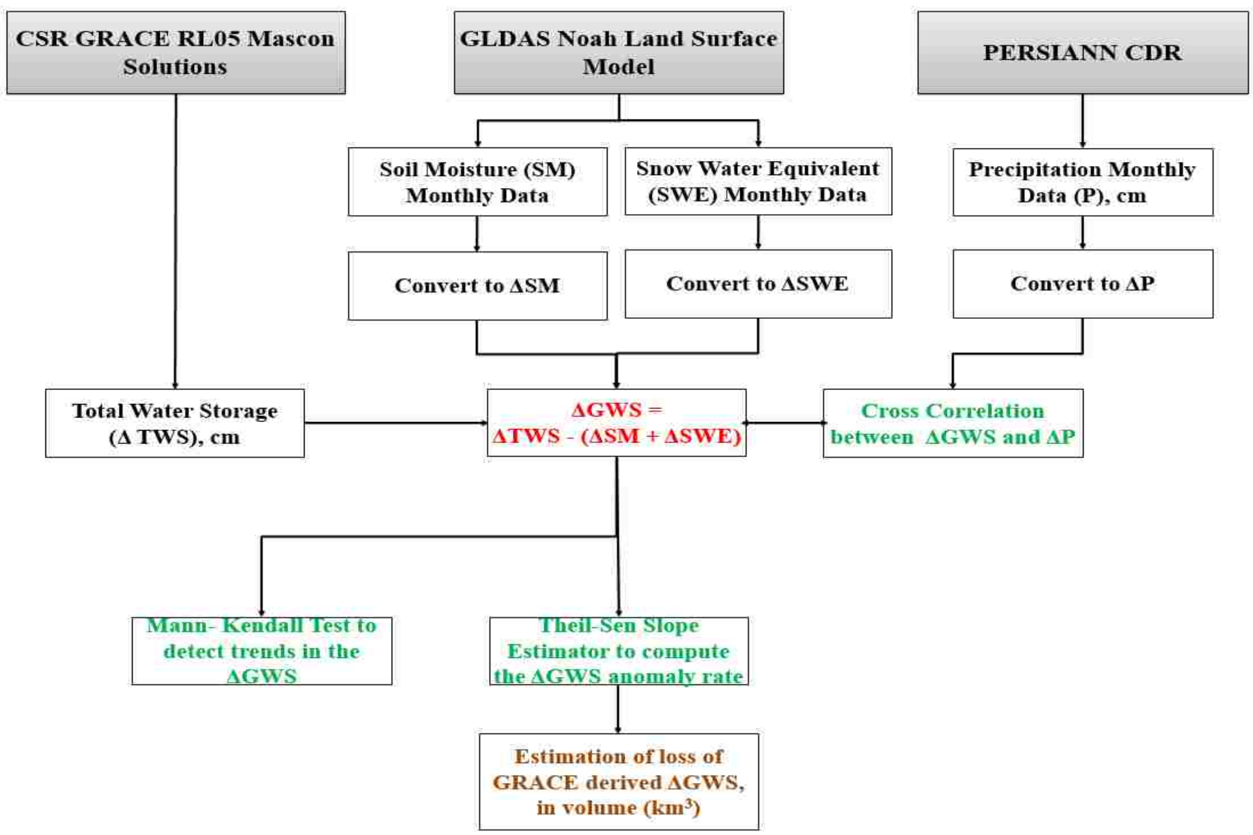
The soil moisture storage and snow water equivalent monthly values are derived from the GLDAS Noah Land Surface Model version 1 (Rodell et al., 2004). The data can be downloaded from the Goddard Earth Sciences Data and Information Services Center (https://disc.gsfc.nasa.gov/). The land simulation model was developed by the National Centers of Environmental Prediction (NCEP), and is a one-dimensional model, which runs in either uncoupled mode or coupled mode when combined with atmospheric models (Zaitchik et al., 2010). The processed GLDAS output includes the accumulated snow (SWE) and changes in the soil moisture content (SM) for four layers (0 – 0.1 m, 0.1 – 0.4 m, 0.4 – 1 m and 1 – 2 m depth), and is represented on a 1° x 1° grid. A land simulation model is used for this study because, according to Rodell et al. (2004), the total water content obtained from the land simulation model can be directly used to compare with what GRACE measures over land with no empirical filtering or post processing. Thus, these integrated absolute monthly values are converted into monthly anomalies for a comparable replication of the GRACE observation with the same mean anomaly baseline of GRACE (2004-2009).

2.3.3 Precipitation (ΔP) from PERSIANN

The gridded precipitation data for the study area is obtained from the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) CDR system. The system was developed by Ashouri et al. (2015) for NOAA's CDR program at a 0.25° x 0.25° spatial resolution. The precipitation is generated from the PERSIANN algorithm using GridSat – B1 infrared data and is adjusted using the Global Precipitation Climatology Project (GPCP) (Ashouri et al., 2015). Several studies have used PERSIANN CDR to calculate monthly estimates of precipitation over a semi-arid region similar to the study area and have resulted in a good correlation with other models (Hussain et al., 2018; Katiraie-Boroujerdy et al., 2016; 2017; Miao et al., 2015). These integrated values are averaged out of each of the provinces, then converted into monthly mean anomaly observations with the same relative mean anomaly baseline of GRACE (2004-2009), as mentioned in the other sections. The computed precipitation anomalies will be used to determine the correlation between climatic variation and the GRACE derived groundwater storage.

2.4 Methodology

Figure 2-2 is a flowchart of the methodological approach used to calculate the groundwater storage anomalies from the GRACE solutions. The monthly ΔTWS anomalies are obtained from the GRACE solutions. The absolute monthly soil moisture and snow-water equivalent values are derived from GLDAS NOAH, and the monthly precipitation value is obtained from PERSIANN CDR System. Primarily, the GRACE solutions are not the absolute monthly values, but instead are in terms of monthly anomalies in reference to their base mean period (2004 – 2009), and have a few months missing due to a satellite battery problem. These gaps are filled using linear interpolation. The GLDAS Noah components are at a spatial resolution of 1° x 1°; hence, the data is downscaled to match GRACE 0.5° x 0.5° spatial resolution. Once the resolutions match up, absolute monthly values for soil moisture and snow-water equivalents are converted into monthly anomalies by subtracting the values by the base mean period (2004 – 2009). Finally, the groundwater storage anomalies (ΔGWS) in Pakistan is obtained by subtracting the ΔSM and ΔSWE from ΔTWS, which is further explained in the following subsection. The average monthly precipitation data is also converted into monthly anomalies with the same base mean period as GRACE to verify the relationship with GRACE derived ΔGWS. The GRACE derived ΔGWS is further used for statistical analysis, which is also explained in the next section.



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2.4.1 Groundwater Storage (ΔGWS) Estimation

The ΔTWS anomalies can be expressed (Iqbal et al., 2016, 2017);

$$\Delta TWS = \Delta SR + \Delta CS + \Delta SWE + \Delta SM + \Delta GWS. \quad (2\text{-}1)$$

where Δ refers to the change over time with respect to base period; ΔTWS is the Terrestrial Water Storage anomalies; ΔCS is the Canopy Storage anomalies; ΔSWE is the Snow Water Equivalent anomalies; ΔSM is the Soil Moisture anomalies; ΔSR is the Surface Runoff anomalies; and ΔGWS is the Groundwater Storage anomalies.

According to Yin et al. (2017), groundwater storage, soil moisture, and, snow water equivalent are the significant contributors that are responsible for the variation in regional water storage observations. Moreover, Pakistan, being in an arid region, has soil moisture and snow water equivalents in the northern region, as an important factor responsible for the variations in the ΔTWS. Therefore, to obtain the monthly ΔGWS, Equation 1 can be re-written:

$$\Delta GWS \approx \Delta TWS - (\Delta SM + \Delta SWE). \quad (2\text{-}2)$$

2.4.2 Groundwater Trend Analysis and Rate of Depletion

The Mann-Kendall Statistical test is used to detect trends in the ΔGWS time series in Pakistan. Mann-Kendall Statistical test is a non-parametric test which helps in determining the behavior of the trends in a time series. For the test, the null hypothesis (H_o) of no trend and an alternative hypothesis (H_a) of data trend (positive or negative) were used.

Following the trend analysis, the rate of depletion in the ΔGWS is determined using the Theil Sen Estimator. The Theil Sen Estimator is a simple, robust, median, unbiased estimator, which provides accurate confidence intervals for the slope on the Mann-Kendall Statistics, as it is resistant to outliers and has a smaller standard error (Sen & Kumar Sen, 1968). According to El-Shaarawi and Piegorsch (2002), it is called "the most popular nonparametric technique for estimating a linear trend"(Acid Rain p. 6). It computes the magnitude of the trend by calculating the slope between the median of the slopes of all lines through the pairs of points (Banerjee & Kumar, 2018).

To determine a correlation between the ΔGWS and ΔP and ΔSM and ΔP, the research uses a cross correlation statistical technique. Cross correlation between two different time series is examined at varying lags. According to Davis (1986), cross correlation "is carried out on two column(s) of evenly sampled temporal data, where the x axis shows the displacement of the second column with respect to the first and the y axis shows the correlation between the two time series for a given displacement" (p. 248). It can also help in determining any periodicities in the series to check how they are impacted by dependence within-series across different time lags. For this study, the correlation between the two-time series is computed at various lags.

2.5 Results

The study found that in Punjab, Sindh, and Balochistan, soil moisture and groundwater storage were the major factors responsible for variations in the ΔTWS. However, in Khyber Pakhtunkhwa, along with the soil moisture and groundwater storage, snow water equivalent was equally accountable. Overall, the variations in the ΔSM, GRACE derived ΔTWS, and ΔGWS exhibited a clear annual cycle, peaking during the monsoon season and exhibiting minima in the winter. The results also depicted a declining trend in the ΔGWS. However, the rate of depletion varied throughout the country.

2.5.1 Groundwater Storage (ΔGWS) Estimation and Rate of Depletion

Figure 2-3 depicts the average fluctuation in the GRACE derived ΔGWS (black line) and ΔTWS (blue line) for Punjab. It is computed that ΔGWS in Punjab is depleting at an average rate of 0.623 mm per month, obtained from Theil- Sen's slope estimator, and has this resulted in an approximated loss of 28.02 km^3 in the groundwater storage over a 183-month period. Punjab started facing a severe depletion in groundwater storage stock from 2002, due to increases in agricultural production. The highest variation in ΔGWS was observed for the year 2010, where the average ΔGWS was about – 0.44 mm, which concluded with a weak drought and resulted in an approximated loss of 1.28 km^3. The depletion rate estimated for Punjab also corroborates with the results from Iqbal et al. (2017), where the study reported a total decline in ΔGWS in the Indus Basin at a mean rate of 8.5 mm per year, with a total loss in ΔGWS by about 7.43 km^3 over the period of 2003 to 2010. As the Indus Basin is a part of Punjab, and has high reliability on groundwater stock for agricultural activity, the depletion rate seems higher than that of the other provinces. In Punjab province, the major causes for such rapid depletion could be the intensive growth of population and establishment of various industries, which have resulted in higher water demand with a poor rate of recharge over the years (Ahmad et al., 2002).

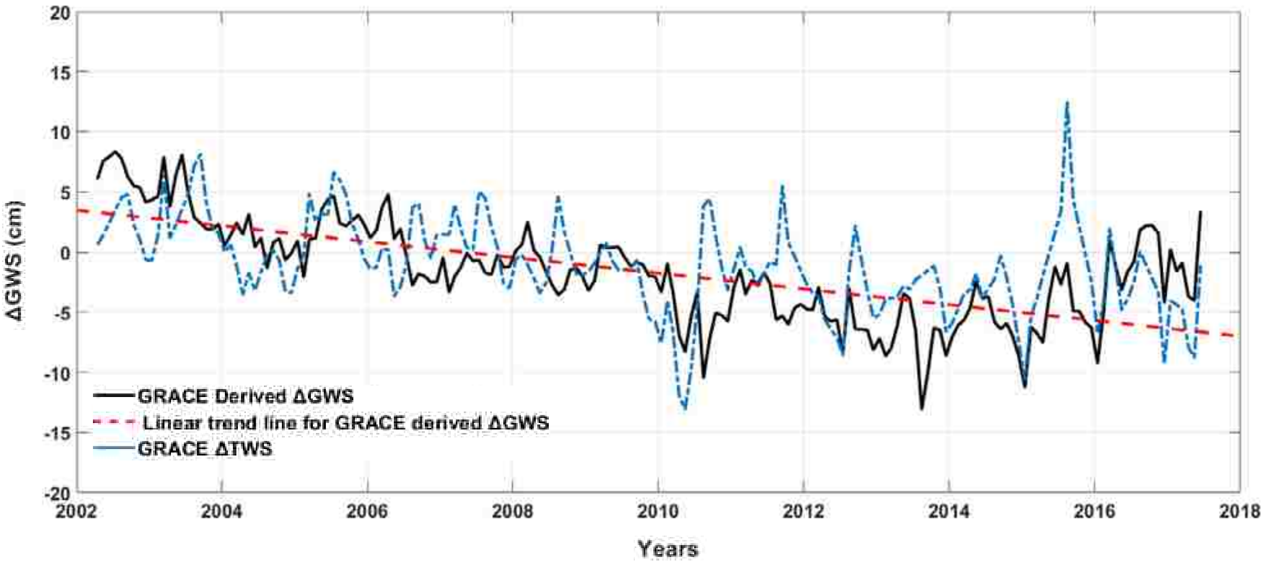

Figure 2-3. Time series of the GRACE derived ΔGWS (averaged) and ΔTWS (averaged) in Punjab.

Figure 2-4 illustrates the average fluctuation in the GRACE derived ΔGWS (black line) and ΔTWS (blue line) for Sindh, Balochistan, and Khyber Pakhtunkhwa. It is observed that the GRACE derived ΔGWS in each of the provinces also follows a declining trend (red line) and has an annual cycle. It is estimated that in Sindh, the ΔGWS is depleting at an average rate of 0.19 mm per month, which is the lowest depletion rate among the provinces, and has resulted in an approximated volumetric loss of 5.46 km^3 in the ΔGWS over a 183-month period. Sindh also experiences a high amount of precipitation, and has encountered frequent floods throughout the years. These floods could be responsible for the groundwater recharge, which resulted in smaller variations of ΔGWS. In Balochistan, ΔGWS is depleting at an average rate of 0.28 mm per month, and has resulted in an approximate loss of 19.57 km^3 of ΔGWS over a 183-month period. The major cause for this depletion is predominately the dependence of agriculture and livestock production on groundwater resources (Frank Van Steenbergen et al., 2015). From the Figure 2-4b), it can be inferred that a weak drought in 2004 led to a decline in ΔGWS in Balochistan. Since then, ΔGWS followed a declining trend until 2015. High precipitation in 2015 also lead to a flood event in the province, which resulted in a sudden spike in ΔGWS, as observed in Figure 2-4. In Khyber Pakhtunkhwa, the study observed that changes in the soil moisture, groundwater storage, and snow water equivalent were responsible for the variations in ΔTWS. It was estimated that ΔGWS is depleting at an average rate of 0.56 mm per month and has resulted in a total volumetric loss of 9.84 km^3. The rate of depletion seems high for a province with minimal agricultural practices; however, due to a smaller area coverage, the estimated volumetric loss is the lowest of the studied provinces.

Overall, groundwater use has markedly increased in Pakistan due to a large rise in the human population, leading to increased water demand in the agricultural, domestic, and industrial sectors. In Pakistan, the total numbers of tube wells have considerably increased over the years, from 2700 tube wells in 1950 to over 600,000 in the year 2003 (Amin, 2004), where considerable withdrawal increases have caused a negative impact on groundwater reserves. Latif and Ahmad (2009) reported that 50 percent of the total wells in Pakistan are being used for irrigation purposes. This highly variable usage, with little understanding of the interactions between farmers and the groundwater recharge, has made groundwater exploitation a major issue in terms of sustainability of the groundwater resource.

The results depict that Pakistan is facing a water crisis with varying rates of groundwater depletion across the country. Punjab has observed the highest loss in the total volume of groundwater storage, followed by Balochistan, Khyber Pakhtunkhwa, and Sindh. In Punjab, the importance of groundwater can be understood, as it is the most agriculturally active province. There are presently about 500,000 private tube wells in the province, extracting 37 BCM of groundwater per year (Amin, 2004). This abstraction has resulted in one of the highest losses in the groundwater stock in Pakistan. In Balochistan, the groundwater storage depletion rate is lower than in the other studied provinces. Due to a larger land area, the overall volumetric loss in the groundwater storage makes the province the second highest in volumetric loss. Khyber Pakhtunkhwa has the second highest depletion rate. However, due to a smaller area, the overall volumetric loss is lower than the others. The groundwater use accounts for an only an estimated 11 percent of the agricultural activities in Khyber Pakhtunkhwa (Van Steenbergen & Oliemans, 2013) which are being exploited by dug-wells and tube wells. An estimation of 2.5 BCM per year of the groundwater is being abstracted through 13,000 private and 491 public tube wells in Khyber Pakhtunkhwa (Amin, 2004). In Sindh, due to significant amounts of annual precipitation and access to large areas of surface water, the province has the least amount of loss in its groundwater storage. A very small amount of groundwater resources are also being exploited by public and private tube wells, as well. The total groundwater extraction in Sindh is about 4.32 BCM per year, which includes pumping from 25,000 private tube wells and 4,100 Salinity Control and Reclamation Programme (SCARP) tube wells (Amin, 2004). To summarize, the selected provinces in this study are experiencing a depletion in the groundwater storage at a varying rate. If there is no controlled use of water resources, Pakistan might face a severe water shortage, which will ultimately lead to secondary salination of the groundwater.

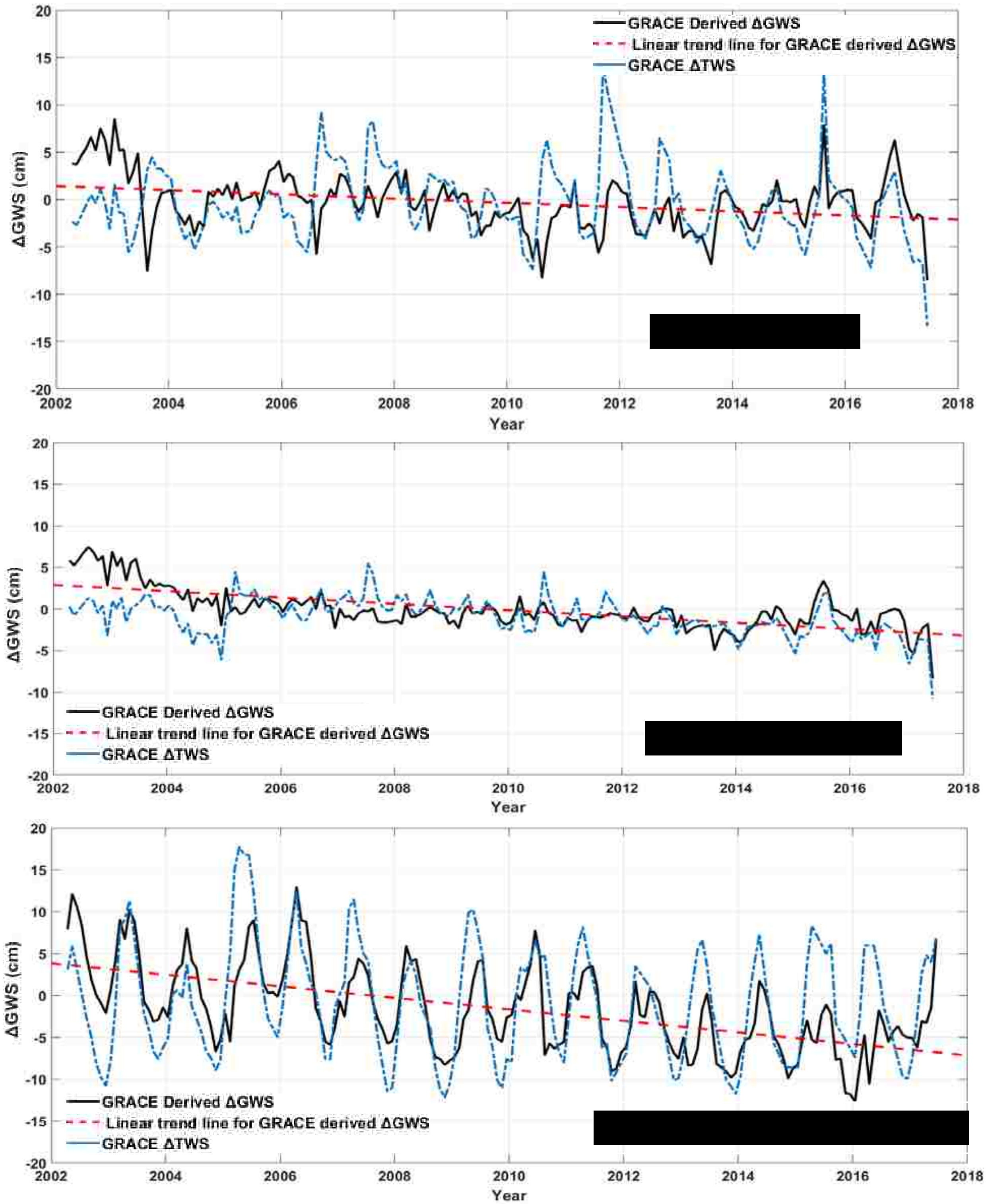

Figure 2-4. Time series of the GRACE derived ΔGWS (averaged) and ΔTWS (averaged) in a) Sindh b) Balochistan and c) Khyber Pakhtunkhwa.

2.5.2 Trend Analysis

This section provides a detailed analysis of the trends present in the ΔSM, ΔSWE, and GRACE derived ΔGWS and ΔTWS for each of the provinces. It also discusses the cross correlation between the ΔSM and ΔP, and GRACE derived ΔGWS and ΔP. The trend analysis for ΔTWS, ΔSM, and GRACE derived ΔGWS anomalies is performed using the Mann-Kendall Trend Test by normal approximation and the rate of change shown (mm per month) is estimated using the Theil's slope estimator. Table 2-2 is the summary of the trends and rates present in the ΔTWS, ΔSM, and GRACE derived ΔGWS in each of the provinces. In Punjab, the result showed that ΔGWS and ΔTWS followed a statistically significant declining trend. The ΔSM followed a statistically increasing trend. In Balochistan, ΔGWS and ΔTWS also followed a declining trend. The soil moisture experienced a slow positive trend. In Khyber Pakhtunkhwa, the results showed that there is a significant increasing trend present for ΔSM and ΔSWE. However, the GRACE derived ΔTWS and ΔGWS followed a declining trend. Lastly, in Sindh, the GRACE derived ΔTWS and ΔGWS followed a declining trend, and ΔSM followed an increasing trend.

Table 2-2. The slope (rate) for the change in GRACE derived ΔTWS & ΔGWS, and ΔSM (cm per month) for studied provinces for the study period obtained using Theil Sen Estimator.

Province	**ΔTWS**	**ΔSM**	**ΔGWS**
Punjab	-0.34	0.23	-0.63
Balochistan	-0.22	0.032	-0.28
Khyber Pakhtunkhwa	-0.13	0.34	-0.56
Sindh	-0.09	0.053	-0.19

2.5.3 Impact of Precipitation on Soil Moisture and Groundwater Storage

Figure 2-5 depicts the comparison between ΔSM and ΔP in the Sindh province. It is noted that extreme rainfall is frequent in Sindh. The super floods of 2010 and 2011 particularly, affected the province and caused a decline in agricultural growth by 3.1 percent (Khan Tagar, 2013). The floods also destroyed almost 10 districts in the province causing damage of 2 billion USD (Khan Tagar, 2013). Due to the frequent floods, it is observed that ΔSM in the province follows an increasing trend until 2012 and then is seen to decrease. It was determined that the precipitation had a significant impact on the soil moisture from the cross correlation test. The coefficient at lag 1 month was the maximum (0.67, with a significance level of 0.05) between ΔP and ΔSM. The study also looked into the relation between the ΔP and ΔGWS. It was determined that the correlation between the ΔP and ΔGWS was maximum at a lag of 4 months (0.156, with a significance level of 0.05). In summary, the ΔSM and ΔP had a significant correlation in Sindh. However, precipitation had a very weak impact on the ΔGWS.

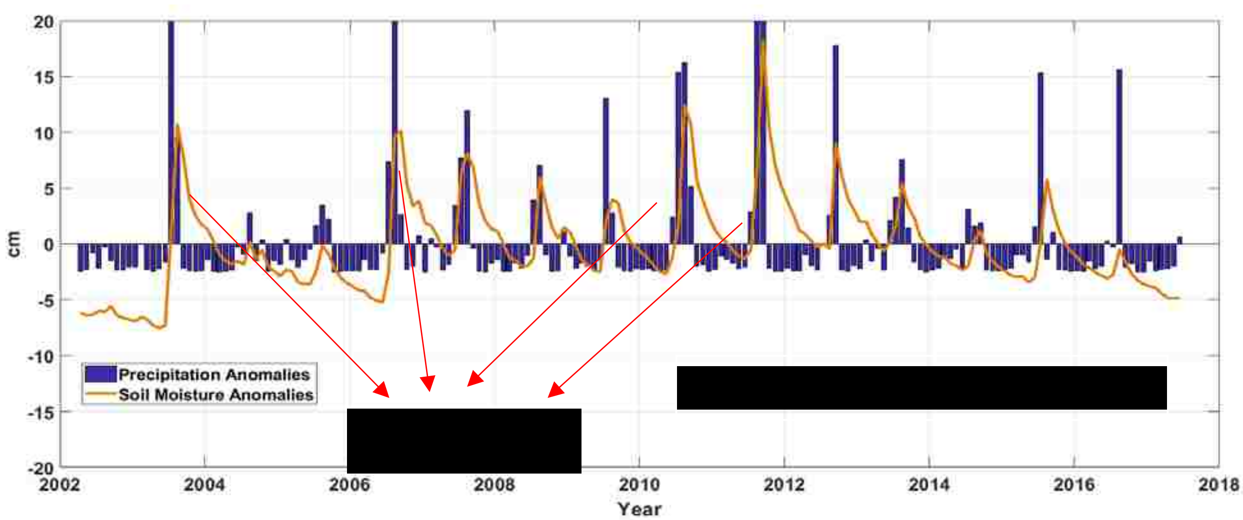

Figure 2-5. Time series of Soil Moisture anomalies (averaged) and Precipitation Anomalies in Sindh (averaged) in Sindh.

Figure 2-6 illustrates the average fluctuation in the ΔSM and ΔP in a) Punjab, b) Balochistan, and c) Khyber Pakhtunkhwa. The figure depicts a relation between ΔSM and ΔP, and it can be observed that high precipitation had an impact on the soil moisture. In Punjab, the ΔSM experiences a gradual increasing trend until 2016, and then declines. From the cross correlation test, it was determined that precipitation had a very weak impact on the ΔSM and ΔGWS in Punjab. The correlation was found maximum at lag of 1 month between ΔP and ΔSM (0.27, significance level is 0.05), and correlation between ΔP and ΔGWS was also maximum at a lag of 1 month. The correlation coefficient was 0.24 (significance level is 0.05). In Balochistan, there was no sign of extreme precipitation patterns. Due to low annual precipitation, the province does not have a high variability in ΔSM, as compared to the other provinces. Balochistan experienced an increasing trend in the ΔSM until 2005, and then it was hit by a major drought from 2004 – 2005, and has been decreasing since then at a slow rate. The correlation between the ΔP and ΔSM was not as strong, and was maximum at lag of 1 month with a coefficient of 0.47 (significance level is 0.05). The cross correlation value of -0.16 (significance level is 0.05) between ΔP and ΔGWS was maximum at lag 5. From this, it can be interpreted that precipitation had an effect on the ΔSM, but no impact on the ΔGWS in Balochistan.

Khyber Pakhtunkhwa experienced a seasonal pattern of ΔP and ΔSM as seen in Figure 2-6 c). The province also undergoes a recurring pattern of heavy rainfall, and was severely affected by the monsoon floods in 2010. The catastrophic flood resulted in the destruction and dislocation of many communities and land in the province(Gul et al., 2016). From the cross correlation test, it was determined that the correlation at lag 1 month was the maximum of 0.56 (significance level is 0.05) between the ΔP and ΔSM. The correlation between the ΔP and ΔGWS was estimated to be a maximum at lag of 6 months with a coefficient of 0.3 (significance level is 0.05). In Khyber

Pakhtunkhwa, precipitation had a positive and significant impact on soil moisture and groundwater storage. The cross correlation test suggested a significant correlation between soil moisture (ΔSM) and precipitation (ΔP) in the country as expected. However, there was a weak or no correlation determined between the precipitation and the groundwater storage in Pakistan. Overall, the depletion in the ΔGWS is not a factor of the variations in the precipitation pattern, but a result of the anthropogenic and agricultural activities. The point of the cross correlation test was to determine if variations in precipitation variability accounted for the changes in soil moisture and groundwater storage.

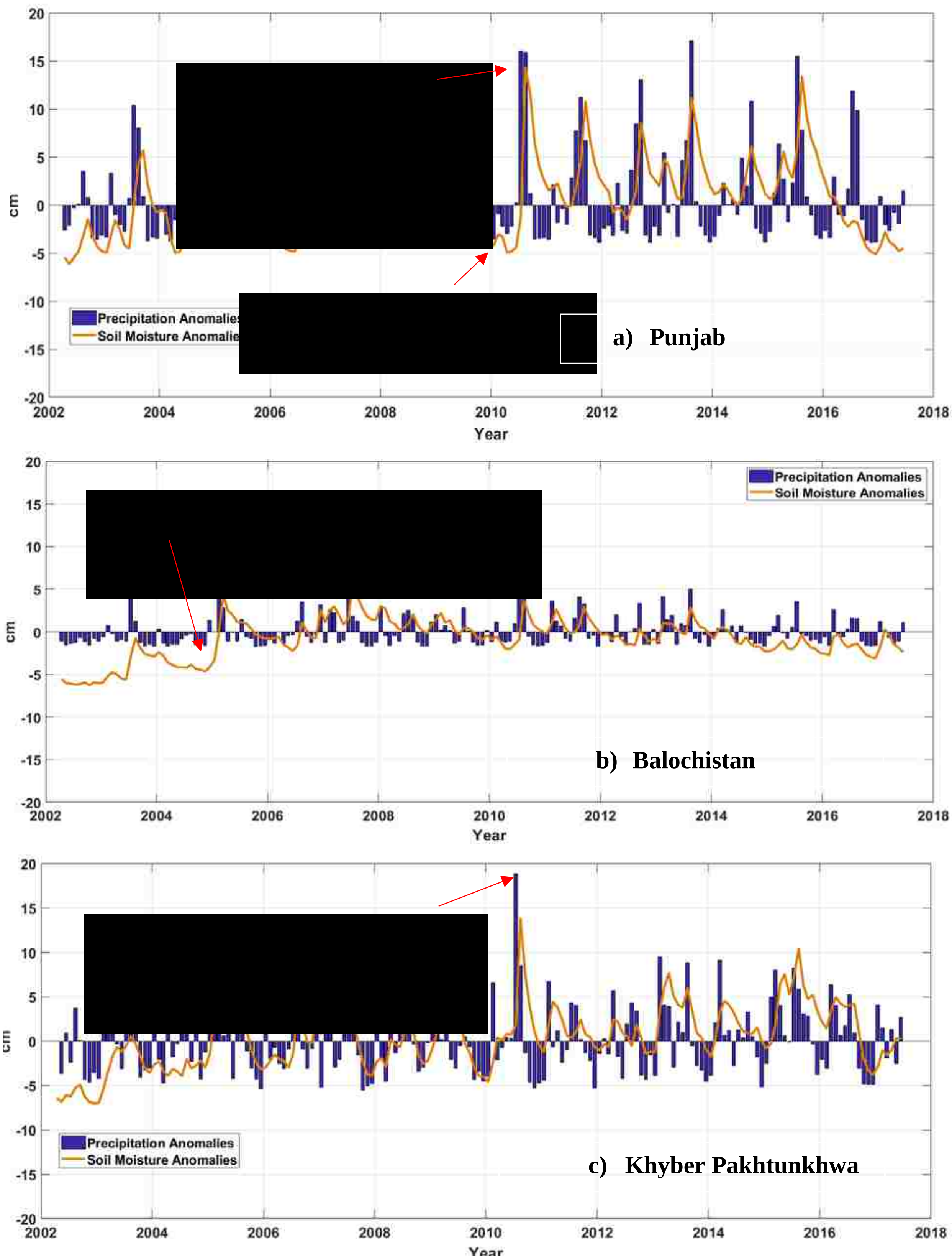

Figure 2-6. Time series of Soil Moisture anomalies and Precipitation Anomalies in a) Punjab, b) Balochistan and c) Khyber Pakhtunkhwa.

2.6 Conclusion

This study presented an analysis of the trends in the variations of GRACE derived ΔTWS and ΔGWS, and ΔSM and ΔSWE at a provincial level in Pakistan. The study also estimated the volumetric loss in groundwater storage at a provincial level and presented an analysis to determine if there was a relation present between the soil moisture (ΔSM) and precipitation (ΔP), and between the groundwater storage (ΔGWS) and precipitation (ΔP). It was found that ΔTWS and ΔGWS followed a seasonal pattern, reaching their maximums during the monsoon season and had their lowest peaks during the winter season. From the Mann-Kendall trend test, it was determined that ΔGWS has been following a declining trend all over Pakistan. However, positive trends were observed for soil moisture and snow water equivalents.

The cross correlation test suggested a significant correlation between soil moisture (ΔSM) and precipitation (ΔP) in the country, as expected. However, there was weak or no correlation determined between the precipitation and the groundwater storage in Pakistan. It can be summarized that the depletion in the groundwater storage was not related to the variability of the precipitation pattern. The reason for such depletion could instead be the anthropogenic activities occurring in the provinces, as Latif & Ahmad (2009) mentioned that 50 percent of the total wells in Pakistan are being used for irrigation purposes.

Currently, Pakistan is experiencing a depletion in its groundwater reserves. However, the rate of depletion has been varying within the country. Punjab observed the highest loss in total volume of groundwater storage (28.2 km^3), followed by Balochistan (19.57 km^3), then Khyber Pakhtunkhwa (9.84 km^3), and Sindh (5.46 km^3). As groundwater has been a major source of water supply in the country. With this current rate of depletion, the country is nearing a chronic water stress condition or drought like situation. If there is no controlled use of water resources, Pakistan might face a severe water shortage, which will ultimately lead to secondary salination of the groundwater. The government should consider potential management needs in assessing the quality and the quantity of these groundwater resources. The government and policy makers could also help by focusing on the recharge aspects of groundwater storage, by increasing the canal diversions or implementing rainwater harvesting and check dams.

Lastly, this study also demonstrated the potential use of GRACE data to determine the long-term variations of groundwater for regions where data is not available. GRACE data is cost effective and does not require much data for processing. With its success, NASA and GFZ have relaunched a follow up mission called GRACE Follow-On (GRACE FO), and it will continue to measure the changes in the gravity caused due to change in mass. GRACE FO will be using the same configuration as before, but with an improved laser system to track the changes more precisely.

GROUNDWATER STORAGE CHANGES AND CROP AREA MAPPING USING REMOTELY SENSED DATA IN PUNJAB, PAKISTAN

3.1 Introduction

As the largest province in terms of population and contribution to agricultural production, Punjab's population has directly or indirectly been dependent on agricultural production for livelihood. According to Badar (2007), Punjab contributes about 60 percent towards the overall crop production, where more than 50 percent of the total irrigated lands are being served through groundwater wells (Aamer & Sabir, 2014). The annual groundwater abstraction in the province has increased from 4 BCM (Billion Cubic Meter) in 1959 to around 60 BCM in 2000, and has been increasing at an uncontrolled rate. This is an indication that without groundwater, not only Punjab, but the whole country could face food shortages, as groundwater has helped in increasing the cropping intensity from 60 percent in 1947 to 150 percent or more in 2015 (Hassan & Hassan, 2017). Thus, the agricultural productivity and its groundwater use is an important concept to assess, as the abstraction in the groundwater reserves has resulted in the deterioration of the groundwater quantity and quality over the years (Hassan & Hassan, 2017).

The depletion in groundwater reserves is also a result of various other factors including changes in precipitation, pumping, changes in land use and land cover, and changes in river flow. Studies have shown that climate change, particularly, has created uncertainty in the supply and management of the groundwater resources (Kumar, 2012). Kumar (2012) mentions that the global mean surface temperature is predicted to increase by 2 – 4 degree Celsius over the next 100 years, which will ultimately affect the hydrological cycle overall. The change in the hydrological cycle will affect the rates of precipitation and evaporation, creating situations of severe weather events like flooding or more drought, and eventually impacting groundwater reserves (Kumar, 2012). In addition to climate change, groundwater reserves are also being impacted by humans through frequent pumping for personal, agricultural and industrial use. The depletion in the groundwater reserves will have a negative effect on the water table, which will lead to increased cost and reduced water supplies, as well as land subsidence and water quality concerns (Groundwater Overuse).

As the spatial distribution of crops, as well as groundwater-use varies across the province. This study uses remote sensing techniques to interpret the relationship. This research focusses on the impact of precipitation and agricultural productivity on the groundwater reserves in Punjab. Punjab consists of 36 districts, and each district is known for cultivating respective sets of crops, which have varying water demands for cultivation. For example, the same crop grown in southern Punjab has a higher water demand than in the northern Punjab region due a much more arid climate. To understand the relationship between crop cultivation and groundwater use, it is important to map the spatial distribution of cropping. Traditionally, crop mapping is done using census and ground surveying information. However, remote sensing can also be an effective and reliable way to map crops and monitor groundwater. Apart from providing a synoptic view, remote sensing products can provide structured information about the health of vegetation, as well as how crop cultivation has impacted the groundwater reserves (Ozdogan et al., 2010).

The groundwater information for the study has been obtained from the Gravity Recovery and Climate Experiment (GRACE) mission. GRACE is a unique and a valuable remote sensing platform to monitor the groundwater storage variation under all types of terrestrial conditions (Tapley et al., 2004). Along with the Global Land Data Assimilation System (GLDAS), a land surface modeling system, GRACE can provide monthly groundwater storage variations for an area. Several studies, across multiple sites on various spatial scales, have used GRACE to remotely monitor groundwater and have shown the potential of using GRACE in the estimation of groundwater storage variation globally.

To estimate the crop water demand, this study uses CROPWAT. CROPWAT is a computer program developed by the Food and Agriculture Organization (FAO), which helps in estimating crop water and irrigation requirements for a ranges of crops using climatic and crop data. Studies have shown that CROPWAT estimation strongly correlates with the results from actual observations (Ravishankar et al., 2018), and can be used to determine the water demand for the crops for effective irrigation planning and management. Moreover, the crop area mapping for this research is done using an image classification technique of the satellite images. The image classification is based on the analysis and distribution of similar pixel groups, with similar spectral characteristics, offering a high accuracy of image analysis and showing implicit areas that are represented by different crops. Studies have used Landsat images to classify agricultural land use and results have shown potential. The Landsat satellites provides high quality multi-spectral images at moderate resolutions along the visible and invisible light spectrum at no cost (Agriculture from "Landsat Imagery: A Unique Resource"). Apart from the agriculture land use mapping, Landsat images can also provide information related to the estimation of crop production, monitoring of consumptive water use, crop specific land cover classification, and global economic and food security forecasting (Leslie et al., 2017.)

The overall purpose of this study is to identify the long-term variations in groundwater storage and relate it to the long-term impact of precipitation and the crop production in the Vehari, Khanewal, Rahim Yar Khan, and Bahawalpur districts of Punjab. In particular, groundwater storage data derived from GRACE is related to precipitation. The cultivation of four major crops in the districts including sugarcane, rice, wheat, and cotton are evaluated, on the basis of agriculture production and annual water demand, with respect to groundwater storage, using statistical analysis. Moreover, cultivated areas of wheat and cotton are mapped using Landsat data for the years 2016 and 2017 to illustrate the spatial distribution of the crops. This research is organized as follows. This introduction is followed by the description of the study area, data, and methodology. It is then followed by results and discussion sections. Finally, a conclusion is provided.

3.2 Study Area

This study is conducted for Vehari, Khanewal, Rahim Yar Khan (RYK), and Bahawalpur districts located in Southeast Punjab, Pakistan (Figure 3-1). These districts are selected on the basis of their total agriculture production. RYK and Bahawalpur have experienced a significant increase in the total crop production since 2000, whereas the total crop production in Vehari and Khanewal is observed to be declining. Bahawalpur is the largest among the selected districts, with an area of 24,000 km^2. Seventy-six percent of the total land in Bahawalpur is bare, with sparse vegetation; Twenty-two percent is used for crop cultivation; and the rest is urban built up areas. RYK has an area of 12,000 km^2, divided into three main regions. It includes a canal irrigated agricultural area, a desert area called Cholistan, and a riverside area adjacent to the river Indus (AQUASTAT FAO, 2011). About 50 percent of the total land in RYK is used for agriculture. 2.5 percent of the area in RYK is urban, and the rest of the area is bare soil with sparse natural vegetation (AQUASTAT FAO, 2011). Vehari district has an area of 4400 km^2. It lies between the Ravi, Beas, and Sutlej rivers and has the most fertile land, being a part of the Indus plain with a big canal system. Ninety-three percent of the total area in the district is used for crop irrigation, and the rest is urban areas and natural vegetation. Lastly, Khanewal district was created in 1985 by combining two tehsils from the Multan district: Kabirwala and Mian Channu (AQUASTAT FAO, 2011). It has an area of 4300 km^2, where 85 percent of the total land is being used for crop cultivation, and the rest is covered by water bodies, other vegetation, and urban areas. All of the selected districts are highly intensive in agriculture production and are known for their high production of cotton, sugarcane, rice, and wheat. The selected districts experiences a very hot and dry climate, with an average annual rainfall of 150 mm. This average rainfall is low compared to the country's average of 255 mm. Lastly, the green circles in Figure 3-1 are the FAO weather climatic stations that provides the meteorological data in this study.

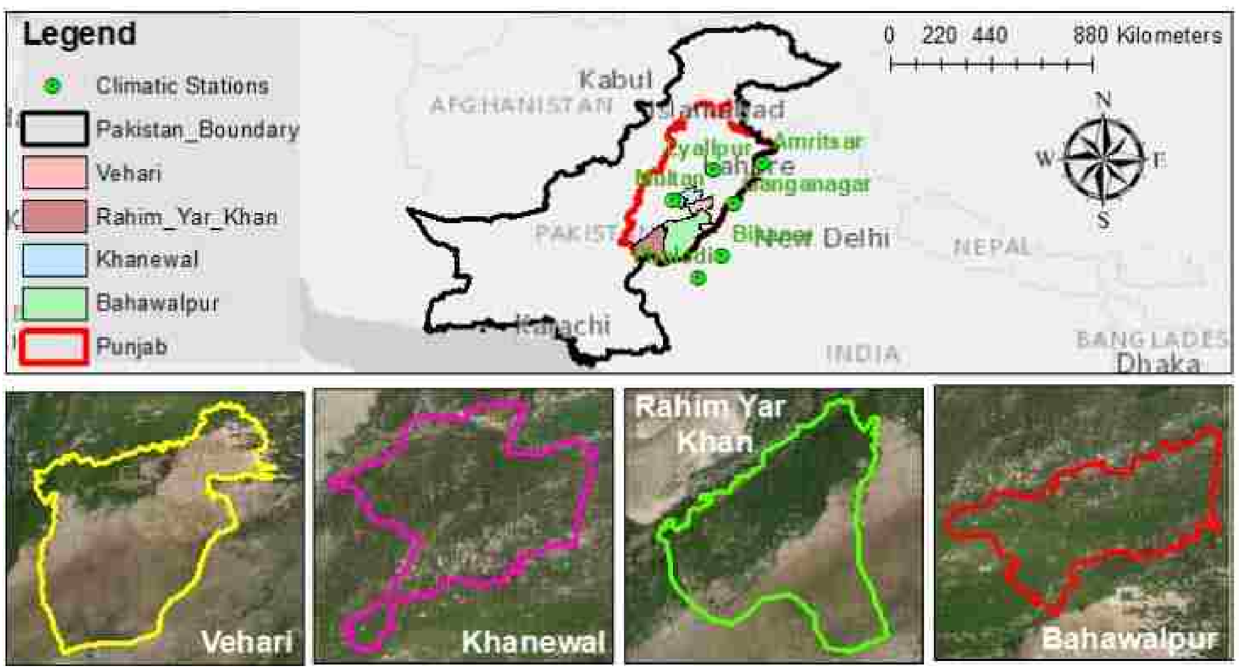

Figure 3-1. Location of the study area in Pakistan. Climatic stations are the FAO weather stations from CLIMWAT, which provides the meteorological data to estimate the average crop water requirement for the study area.

3.3 Data and Data Sources

This study uses data from various sources, which includes remote sensing and survey data that is summarized in Table 3-1. The groundwater storage variations for the districts are derived from GRACE and GLDAS. The monthly average precipitation values for the study are obtained from the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) CDR system. The annual area of the crop irrigated and crop production is obtained from the Bureau of Statistics Punjab, which is a department under the government of Punjab, Pakistan. The total tube wells installed data in the studied districts for the year 2006 – 2015 are also obtained from the Punjab Development Statistics. For the crop area mapping, the satellite images are obtained from the Landsat 8 for the years 2016 and 2017. Images for the months of February and September are chosen because of the prominent crop spectral signature being the fully-grown stage for the crops. Lastly, to determine the water demand for respective crops annually, this study uses the climatic data obtained from CLIMWAT and CROPWAT for the average crop water requirement. Table 3-1 provides a summary of the datasets used for the study and is followed by an explanation of the processed data sources.

Table 3-1. Summary of the datasets used for the study

Type	Source	Variable
Satellite	CSR GRACE RL05 Mascon Solutions	Terrestrial Water Storage (ΔTWS)
Model	GLDAS Noah Land Surface Model L4	Soil Moisture (ΔSM)
Network	PERSIANN CDR	Precipitation (ΔP)
Report	Bureau of Statistics Punjab	Annual Crop Area Irrigated and Crop Production
Satellite	Landsat 8	Crop Area
Computer Program	CropWAT	Crop Water Requirement (CWR)
Climatic Database	CLIMWAT	Observed Agro - Climatic Data

3.3.1 Hydrological Data

The monthly estimates of Terrestrial Water Storage anomalies (ΔTWS) are obtained from GRACE RL05 Mascon solutions, provided by the Center for Space Research (CSR) at the University of Texas, Austin (Save et al., 2016). This data is represented on a 0.5° x 0.5° grid and provides anomalies relative to a baseline mean value of the 2004 to 2009 period. The data is expressed in terms of equivalent water height (cm), with respect to the mean of the baseline period. The monthly soil moisture is available on a 1° x 1° grid and is derived from GLDAS Noah Land Surface Model version 1 (Rodell et al., 2004). The processed GLDAS output includes changes in the soil moisture content for four soil layers (with depth 0 – 0.1 m, 0.1 – 0.4 m, 0.4 – 1 m and 1 – 2 m). The monthly precipitation data is presented on a 0.25° x 0.25° grid, which is obtained from the PERSIANN CDR System developed by Ashouri et al., (2015) for NOAA's CDR program.

3.3.2 Irrigation Water Requirement

The crop cultivation information for the study area is obtained from the Punjab Development Statistics (Bureau of Statistics, Punjab). The information consists of the total area irrigated for wheat, rice, sugarcane, and cotton (in thousand hectares) and the annual crop production (in thousand tons). The climatic data used in CROPWAT in this study is obtained from CLIMWAT. CLIMWAT is a climatic database created by FAO, which provides the observed agro climatic data for the six stations selected (Amritsar, Bikaner, Ganganagar, Lyallpur, Multan, and Phalodi), as shown in Figure 3-1. This climatic data is used in CROPWAT to estimate the crop water requirements for the selected of crops in the selected districts.

3.3.3 Satellite Images

The monthly satellite images used in the study are downloaded from the Earth Explorer (https://earthexplorer.usgs.gov/), controlled by the United States Geological Survey (USGS). The data used in the study are based on the clarity of the images for the given day with minimal cloud cover or any other obstructions. Initially, this study targeted the whole Punjab province. However, due to unclear images from cloud cover and irregular temporal data, this research focusses on the Vehari, Rahim Yar Khan, Khanewal, and Bahawalpur districts. The Landsat 8 images are selected for the month of February (wheat) and September (cotton) for the years 2016 and 2017. These months are selected on the basis of the prominent crop spectral signature being the fully grown stage for the crops. The description of the satellite images is given in Table 3-2, and more information on the different band characteristics and spatial resolutions can be obtained from Barsi et al., (2014).

Table 3-2. Landsat images used in the study.

District	**2016**	**2017**
Bahawalpur	Landsat 8 OLI, February 27 Landsat 8 OLI, September 06	Landsat 8 OLI, February 13 Landsat 8 OLI, September 09
Rahim Yar Khan	Landsat 8 OLI, February 18 Landsat 8 OLI, September 13	Landsat 8 OLI, February 20 Landsat 8 OLI, September 16
Vehari	Landsat 8 OLI, February 27 Landsat 8 OLI, September 22	Landsat 8 OLI, February 13 Landsat 8 OLI, September 25
Khanewal	Landsat 8 OLI, February 27 Landsat 8 OLI, September 22	Landsat 8 OLI, February 13 Landsat 8 OLI, September 25

3.4 Methodology

The overall approach in this analysis includes the volumetric estimation and trend analysis of the GRACE derived ΔGWS. Furthermore, the relationship between the agriculture productivity and groundwater storage, as well as the temporal changes in precipitation and the groundwater storage are examined. Lastly, the spatial distribution of wheat and cotton is mapped using an image classification technique of the Landsat images. Figure 3-2 is the schematic flowchart of the overall methodological approach in this study.

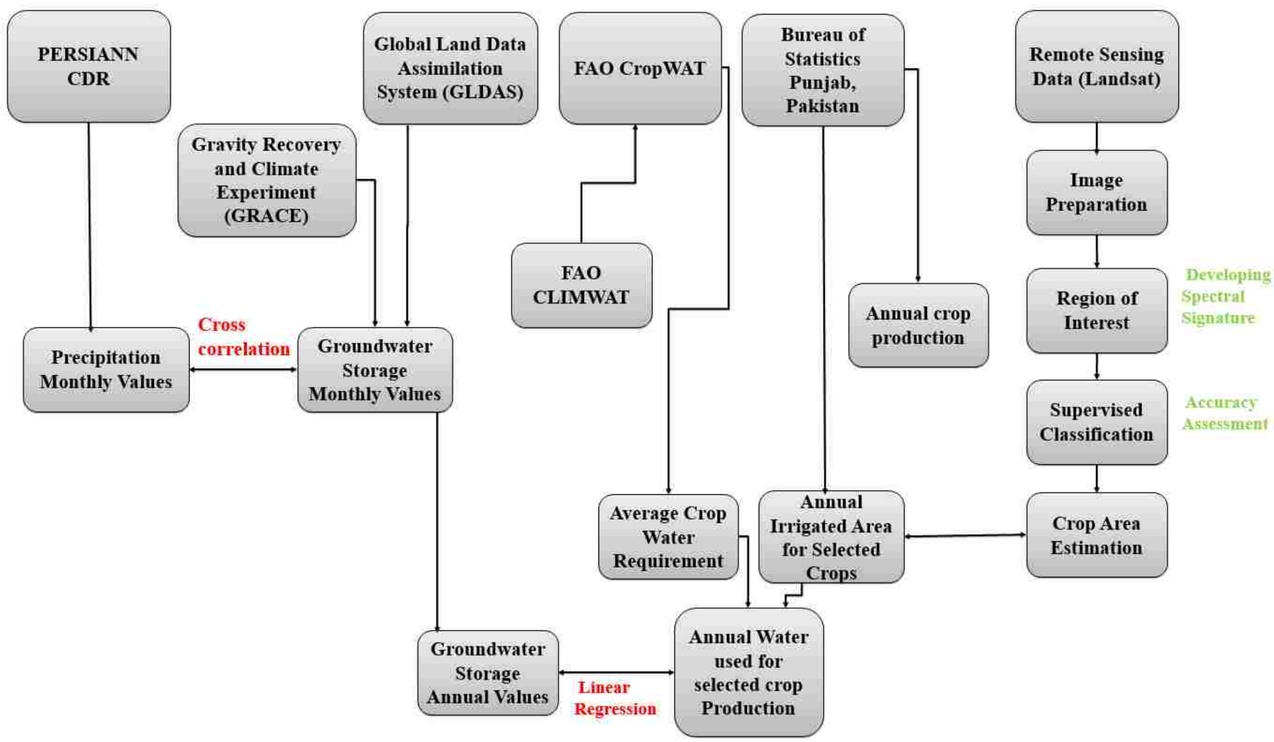

Figure 3-2. Methodological approach used in the study.

3.4.1 GRACE derived Groundwater Storage (ΔGWS)

This study uses GRACE and GLDAS Noah to compute the monthly groundwater storage variations in Punjab. GRACE provides the monthly ΔTWS and has a few months missing (January 2011, June 2011, May 2012, October 2012, March 2013, August 2013, September 2013, February 2014, July 2014, and December 2014). These missing months are filled in using linear interpolation. The soil moisture data is derived from GLDAS NOAH at a resolution of 1° x 1° and is downscaled to a resolution of 0.5° x 0.5°. The downscaled data is then converted into monthly anomalies by subtracting the absolute value by the baseline period (2004 – 2009). In Punjab, groundwater storage and soil moisture are considered as the significant contributors inducing the variation in terrestrial water storage. Therefore, the ΔGWS is computed by using the following equation:

$$\Delta GWS \approx \Delta TWS - \Delta SM \qquad (3\text{-}1)$$

where Δ refers to the change over time with respect to base period; ΔTWS is the Terrestrial Water Storage; ΔSM is the Soil Moisture and; ΔGWS is the Groundwater Storage.

Once the monthly ΔGWS is estimated, then the temporal variations of ΔGWS and the precipitation anomaly (ΔP) are statistically analyzed for correlation. The ΔP values derived from PERSIANN are also re-gridded to match the ΔTWS grid of 0.5° x 0.5°. The correlation between the ΔGWS and ΔP is examined using a cross correlation statistical technique.

3.4.2 Irrigation Water Requirement

The temporal variations of ΔGWS are also examined with crop data. Since crop data samples are only available annually, the analysis is conducted by converting the monthly ΔGWS into annual values. The crop data includes the crop production, area, and water demand, where the crop water demand is estimated for each crop using CROPWAT. The CROPWAT values computed at the six weather stations are interpolated using the Inverse Distance Weighted (IDW) interpolation in GIS to give a spatial distribution of the average crop water requirement in the Punjab province. IDW is used in this study, as it linearly weighs the combination of the sample points. From the spatially interpolated image, the average CWRs for sugarcane, rice, cotton, and wheat (mm per season) are computed and converted into total volumetric demand (million acre-feet per year) for each crop. To determine the relationship between the annual water used and the groundwater storage, this study uses regression and correlation analyses.

3.4.3 Crop Area Mapping

The crop cover maps are prepared based on the basis of the spectral signatures of the Landsat images. In this study, the maximum likelihood classifier (MLC) method is used with training samples created on the foundation of the crop mask developed by the Agriculture Information System (AIS) Pakistan for the years 2014 – 2015 in Punjab. This study uses a prior crop area mask, due to lack of availability of ground truth data and prior information available for areas where wheat and cotton is cultivated. To estimate the crop area, supervised image classification is used. Supervised classification produces more accurate results, compared to unsupervised classification, as the user has the control to create a quality image. Sample signature plots of the six classes used in this study are shown in Figure 3-3.

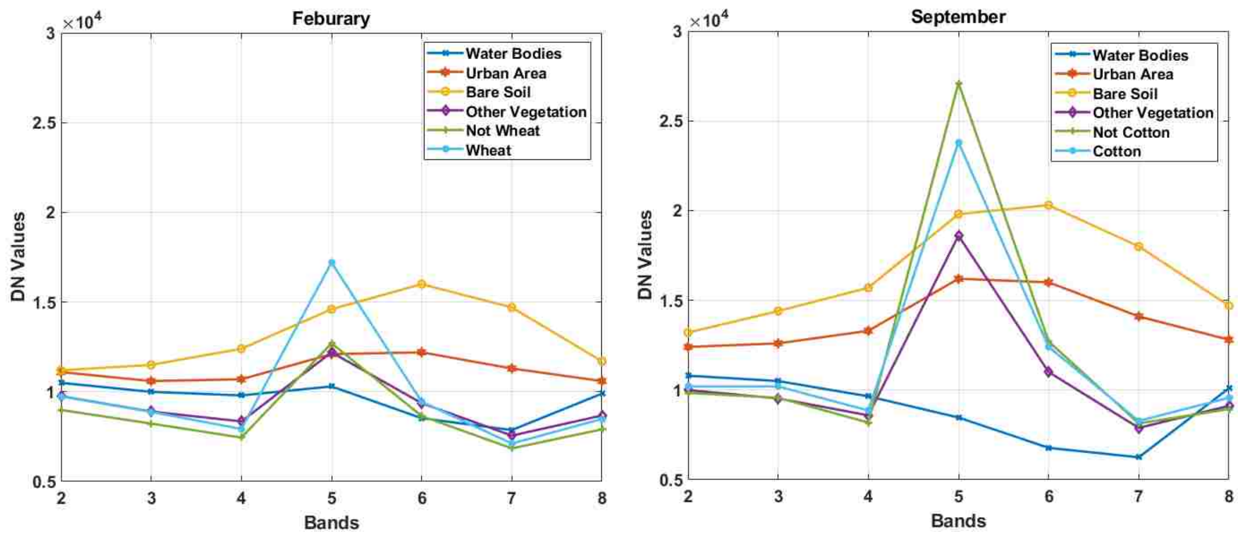

Figure 3-3. Sample signatures of the cover classes used.

Accuracy assessment for the classified image is performed by comparing the map created by remote sensing analysis to a reference map based on testing samples taken by a creating confusion matrix or error matrix (Congalton & Green, 2009). The accuracy generated is based on the computed user's accuracy, producer's accuracy, and overall accuracy, and is reported in percentage. The user's accuracy of the image is computed using the number of correctly classified pixels to the total number of pixels assigned to a particular class. The producer's accuracy is computed by using the image analyst of the number of pixels correctly classified in a particular class as a percentage of the total number of pixels actually belonging to that same class. The producer's accuracy measures errors of omission. Lastly, the overall accuracy is the percentage identifying to what extent the classes were properly created.

3.5 Results and Discussion

The results show a general decreasing trend in ΔGWS and an increasing trend the overall crop production in the study area. This section first discusses the rate of depletion and the overall volumetric loss in ΔGWS in the respective districts. It further explains the relationship between the temporal changes in precipitation and groundwater storage, as well as crop water demand and groundwater storage for the selected crops in the district. Lastly, a spatial crop area map for wheat and cotton is provided and analyzed for the study area.

3.5.1 GRACE derived Groundwater Storage (ΔGWS)

In Punjab, the groundwater is declining at a high rate. However, the magnitude of the change in the ΔGWS varies within the districts (Figure 3-4). These variations are highly dependent on recharge from the hydrological cycle and abstractions. The results revealed that Vehari has the highest depletion rate in groundwater storage among the selected districts, followed by Bahawalpur, Khanewal, and RYK. It is estimated that ΔGWS in Vehari is declining at a rate of 1.1 mm per month and has resulted in a volumetric loss of 0.92 km^3 over 13 years. In the Bahawalpur district, ΔGWS is depleting at a rate of 0.94 mm per month and has resulted in a total volumetric loss of 4.12 km^3. Khanewal's ΔGWS is depleting at a rate of 0.77 mm per month, leading to an overall volumetric loss of 0.60 km^3. Lastly, In RYK, ΔGWS is depleting a rate of 0.51 mm per month. This depletion resulted in a total volumetric loss of 1.38 km^3 of ΔGWS in the district. These four districts together are accountable for the overall volumetric loss of 6.75 km^3 of ΔGWS in Pakistan in 183 months. This loss in ΔGWS is alarming, as Punjab is already facing severe issue of water scarcity. Kahlown et al. (2007) also reported that in the Punjab province, the groundwater table is decreasing by three feet per year. If not controlled, the over abstraction of the groundwater storage can create a drought like situations for the districts and the province. The analyses presented here revealed that ΔGWS has been contributing significantly to the decreasing trend in the ΔTWS. Figure 3-4 also depicts a seasonal decreasing trend in ΔGWS in the respective districts. The seasonal variation has the maxima occurring during the monsoon season and low peaks during the dry season.

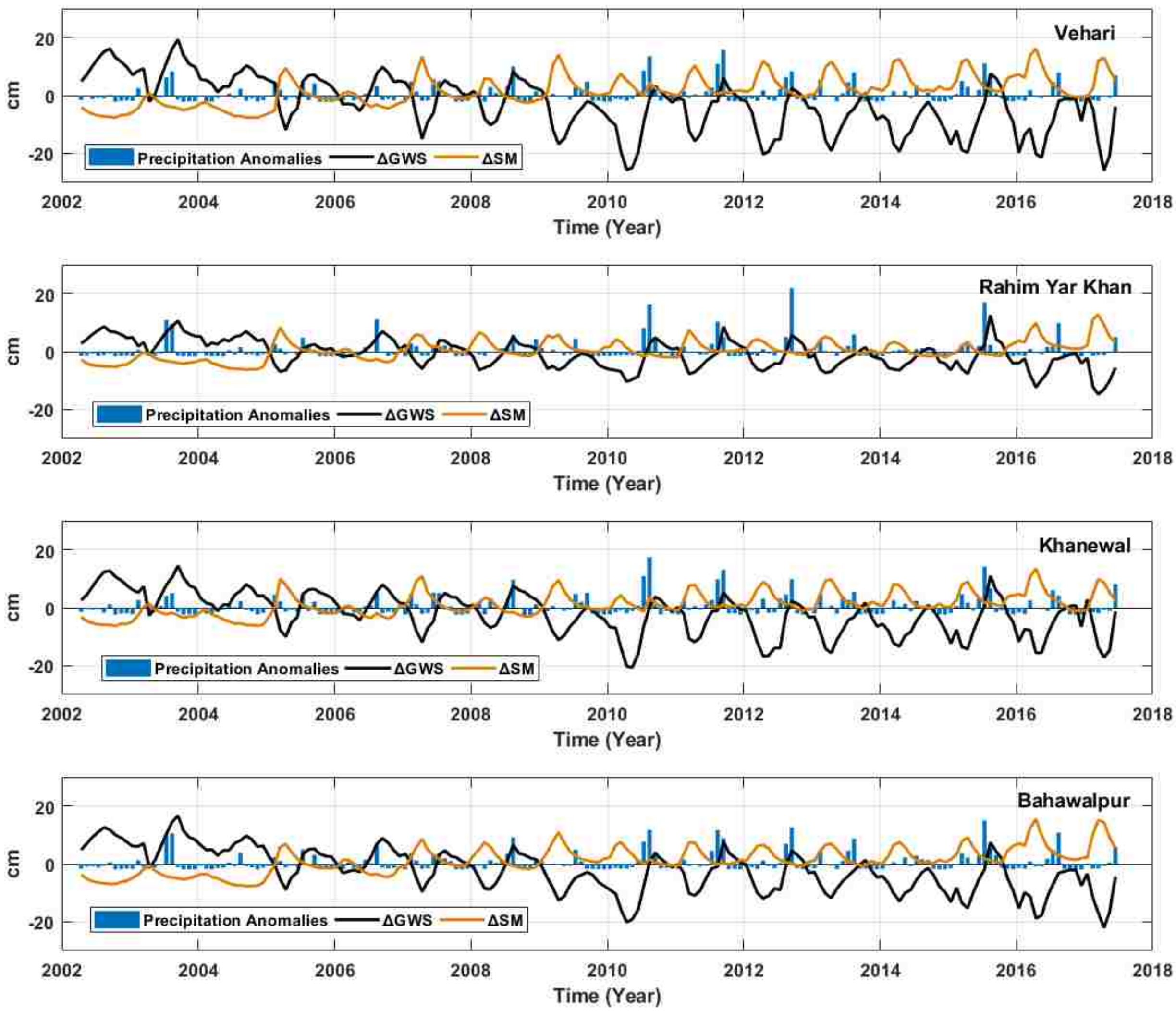

Figure 3-4. Time series of GRACE derived ΔGWS and ΔSM along with ΔP in Vehari, Rahim Yar Khan, Khanewal, and Bahawalpur.

3.5.2 Impact of Precipitation on ΔGWS and ΔSM

To analyze the impact of rainfall amounts on groundwater storage and soil moisture, this study compares the precipitation derived from PERSIANN CDR with ΔGWS and ΔSM, as shown in Figure 3-4, using a cross correlation method. Figure 3-4 illustrates that the selected districts generally receive a low amount of rainfall annually. However, there were a few years, when heavy floods or flood like events (high peaks) occurred, which resulted in higher recharge in the ΔGWS compared to other years. As groundwater and precipitation are linked through the hydrological cycle, from the cross correlation test it was established that the precipitation had a weak positive impact on the groundwater storage in all of the respective districts. However, the time of this positive impact differed within the districts. It was determined that in Vehari, precipitation had the maximum impact on the groundwater storage at a lag of three months, with a coefficient of 0.52 (significance level is 0.05). Even with the highest correlation between the ΔGWS and precipitation among the selected regions, Vehari had the highest depletion rate for the ΔGWS. The rate of abstraction in Vehari is higher than the recharge, being an agriculture intensive district. In RYK and Bahawalpur district, precipitation also has a positive impact on the ΔGWS, at a lag of three months. RYK and Bahawalpur receives low amounts of precipitation annually, compared to the other districts, resulting in a correlation coefficient of 0.37 (significance level is 0.05) and 0.46 (significance level is 0.05), respectively. Lastly, in Khanewal the cross correlation test also revealed a three-month lag between the precipitation and groundwater storage, with a maximum coefficient of 0.42 (significance level is 0.05).

As the interaction between precipitation and ΔGWS can be altered due to climate change and shifts in precipitation (Thomas et al., 2016), groundwater storage shows a pattern of seasonal fluctuation and a varying lag. These fluctuations are also influenced by the recharge of rainfall and irrigation, and the discharge from irrigated canals, which have been following a well-defined cycle (Tahir et al., 2004). This study also looked into the relation between the ΔP and ΔSM. It was determined that the correlation between the precipitation and soil moisture was maximum at lag of 4 months in the studied districts. Vehari had the strongest correlation coefficient of 0.42, followed by Bahawalpur (0.41), Khanewal (0.40), and Rahim Yar Khan (0.28), with a significance level of 0.05. In summary, precipitation had a positive weak impact on the ΔGWS and ΔSM in the studied districts.

3.5.3 Irrigation Water Requirement

Pakistan, being an agricultural country, is required to double its annual food production every 15 years to meet people's food requirements (Raza et al., 2017). In order to feed 120 million additional people by 2025, Pakistan is heavily dependent on the irrigation of agricultural crops and other agricultural activities (Raza et al., 2017). Kahlown and Majeed (2003) reported that the water demand for cotton, wheat, sugarcane, and rice in Punjab will increase from 80.2 Million Acre Feet (MAF) in 2000 to 106.9 MAF by 2025. For this significant increase in crop production, more groundwater will be used. The interdependence of crop water demand and cultivation is also examined for the selected districts, where the annual crop water demand for cotton, wheat, sugarcane, and rice in the selected districts is derived using CROPWAT. Figure 3-5 illustrates the spatial distribution of the CWR for the respective crops (mm per cropping season) in Punjab. Sugarcane has the highest CWR compared to the other crops, followed by rice, cotton, and wheat. It is also observed from Figure 3-5 that the northern side of Punjab has much lower crop water requirement compared to the southern side for the selected crops. The southern side, being much more arid and dry, requires a higher amount of water for crop cultivation. The estimated average

CWR for the respective crops for each district is given in Table 3-3. These average CWR values are used to estimate the annual water demand for each of the respective crops.

Table 3-3.Average CWR for selected crops.

District	Cotton	Sugarcane	Wheat	Rice
Bahawalpur	609.6	1807.0	198.7	628.9
Khanewal	581.6	1824.3	187.1	616.3
Rahim Yar Khan	579.8	1724.1	184.6	608.2
Vehari	596.0	1815.2	193.6	622.6

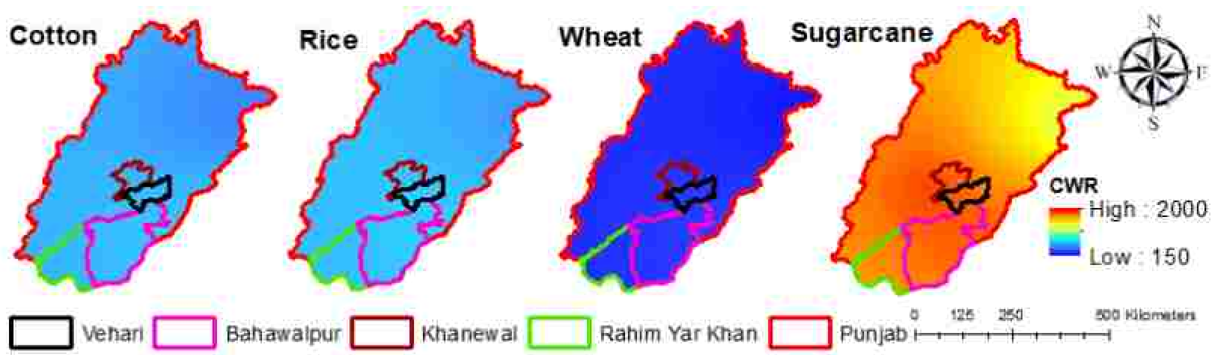

Figure 3-5. Spatial distribution of the Crop Water Requirement for Cotton, Rice, Wheat, and Sugarcane in Punjab from CROPWAT (mm per cropping season).

3.5.4 Correlation and Regression Analysis

A decreasing trend is observed in ΔGWS and an increasing trend is observed in the average water demand for the respective crops in each of the districts. This study considered the cross correlation between ΔGWS and the water demand for the respective crops and found the maximum correlation at a lag of 1 year. The analysis suggested that the present year's crop production was an outcome of the previous year's groundwater storage. Thus, the regression and correlation analysis were determined at a shifted time series. Figure 3-6 and 3-7 show the time series of the total crop production (in thousand tons) and the annual ΔGWS in the respective districts.

Bahawalpur and RYK have both observed to have significant growth in total crop production. However, the magnitude of the total production differs between the two districts (Figure 3-6). RYK accounts for producing triple the amount of crops as Bahawalpur. There has been 184 percent and 75 percent increase in total crop production in RYK and Bahawalpur, respectively, since 2003. This increase in crop production has resulted in more water being used for cultivation.

In particular, in Bahawalpur, there has been a 54 percent increase in the wheat production, leading to a 12 percent increase in the wheat-water demand for irrigation, since 2003. Rice and sugarcane production have also increased significantly, by 266 percent and 117 percent, respectively, which led to an increase in the water demand by 163 percent and 100 percent, respectively. In RYK, rice and sugarcane production have also greatly increased by 159 percent and 234 percent, which has led to increase in the water demand by 98 percent and 181 percent, respectively. From the correlation and regression analyses, it was revealed that in RYK, wheat production has a weak positive correlation with ΔGWS. The correlation coefficient between the two was 0.15. A strong positive correlation was also found between ΔGWS and the cotton water demand in RYK, with a coefficient of 0.62. In Bahawalpur, only cotton had a positive correlation, with a coefficient of 0.35. Positive correlation in this study denotes that the increase in crop water demand resulted in the increase in the ΔGWS, which in this case is not possible.

Rice and sugarcane have had a significant increase in production, which has resulted in increased water used for their cultivation. The test suggested a strong negative correlation between ΔGWS and rice water demand (-0.59), as well as ΔGWS and sugarcane water demand (-0.67) in RYK. There was also a strong negative correlation found between wheat water demand and ΔGWS (-0.49) in Bahawalpur. The correlation between ΔGWS and the water demand for sugarcane cultivation was -0.63, and between ΔGWS and the water demand for rice cultivation was -0.43 in Bahawalpur. The correlation between total water used for cultivation in RYK and the ΔGWS was determined to be -0.65 and in Bahawalpur it was -0.68. The negative correlation suggests that the increase in the crop production led to more water being used for cultivation, which negatively impacted the groundwater storage. The overall analysis suggested that in Bahawalpur and RYK, as the total crop production increased, it had a negative impact of the groundwater storage. In particular, wheat, rice, and sugarcane production have primarily been responsible for the variations in the ΔGWS. In RYK, rice and sugarcane production shared a strong correlation with the ΔGWS as they observed a growth in the production.

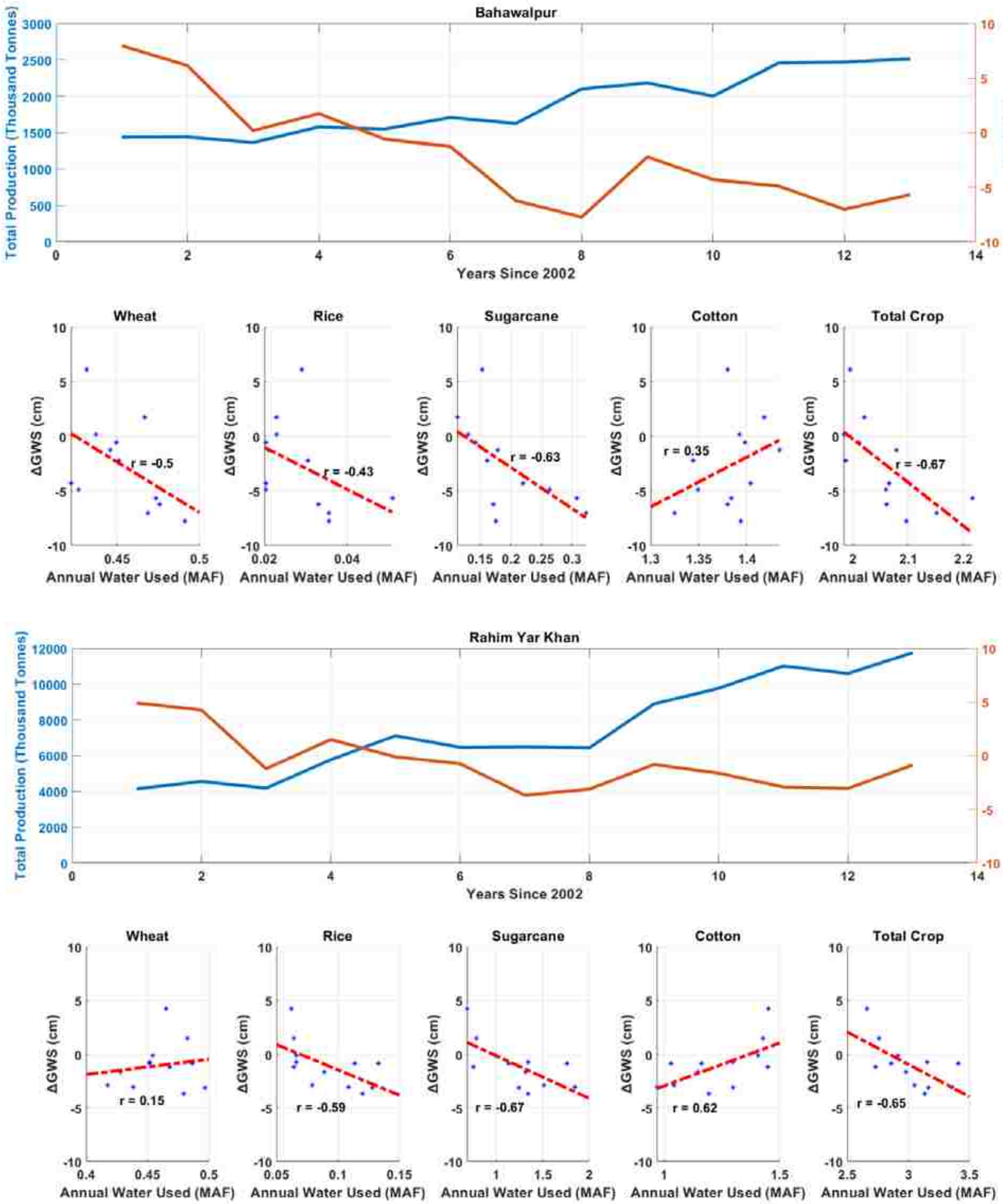

Figure 3-6. Time series of annual total crop production (thousand tons) and groundwater storage, and the correlation between groundwater storage and annual water used by respective crops in Bahawalpur and Rahim Yar Khan.

Vehari and Khanewal districts follow a different type of behavior in their total crop productions. Both the districts have declining trends in the total production of crops as well as groundwater storage. This decline has resulted in an approximate reduction in their total productions by 5 percent since 2003 (Figure 3-7). In Khanewal, there has been a 12 percent and 10 percent increase in the wheat and rice production, respectively, since 2003. However, a total of a 50 percent decrease was observed in sugarcane and cotton production. In Vehari, there was an average 60 percent increase in wheat and rice production, but a 55 percent decrease in sugarcane and cotton production. From the statistical test, it was determined that in Vehari, wheat and rice production had a negative impact on the ΔGWS. The correlation coefficient between the ΔGWS and the wheat and rice water demands is -0.4 and -0.23, respectively. The negative correlation is not as strong compared to the other districts, as the crop production did not increase significantly. In Khanewal, rice cultivation was only responsible for the impact on the ΔGWS. The rice production in Khanewal increased by 15 percent, leading to a 32 percent increase in the annual rice water demand. It was determined that the correlation coefficient between the ΔGWS and water demand for rice cultivation was -0.47, suggesting a decrease in the ΔGWS lead to an increase in the rice production. The rest of the crops in Vehari and Khanewal districts had either very weak correlations or none at all.

To summarize, in Bahawalpur, sugarcane, wheat, and rice cultivation had a negative impact on the groundwater storage of the district. The heavy production of the three crops, and other anthropogenic activities, led to 4.12 km^3 of the ΔGWS in the district in 13 years. In RYK, 1.1 km^3 of ΔGWS have been lost due to heavy wheat and sugarcane production and other anthropogenic activities. In Khanewal, the ΔGWS was correlated with the rice cultivation, and in Vehari the

ΔGWS was correlated with wheat and rice cultivation. Vehari and Khanewal have not had major increases in the total crop production compared to the other districts, and thus resulted in total losses in the ΔGWS by 0.92 km^3 and 0.6 km^3, respectively.

Furthermore, ΔGWS was also correlated with the tube well installation data for the studied districts. It was estimated that there was an increase in the number of tube wells in each of the studied districts, except Khanewal, from 2006 until 2014. The increase in the number of tube wells during the study period is indicated by increase in pumping of groundwater, resulting in the depleting groundwater storage. A strong negative correlation was established between the ΔGWS and the number of tube wells, with the coefficient being -0.70 for Bahawalpur, -0.78 for Rahim Yar Khan, and -0.81 for Vehari districts. The results revealed a weak correlation coefficient of -0.0015 between the ΔGWS and the total number of tube wells in the Khanewal district. To conclude, apart from crop cultivation, the anthropogenic activities in the districts have also been a factor for the depletion in the ΔGWS.

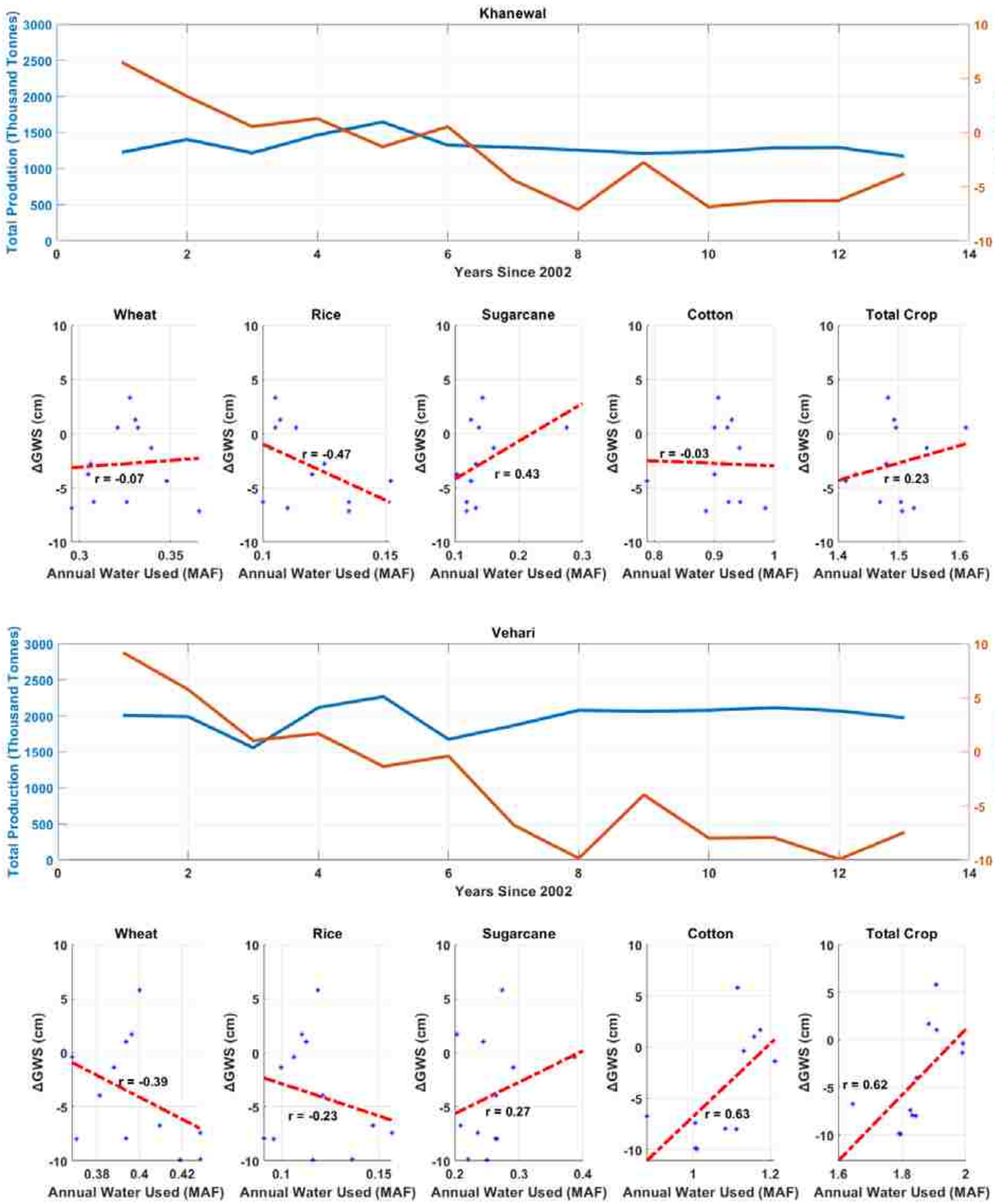

Figure 3-7. Time series of annual total crop production (thousand tons) and groundwater storage, and the correlation between groundwater storage and annual water used by respective crops in Khanewal and Vehari

3.5.5 Crop Area Mapping

A spatial crop area map for wheat and cotton crop was created using a supervised image classification method (Figure 3-8 and 3-9). The Landsat 8 images were digitally classified into six land use classes, including water body, urban area, bare soil, other vegetation, not wheat, and wheat for the February images. For the month of September, the images were digitally classified as water body, urban area, bare soil, other vegetation, not cotton, and cotton. The crop area estimates are justified on the basis of accuracy assessment and the information available from the bureau of statistics.

In RYK and Bahawalpur, the majority of the area is covered by bare soil and sparse vegetation. In Khanewal and Vehari crop cultivation dominates the most area. The classified image generated more accurate results, compared to the bureau of statistics data. The classified image revealed that RYK was the highest producer of wheat in 2016, with an irrigated area of 311.4 thousand hectares. It was followed by Bahawalpur, with an irrigated area of 294.7 thousand hectares. Khanewal cultivated 229.1 thousand hectares of wheat, and lastly, Vehari had 202.4 thousand hectares of wheat in the district.

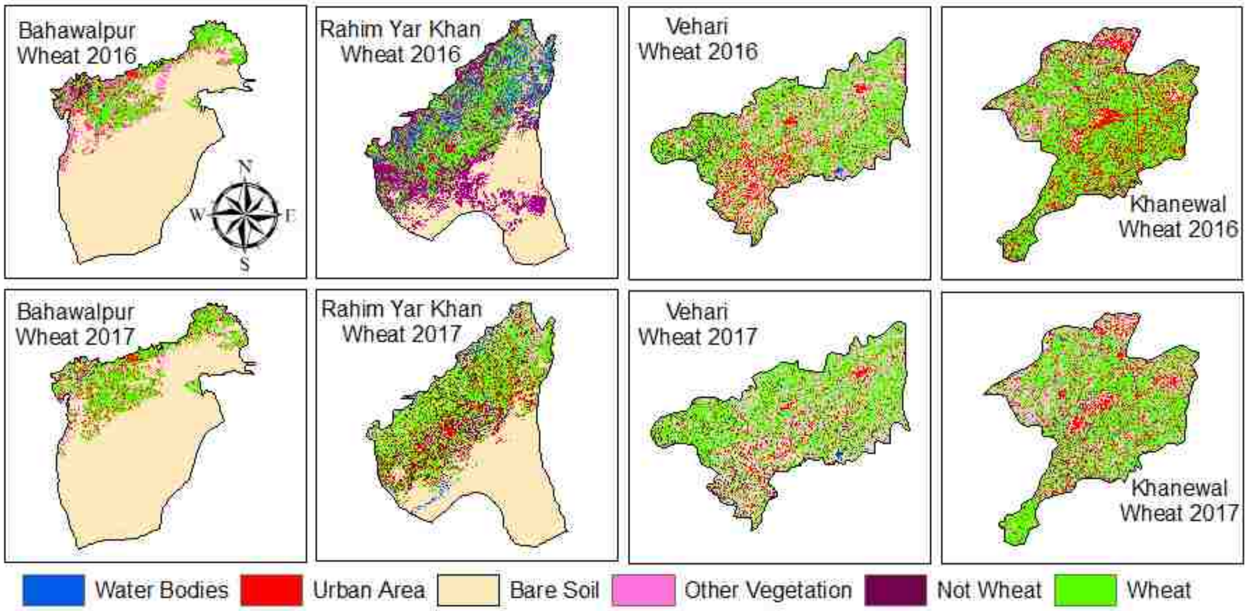

Figure 3-8. Classified images for Wheat in the selected districts for the years 2016 and 2017.

Compared to 2016, the classified image for February 2017 showed an increase in the wheat production in the Khanewal and Vehari districts by 11 percent and three percent, respectively. However, in RYK and Bahawalpur, the results revealed that the wheat cropping area had decreased by 14 percent and 19 percent, respectively. As previously mentioned, confusion matrices are developed to test the accuracy of classification against reference points acquired from crop mask data. Tables 3-4 and 3-5 show the calculated accuracy statistics for cotton and wheat crop-type maps, respectively. From the accuracy assessment of the classified image, it was determined that the range of overall accuracy of the classified image achieved for the regions was 85 percent to 98 percent. The overall accuracy of the image classification process for all of the districts for the month of February is given in Table 3-4, along with user's and producer's accuracies.

These results also strongly corroborates with the values obtained from the bureau of statistics. There was a 24 percent overestimation, which was the highest between the classified area and the actual area of wheat in Vehari for the year 2016. Khanewal, RYK, and Bahawalpur observed an underestimation of 12 percent, 1 percent, and 2 percent, respectively, with the irrigated areas for wheat obtained from bureau of statistics.

Table 3-4. Accuracy Assessment for February Classified Image.

District	**Image Classification Accuracy (%) for Wheat**					
	2016			**2017**		
	User's Accuracy	**Producer's Accuracy**	**Overall Accuracy**	**User's Accuracy**	**Producer's Accuracy**	**Overall Accuracy**
Bahawalpur	98.2	97.4	97.3	98.6	97.8	98.2
Rahim Yar Khan	92.9	81.0	87.0	98.4	86.3	92.4
Khanewal	98.2	98.3	98.2	98.8	98.8	98.8
Vehari	97.3	97.2	97.3	97.9	97.8	97.9

For the cotton crop area mapping, Bahawalpur has the highest amount of cotton irrigated land, with a classified area of 254.4 thousand hectares in the year 2016. The district also observed an increase in the crop’s cultivation the following year. It was determined that there has been a 20 percent increase in cotton cultivation in Bahawalpur. The other selected districts did not follow a similar trend In RYK, the classified cotton area decreased from 240.6 thousand hectares to 219.1 thousand hectares. There has also been a 14 percent decrease in the cotton cropping area in

Khanewal and 11 percent decrease in Vehari from 227.9 thousand hectares to 197.9 and from 187.8 to 168.7 thousand hectares, respectively, since 2016.

Comparing the classified areas with the cropping areas, reported by the bureau of statistics, the results are in a similar range from one percent to 20 percent. Khanewal had the highest difference of 21 percent of misclassification, compared to the bureau of statistics. For the accuracy assessment of the classified images, the overall accuracy for cotton classification is between 90 percent and 99 percent, and is given in Table 3-5. The lowest overall accuracy was determined for Khanewal in 2013, with 93.3 percent.

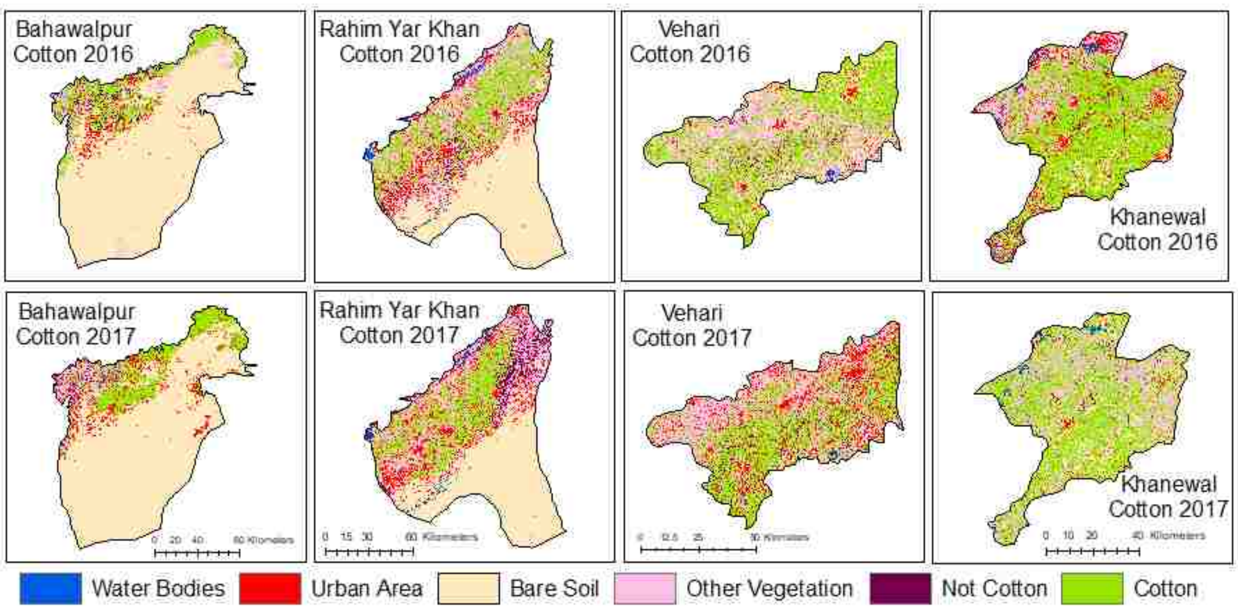

Figure 3-9. Classified images for Cotton in the selected districts for the years 2016 and 2017.

Table 3-5. Accuracy Assessment for September Classified Image.

District	Image Classification Accuracy (%) for Cotton					
	2016			2017		
	User's Accuracy	Producer's Accuracy	Overall Accuracy	User's Accuracy	Producer's Accuracy	Overall Accuracy
Bahawalpur	98.6	95.5	97.1	98.9	99.8	99.3
Rahim Yar Khan	97.9	96.7	97.3	94.5	94.2	94.4
Khanewal	92.3	94.3	93.3	98.0	97.9	98.0
Vehari	93.5	93.5	93.5	95.7	95.6	95.7

To summarize, this supervised classification was based on the crop mask provided by FAO. It was based on the foundation that the areas where cotton and wheat were grown in the years 2014 and 2015 did not change until 2017. Overall, the classification has good accuracy, but it also comes with a level of uncertainty. The majority of crops in Punjab are not grown on a large scale. With a satellite image resolution of 30 meter by 30 meter, it can be hard to classify more than one crop grown in each area. Additionally, with the absence of a pure spatial reference for each type of crop grown in the region of interest, the dominant crop was chosen as the primary classifier (wheat and cotton). This likely resulted in a large range of pixels to include other crops, resulting in increased uncertainty. The results showed that the cropping areas for wheat and cotton areas are consistent with the irrigated areas obtained from the bureau of statistics. It is recommended to use these remote sensing techniques, coupled with regular field data or ground truth data to obtain essential and more accurate results.

3.6 Conclusion

This study presented an overall analysis of variations in groundwater storage for the districts of southern Punjab, Pakistan. The study is based on the premise that soil moisture and groundwater are the primary factors leading to variations in the ΔTWS. The results depict a decreasing trend in the ΔGWS at an alarming rate. However, the average declining rate varies within the districts in Punjab. It was estimated that Bahawalpur had the highest volumetric loss in the ΔGWS by 4.12 km^3 over a 13 years period, followed by RYK (1.11 km^3), Vehari (0.92 km^3), and lastly Khanewal (0.60 km^3).

Analysis of the results showed that precipitation has a weak positive impact on groundwater storage and soil moisture at varying time lags in Vehari, RYK, Khanewal, and Bahawalpur districts. The results also revealed that the ΔGWS in the selected districts followed a declining seasonal pattern, reaching the maximum during the monsoon season and a minimum during the winter season. Even with a limited amount of precipitation, the rate of recharge is much lower than the rate of abstraction, resulting in a considerable depletion of the groundwater reserves.

The impacts of crop cultivation on groundwater storage were also evaluated. Results showed that sugarcane, wheat, and rice production have had significant impacts on the groundwater reserves, depending on the district studied. Due to a significant increase in rice, wheat and sugarcane production since 2003, increasing amounts of groundwater are being used for cultivation purposes. Although the depletion in the groundwater storage was weakly related to precipitation, it shows a greater dependence on agricultural and anthropogenic activities occurring in the districts. There exists a negative correlation between ΔGWS and tube well installation data, showing that more tube wells have resulted in a decline of groundwater storage. Lastly, the major crops of wheat and cotton were mapped using Landsat data for the years 2016 and 2017 in the selected districts to define their spatial distribution. Results showed a spatial variation in the cropping areas over time in the study area.

In conclusion, this study combined the information derived from remote sensing and other sources, in order to compute the variations in groundwater storage over time; then examined the impacts of precipitation and crop cultivation on the groundwater storage in southern Punjab. GRACE data have been shown to be cost effective in estimating long-term variations of groundwater storage for regions where water level data are not available. Image classification has also been shown to be effective in creating a spatial map of crop cultivation to identify changes in agricultural patterns. These results can provide government agencies and agricultural managers useful information about groundwater changes in relation to crop water demands and precipitation in the studied districts.

CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary

Pakistan, being once a water surplus country with extensive amount of water resources, is now a water deficit country (Kahlown & Majeed, 2003). With increases in the population and industrialization, annual food production in Pakistan is required to double every 15 years, just to maintain the status quo (Hayat et al., 2016). In addition, Pakistan does not follow any regulations for groundwater extraction or use, as water rights are not protected under law. Therefore, anyone with sufficient financial capital and land is in a position to install a tube well and extract water at his/her convenience, without consideration of safe yields (Bhutta & Alam, 2006). Studies have shown that the current net groundwater extraction in the country is comparatively higher than the recharge, and has resulted in lower water table levels (Bhutta & Alam, 2006). Wada et al., (2010) studied groundwater depletion around the major regions of the world, and identified that Northeastern Pakistan and Northwestern India have the highest depletion rates for their groundwater reserves. With this motivation, this thesis used GRACE to obtain groundwater information in Pakistan, and focused on identifying the long-term variations in groundwater storage in the country. Furthermore, this thesis also examined the impact of precipitation and crop production on groundwater reserves in Pakistan.

The first objective presented an analysis of the trends in the variations of the GRACE derived ΔTWS and ΔGWS, as well as ΔSM and ΔSWE on a provincial basis in Pakistan. The study estimated volumetric losses in groundwater storage at a provincial level, and presented an analysis to determine if there were relationships present between soil moisture and precipitation, and between the groundwater storage and precipitation. The study was based on the hypothesis that climatic variability had an impact on groundwater storage in Pakistan. Results from the study showed, in the studied regions in Pakistan, there was a declining trend in the GRACE derived ΔGWS overall. The highest volumetric loss in the ΔGWS was estimated for Punjab (28.02 km^3), followed by Balochistan (19.57 km^3), Khyber Pakhtunkhwa (9.84 km^3), and lastly Sindh (5.46 km^3), over a period of 183 months. Cross-correlation statistical test suggested a significant correlation between soil moisture and precipitation in the studied provinces. However, a statistical result of weak or no correlation was determined between precipitation and groundwater storage.

The second objective focused on identifying the long-term variations in the groundwater storage. It examined the impact of precipitation with the addition of the crop production on the groundwater reserves in the Rahim Yar Khan, Bahawalpur, Vehari, and Khanewal districts in Punjab, Pakistan. In addition, this study also performed an image classification to illustrate a spatial map of the wheat and cotton cropping areas for the selected districts. The results revealed that the groundwater storage in Punjab is depleting at a higher rate than expected. The selected districts together were accountable for the overall volumetric loss of 6.75 km^3 of ΔGWS in Pakistan in a 13-year period. The results also revealed that the groundwater storage responded positively to precipitation. Lastly, in regards to agricultural activity, wheat, sugarcane, and rice crop cultivation have had a significant impact on the groundwater withdrawal rates, depending on the district.

In summary, GRACE provided an opportunity to observe and monitor the fluctuations in the groundwater storage at a regional level, based on gridded downscaling, in order to capture finer scaler variations. NASA and GFZ have launched a follow up mission called GRACE Follow-On (GRACE FO), which will continue to measure the changes in gravity caused due to changes in mass. GRACE FO will be using the same configuration as before, but with a much improved laser system to track the changes more precisely. It is expected to create new perspectives in the field of hydrology. Overall, despite its limitations, GRACE is considered as a feasible and a unique way to monitor groundwater storage. It is important for the need of assessment data of groundwater depletion in areas where groundwater monitoring is not available, as it can help with the evaluation of the decreasing trends in groundwater.

4.2 Contributions

While previous authors have performed significant work in these areas, the major contributions of this research are as follows: First, this research is the first of its kind that used remote sensing information to analyze the change in groundwater storage in Pakistan at a provincial level. The study identified and analyzed the temporal changes in the groundwater storage due to precipitation variability. Secondly, this study also presents a comprehensive analysis in the variation of the groundwater change in relation to crop water demand for the agriculturally active regions in the country.

4.3 Limitations

Though this study makes a comprehensive attempt to answer the above described research questions, certain limitations are inevitable. Firstly, uncertainty in the GRACE data can be caused due to instrumental errors or data processing methods from the processing centers. Further, due to the limited time frame of GRACE observations, the fluctuations in the groundwater storage can only be extended to a certain period. Lastly, due to unavailability of actual in situ well data, this research could not compare the actual groundwater storage variation with the GRACE results. However, results with other studies in the region were comparable.

4.4 Future Research

The objectives presented in this thesis evaluated the temporal changes in groundwater storage, and determined the correlation with precipitation variability and agricultural productivity in Pakistan. However, there are many aspects that could be improved in terms of accuracy, or for applications in future research. Future studies or replications of similar methods should consider the following improvement opportunities:

1. Combining the GRACE results with different hydrogeological models (GLDAS VIC, LSM, and CSM), as it may provide categorical information with the variations of groundwater storage.
2. Use of a different hydrological model (MODFLOW) and in situ well data should be done to compare the GRACE derived groundwater variations.
3. More in depth analysis in understating the seasonal relationship between groundwater storage and climatic variability (temperature) and groundwater – related subsidence.

4.5 Recommendations

With the declining trend in groundwater storage in Pakistan, the country should develop and implement a regulatory framework for the sustainability of groundwater (Ahmed et. al, 2018; Ghumman et. al, 2014). It should also consider the following recommendations:

1. Low water requirement crops should be evaluated and promoted over high delta crops where feasible. This will also reduce the virtual water export for high delta crops that are exported.
2. Efficient irrigation methods should be implemented such as drip and sprinkler systems. Moreover, capturing and storing water, growing drought tolerant crops, and improving irrigation efficiency can also help with reduction in groundwater withdrawal.
3. Recharge of groundwater should be increased utilizing check dams, rainwater harvesting, and low impact urban development.
4. Lastly, a policy for groundwater management should be developed and implemented that involves permits for the installation of tube wells and limits on groundwater extraction (permissible withdrawal).

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Conference Proceedings

1. Mistry, G., Kalra, A., and Ahmad, S., 2018, Financial management of a hypothetical water network using System Dynamics, ASCE. Environmental & Water Resources- World Water and Environmental Resources Congress, Minneapolis, MN.
2. Mistry, G., Stephen, H., and Ahmad, S., 2019, Impact of Precipitation and Agricultural Productivity on Groundwater storage in Rahim Yar Khan District, Pakistan, ASCE. Environmental & Water Resources- World Water and Environmental Resources Congress, Pittsburgh, PA.

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