ESTIMATION OF GROUNDWATER STORAGE CHANGE AND RECHARGE USING GRACE AND GLDAS DATA, FIRAT BASIN, TURKEY CASE

Master of Science Thesis

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MASTER OF SCIENCE THESIS

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This thesis titled " Estimation of Groundwater Storage Change and Recharge Using GRACE and GLDAS Data, Fırat Basin, Turkey Case" has been prepared and submitted by Obby Nawa LIKANDO in partial fulfillment of the requirements in "Anadolu University Directive on Graduate Education and Examination" for the Degree of Master of Science in Earth Science Department has been Examined and approved on 23/08/2019.

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ABSTRACT

ESTIMATION OF GROUNDWATER STORAGE CHANGE AND RECHARGE USING GRACE AND GLDAS DATA, FIRAT BASIN, TURKEY CASE

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Department of Earth Sciences
Anadolu University, Graduate School of Sciences, August 2019
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Groundwater plays an important role in the hydrologic cycle and it is one of sources of drinking water for about half the world's population. Groundwater is one of the main sources of water supply used for irrigation in agriculture and human consumption in Fırat basin. The groundwater water storage in Fırat Basin is mostly influenced by soil moisture, groundwater, snow water equivalent and plant surface water. In this research, the GRACE and GLDAS data sets are used, for 11 year period to estimate Terrestrial water storage and change over the Fırat basin on the Turkish side. Subsequently, the estimates are used to derive groundwater storage and to further estimate the groundwater recharge on the entire basin. The groundwater storage anomaly is obtained by subtracting the sum of the state variables of GLDAS from the Terrestrial water storage anomaly of GRACE. The groundwater recharge is estimated from time series of groundwater storage using water table fluctuation method. According to the estimated groundwater storage, the time series shows decreases in the groundwater at rate of -12.40 mm $year^{-1}$ in the entire basin. The averaged annual groundwater recharge in 11 year period over the entire Fırat basin was 279.26 mm $year^{-1}$. The annual recharge varies from 174 to 351 mm/year and 33 % can be explained by the variability in precipitation. And the correlation coefficient of annual recharge and precipitation is 0.33. Understanding the groundwater storage changes and groundwater recharge estimation are important in hydrological fields because this can lead to sustainable use of groundwater resources.

Keywords: GRACE, GLDAS, groundwater storage, water table fluctuation, groundwater recharge, Fırat Basin

ÖZET

YERALTISUYU DEPOLAMA DEĞIŞIMI VE BESLENIMININ GRACE VE GLDAS VERILERI ILE TAHMINI, FIRAT HAVZASI, TURKIYE ÖRNEĞI

Obby Nawa LIKANDO

Yer Bilimleri
Anadolu Üniversitesi, Fen Bilimleri Estitüsü, Ağustos, 2019
Danışman: Dr. Öğr. Üyesi Emrah PEKKAN

Yeraltı uyu dünya nüfüsünün yaklaşık yarısının içme suyu kaynaklarından biriyken hidrolojik döngüde de önemli bir rol oynamaktadır. Fırat Havzası'nda yeraltısuyu, tarımsal sulama ve insan tüketiminde kullanılan ana su kaynaklarından biridir. Fırat Havzası'ndaki yeraltısuyu depoları çoğunlukla toprak nemi, yeraltısuyu, kar suyu eşdeğeri ve bitki yüzey suyu değişiminden etkilenmektedir. Bu araştırmada, 11 yıllık GRACE ve GLDAS veri setleri, karasal su depolamasının tahmin edilmesi ve Türkiye tarafındaki Fırat havzasındaki yeraltısuyu değişimini tahmin etmek için kullanılmıştır.Elde edilen tahminler ile yeraltısuyunun depolamasını belirlemek ve tüm havzada yeraltısuyu beslenimi ile ilgili daha fazla bilgi elde etmeke için kullanılmaktadır. Yeraltısuyunun depolama anomalisi, GLDAS'ın durum değişkenlerinin toplamının GRACE'in karasal su depo anomalisinden çıkarılmasıyla elde edilir. Yeraltısuyu beslenimi, su tablası dalgalanması zaman serisi yöntemini kullanarak yeraltısuyu depolamasıyla tahmin edilmektedir. Tahmi edilen yeraltısuyu depolaması zaman serisine göre, havzanın tamamında -12.40 mm yıl^{-1} oranında azalma gözlenmektedir. Fırat Havzası'nda 11 yıllık ortalama yıllık yeraltı suyu beslenimi 279.26 mm yıl^{-1}'dir. Yıllık beslenim 174 - 351 mm yıl^{-1} arasında değişmektedir. Beslenimde ki bu fark incelenen süreçteki yağıştaki % 33 lük değişkenlikle açıklanabilmektedir. Yıllık beslenim ve yağış arasındaki korelasyon katsayısı 0.33'tür. Yeraltısuyu depolama değişikliklerini ve yeraltı suyu beslenmsini tahmin edebilmek, hidrolojik açıdan yeraltısuyu kaynaklarının sürdürülebilirliğini sağlamak açısından önemlidir.

Anahtar Kelimeler: GRACE, GLDAS, yeraltı suyu depolaması, su tabakası dalgalanması, yeraltı suyu şarjı, Fırat Havzası

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23/08/2019

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with "scientific plagiarism detection program" used by Anadolu University, and that "it does not have any plagiarism" whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

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INDEX OF ABBREVIATIONS AND SYMBOLS

ASCII	: The American Standard Code for Information Interchange
CHIRPS	: Climate hazards infrared Precipitation with Stations
CSR	: Center for Space Research
CU	: Colorado University
CWS	: Canopy Water Storage
CWSC	: Canopy Water Storage Change
DEM	: Digital Elevation Model
DLR	: Deutschen Zentrus für Luft-und Raumfahrt
GES	: Goddard Earth Sciences
GLDAS	: Global Land Data Assimilation System
GR	: Groundwater Recharge
GRACE	: Gravity Recovery and Climate Experiment
GSFC	: Goddard Space Flight Center
GWSA	: Groundwater storage anomaly
GWSC	: Groundwater storage change
ICGEM	: International Centre for Global Earth Models
LSM	: Land Surface Model
NASA	: The National Aeronautics and Space Administration
NetCDF	: Network Common Data Format
NOAA	: National Oceanic and Atmospheric Administration
SMSA	: Soil moisture storage anomaly
SMSC	: Soil moisture storage change
SRTM	: Shuttle Radar Topography Mission
SWE	: Snow Water Equivalent
SWEC	: Snow Water Equivalent Change
TWS	: Terrestrial water storage
TWSC	: Terrestrial water storage change

1. INTRODUCTION

The land surface processes in the Fırat (Euphrates) basin possess a great effect on the hydrology, climate, and social-economic aspects in Turkey. This region is the source of Euphrates river, the longest river in the Western Asia. The river originates in the mountains of eastern Turkey and discharge of this river is mainly controlled by permafrost and terrestrial water storage. The river flows in the southern direction and it is fed by small tributaries before crossing into Syria. The eastern region of the basin is characterized by dry, hot summers and cold, wet winters which is in the Mediterranean climatic zone. The mountainous region in the basin receives precipitation mainly in autumn, winter and spring.

In recent years, understanding the terrestrial water storage variability is really significant because it helps water resource managers to plan its utilization effectively without depletion. Therefore, In March 2002, the joint venture of the National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR) sent the satellite in space known as the Gravity Recovery and Climate Experiment (GRACE) with the purpose of measuring temporal variations in the gravity field on a monthly basis (Tapley, Bettadpur, Ries, Thompson, & Watkins, 2004). The GRACE satellite was launched into polar orbit about 500 kilometers above the earth's surface and it comprises two spacecraft that are identical, flying approximately 220 kilometers apart. Unlike other satellites, the separation between two satellites is monitored by a highly sensitive microwave ranging system as they traverse over areas with high and low gravitational pull.

The GRACE satellite is unique as compared to other Earth-observing satellites, it can sense all forms of water storage at different levels, though it has low spatial and temporal resolutions (Matthew Rodell, Velicogna, & Famiglietti, 2009). The time series gravity data acquired by the GRACE satellite can be accessed from numerous organizations. Some of the processing centers of GRACE time series gravity data are Center for Space Research (CSR), GeoForschungZentrum (GFZ), Jet Propulsion Laboratory (JPL), the data are either provided as a global grid of mass change or band-limited spherical harmonic coefficients to the public . Like any other basin, Fırat basin is affected by climate change, hence water resource must be managed efficiently. Therefore, improved methods must be employed in as far as estimating Terrestrial Water Storage (TWS) and the change (TWSC). In the past, observing terrestrial water storage on a global level was impossible until the launch of GRACE Satellite. In order to estimate TWS and TWSC, both GRACE and Global Land Data Assimilation System (GLDAS) data set are used. In this research, the above mentioned data sets are used, for 11 year period (2003 – 2014) to estimate TWS and TWSC over the Fırat basin on the Turkish side. Subsequently, the estimates are used to derive groundwater storage and to further estimate the groundwater recharge on the entire basin.

Groundwater is one of the main sources of water supply used for irrigation in agriculture and human consumption. The water supply has become scarce in some countries, hence understanding recharge processes is important in preservation. The estimation of groundwater recharge is one of the most important technique in the field of Hydrogeology. There are no direct methods to measure recharge, therefore, indirect techniques are used (Chemingui, Sulis, & Paniconi, 2015). There are various techniques used to estimate groundwater recharge (Scanlon, Healy, & Cook, 2002). Several hydrologists have been attempting to estimate recharge rates in order to predict the long term groundwater yield in the aquifer systems (Sanford, 2002).

The groundwater recharge can be divided into processes, natural and artificial. The natural recharge occurs when it comes from direct infiltration of water in nearby rivers, lakes and precipitation and artificial recharge result from human activities i.e. irrigation, urbanization, or propagation of rivers.

This thesis focuses on approaches for estimating groundwater storage change and recharge using water table fluctuation (WTF). The study was carried out in the Fırat basin of Turkey, where surface and groundwater have various uses. The Euphrates river that runs through the Fırat basin has several dams, used for electricity generation and agriculture irrigation (Tosun et al., 2007). In additional to estimating groundwater storage and recharge, this study will also demonstrate the reliability of using GRACE data in small basins. The utilization of GRACE for groundwater storage studies was validated in larger basin of 200, 000 km^2 and more, for example, in the Mississippi river Basin (Matthew Rodell et al., 2007).

1.1. General objective

The general objective of this research is to estimate groundwater storage change and groundwater recharge in the Fırat basin from 2003 to 2014.

1.1.1. Specific objectives

In order to achieve the general objective, the following specific objectives are set in this research.

- ❖ To estimate the terrestrial water storage and its changes in the Fırat basin from GRACE monthly gravity solutions.
- ❖ To estimate the terrestrial water storage and its changes in the Fırat basin from GLDAS land surface variables (soil moisture, snow water equivalent, canopy water).
- ❖ To compare the storage changes between GRACE TWSC and GLDAS estimated from surface variable.
- ❖ To calculate the groundwater storage from GRACE TWS and GLDAS land surface variables.
- ❖ To evaluate TWSC (GRACE & GLDAS), GWSC and its changes, with meteorological and hydrological variables.
- ❖ To estimate the groundwater recharge in the Fırat basin from the above calculated groundwater storage.

1.1.2. Research questions

With the above mentioned research objectives, research questions can be defined for this study.

- ❖ How can we observe the TWS and its variability in the Fırat basin from GRACE terrestrial water storage anomalies?
- ❖ How can we observe Global Land data assimilation system's surface state variables storage and its changes in the entire basin?
- ❖ Is there a similar trend between GRACE and GLDAS storage estimates and its changes in the study area?
- ❖ How can we calculate the groundwater storage from GRACE TWSC and GLDAS variables?
- ❖ How can we estimate the Recharge from groundwater storage derived from GRACE and GLDAS?

- ❖ Is the estimated groundwater recharge and precipitation comparable in Fırat basin?
- ❖ Is GRACE/GLDAS groundwater storage and Well observed groundwater level measurements and the change comparable?

1.2. Structure of the Thesis

The thesis is structured into seven chapters. In chapter 2, the Literature review, theoretical background of TWS measurement and previous works using GRACE and GLDAS is discussed. In chapter 3, the study area and data are describe in detail. Chapter 4 explains the research methodology and materials and brief description of the study area. In chapter 5, the results of the research and discussion are tabulated. Chapter 6, comprises the research conclusions. And the last chapter, which is chapter 7, includes references used in this study.

2. LITERATURE REVIEW

2.1. General

Terrestrial Water Storage (TWS) is the total water stored on surface and subsurface of land. It comprises groundwater, soil moisture and permafrost, surface water, snow and ice, and wet biomass (M Rodell, Famiglietti, & Connor, 2001). The water storage can be affected by changes in land parameters like, evapotranspiration, precipitation patterns and temperatures (Bovolo, Parkin, & Sophocleous, 2009).

Groundwater storage plays a fundamental role in the global water cycle. Therefore, it is prominent for the eco-system health, agriculture and management of water resources (Yeh et al., 2006). The surface water receives more attention globally because is visible and easily accessible. Most groundwater studies only reflect local estimates, monitoring on a regional scale requires an extensive network and currently such networks are nonexistent. Therefore, groundwater remote sensing holds a key to regional scale studies, but they only employ indirect measures of various aspects of groundwater hydrology (Becker, 2006). And groundwater recharge can also be estimated from the groundwater storage anomalies.

In the year 1971, E. L. Montgomery shows the potential of applying the relation between gravity and hydrology by estimating specific yield through a correlation between water level variation and gravity. Three years later, the U.S Geological Survey suggested the use of temporary gravity survey as a method in a Technique of Water Resource Investigations. Since the launch of GRACE satellite mission in 2002, scientific community found an easily accessible tool to use in Hydrology field. Numerous studies have been conducted with regard to the potential of using GRACE data in hydrology and some of these are mentioned in the next section.

2.2. Previous Works

The ability of GRACE to detect hydrological signals with accuracy was demonstrated by Rodell and Famiglietti as a pre-launch assessments (M Rodell et al., 2001). Thereafter, many post-launch studies have demonstrated the reliability of GRACE satellite to monitor water storage variations.

Ouma et al. (2015) used GRACE time-variable data and GLDAS-LSM for estimating groundwater storage variability in a small basin of Kenya. And the average results for 10 years showed that the TWSC from GRACE recorded an increase of 4.54 mm $year^{-1}$. From the GLDAS average, the TWSC recorded an average rate of loss of 5.18 mm $year^{-1}$. The difference in the trend was attributed to absence of groundwater in GLDAS-LSM which is the many contributors to the TWS. The overall results of the total storage water change and groundwater storage changes in the study showed close similarity and correlation with streamflow discharge, altimetry water and rainfall data.

Lenk (2013) estimated terrestrial water storage variability using GRACE Satellite data. The central Anatolia exhibited a significant decreasing trend, both the estimated TWS and groundwater storages at a rate of 4 cm $year^{-1}$. The satellite based groundwater variation estimates was compared with groundwater level measurements from well measurement in the southern Anatolia. The groundwater data also showed a decrease trend in agreement with the estimated.

Shamsudduha et al. (2012) conducted a study "Monitoring groundwater storage changes in the highly seasonal humid tropics: Validation of GRACE measurements in the Bengal Basin." The results showed a groundwater depletion in the Bengal Basin, estimated from In situ data ranging from -0.52 ± 0.30 km^3 $year^{-1}$ (wet season trends) to -0.8 ± 0.17 km^3 $year^{-1}$ (annual means). And the estimates derived from GRACE and GLDAS ranges -0.44 ± 1.24 to -2.04 ± 0.76 km^3 $year^{-1}$ (wet-season trend) and -0.52 ± 0.50 to -2.83 ± 0.42 km^3 $year^{-1}$ (annual mean trends), clearly these results are highly comparable.

Wahr et al. (1998) studied the hydrological and oceanic effects and their possible detection by utilizing GRACE satellite data. The conclusion of this study was that the monthly values of surface mass can be estimated by GRACE with accuracies of about 2 mm in the water thickness over land and 1 mbar in seafloor pressure.

Seo et al. (2017) demonstrated the reliability of GRACE satellite data by estimating total discharge in the Korean Peninsula. The total discharge estimates were validated with GLDAS LSM (CLM, Mosaic, Noah, and VIC) results and in situ discharge of five river basins in south Korea. The satellite based discharge were well correlated with LSMs with r values of 0.7-0.86.

Wu et al. (2019) determined the groundwater recharge on a regional scale using GRACE satellite data and GLDAS in the Ordos basin of the Chinese Loess Plateau. The study area covers about 640000 km^2, the estimated GR were compared with other recharge estimation methods. The results exhibited the following; The estimated annual groundwater recharge had a correlation coefficient of 0.42 against annual precipitation in the entire basin. The estimated average recharge (48.3 mm $year^{-1}$) was slightly greater as compared to the method of Henry et al (about 20 mm $year^{-1}$ difference). The estimated recharge's standard deviation (16.0 mm $year^{-1}$) and coefficient variation (33.1%) were comparable to other methods.

Huang et al. (2016) used the GRACE and GLDAS data set in mapping the groundwater variation in a case study of Alberta. In his study, he employed the Release 05 (RL05) monthly GRACE models spanning from April 2002 to October 2014. The Groundwater variation was derived by subtracting the four GLDAS models (Mosaic, Noah, VIC, CLM). However, an average model was obtained from the above models and subtracted from the TWS of GRACE to separate the groundwater storage anomaly. Groundwater variations were compared with 256 well data, thirty-six wells showed a good correlation with the estimated GWS variations. The correlation ranged from 0.72 – 0.74 with GWS variation which signifies that the GLDAS models are realistic for groundwater storage estimation.

Voss et al. (2013) studied the groundwater depletion in the Tigris – Euphrates western Iran region. Groundwater storage was calculated by subtracting surface water, snow water equivalent, soil moisture components from the total water storage of GRACE. The results showed a clear decline in the groundwater storage after 2007, and the trend was estimated to be -17.3±2.1mm $year^{-1}$, -91.3±10.9 km^3 for the whole study duration. The research stated that the year 2007 was predominantly a year of drought, this was also reflected in the groundwater storage showing a declining trend.

2.3. GRACE Observation of Terrestrial Water Storage

The GRACE satellite mission was launched into space on the 17th March, 2002, and it is sponsored by NASA and DLR (German Aerospace Center) under the NASA Earth System Science Pathfinder Program (Cazenave & Chen, 2010). It consists of two satellites chasing each other, also called Tom and Jerry, they are flying in polar orbit at 400-500 km attitude and with a separating distance of about 200 km.

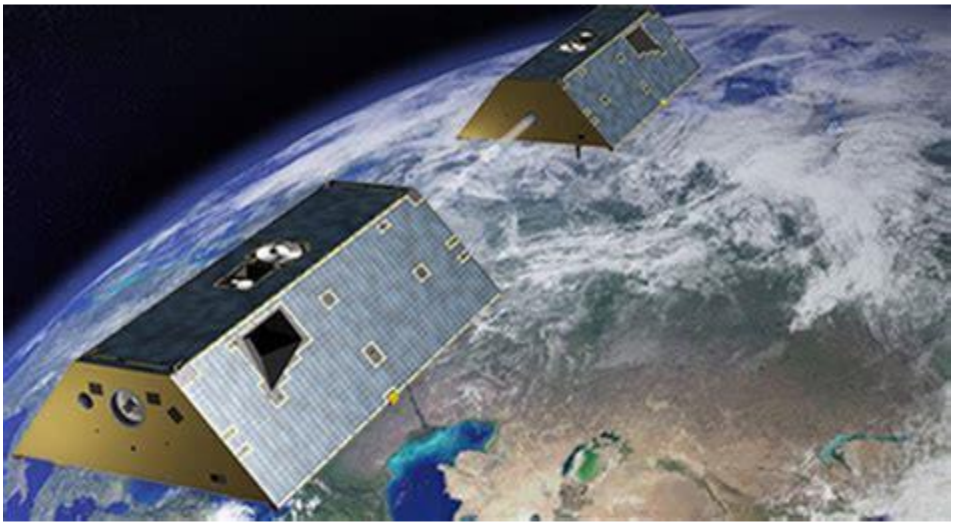


Figure 2.1: *The Gravity Recovery and Climate Experiment twin satellite orbiting the Earth at 500 km altitude. (source; https://grace.jpl.nasa.gov/mission/grace-fo/)*

The satellite measures the variations in the Earth's gravity. When the gravitational pull increases in an area to be mapped, the leading satellite accelerates before the second one reaches the same area, and catches up later hence maintaining 200 km distance apart. It can be noted that the gravity variations induces the distance variations between the two satellites (Strassberg, Scanlon, & Chambers, 2009). The primary causes of gravitation variations are the changes in the ice masses, hydrology or surface deformation (Khaki et al., 2018). The GRACE data has the capacity to show the changes in the water, on or near surface of the earth, whether in a liquid or solid state (M. Rodell, Chao, Au, Kimball, & McDonald, 2005).

The GRACE mission has provided an effective way to track the movement of water and it gives us an initial view of the aquifers from space (R. Huang et al, 2018). The mission provides data in the form of maps, acquired at approximately one month time intervals. The measured Earth' gravitational field can be used to infer the mass anomalies (Crowley, Mitrovica, Bailey, Tamisiea, & Davis, 2006).

The changes in the gravity on land are mainly attributed to variation in TWS. The terrestrial water storage (TWS) is a vertically integrated water storage comprising of surface water, snow and ice water, soil moisture, groundwater, and vegetation water (Strassberg, Scanlon, & Rodell, 2007b).

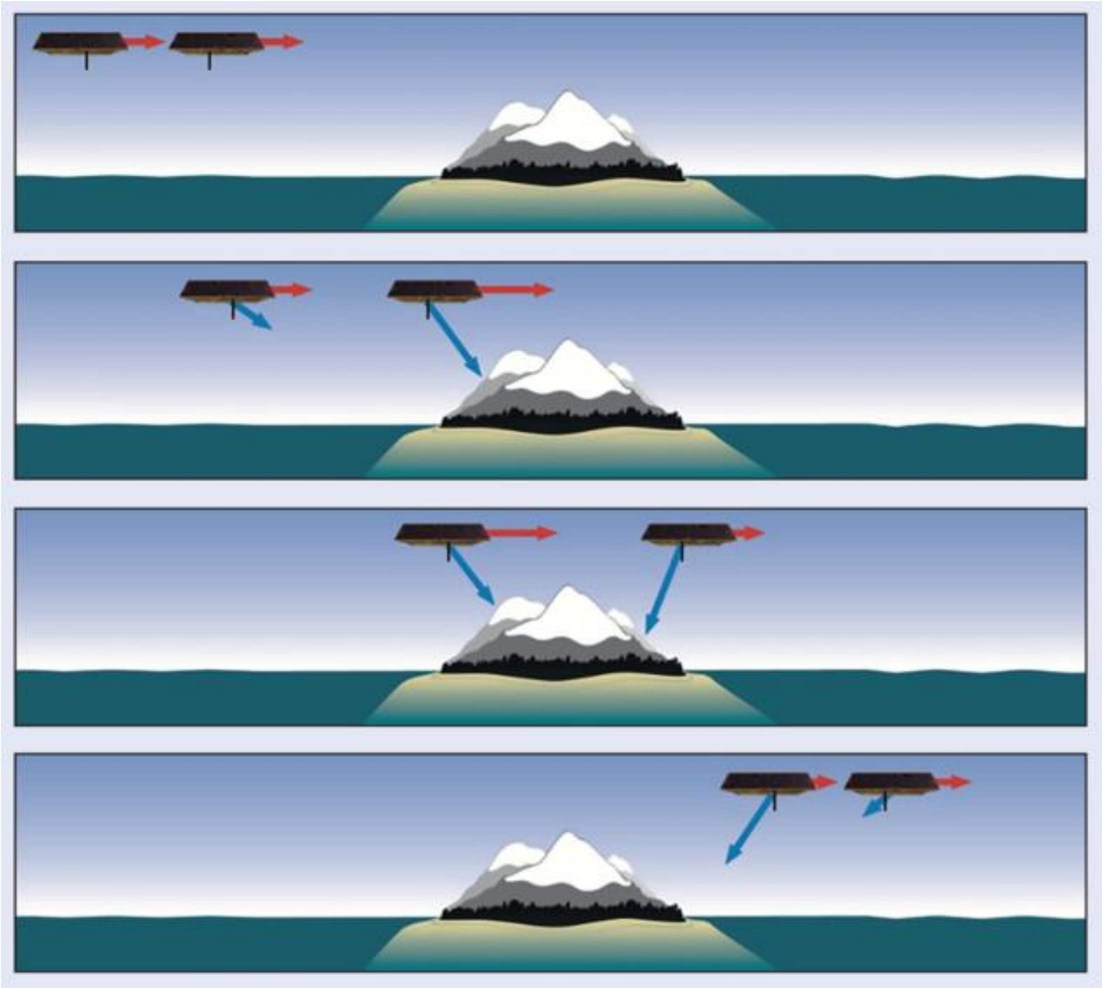


Figure 2.2: *Showing the Twin satellite measuring changes in the gravitational pull (blue arrows) on the two crafts due to Earth's mass changes. (Adopted from NASA/JPL-Caltech).*

The twin satellites carry a microwave range finders whose purpose is to monitor the distance between the two crafts with extreme precision, while providing the feedback to the ground station up five times a day. The GRACE satellite is not like other satellites that uses radars or radiometers to the wavelength of light, which are emitted or reflected from the Earth (Matthew Rodell et al., 2009). The GRACE system has no sensors to observe the Earth, instead it measures the distance between two identical crafts that orbits the Earth by using a highly sensitive K-band microwave ranging system (Tapley et al., 2004).

The Earth's gravity field is mostly described as geoid shape and are disseminated as a sum of spherical harmonics numerically (Yeh, Swenson, Famiglietti, & Rodell, 2006). The GRACE gravity data set is each represented as a set of spherical harmonic coefficients (Crowley et al., 2006). The coefficient can be accessed as a level 2 product. In order to remain with hydrological components, the non-hydrological gravitational parameters are removed from the level 2 product on the basis of a numerical model, including solid Earth tides, oceanic and atmospheric circulation (Yeh et al., 2006).

The Gaussian averaging kernel width is applied to smoothen the spherical harmonic coefficients in order to generate the high quality spatial map of TWS anomalies (Cazenave & Chen, 2010). The filtering of GRACE product affects the spatial resolution and destroys the original signal, hence the scientist have developed methods to repair the signal damage (Vishwakarma & Devaraju, 2018) The Terrestrial water storage anomalies is usually presented in cm as equivalent water height (Wahr, Swenson, Zlotnicki, & Velicogna, 2004). The GRACE temporal variation in the gravity data set is used in different studies by various disciplines (e.g. monitoring water changes, snow and ice storage changes on land surfaces). They are several researchers that used GRACE data to estimate groundwater storage changes (Ouma et al., 2015), terrestrial water storage (Zhao & Li, 2017), drought monitoring (R. Huang et al., 2018) and groundwater recharge (Chinnasamy, Maheshwari, & Prathapar, 2015).

2.4. GLDAS Land Model

The Global Land Data Assimilation System (GLDAS) was developed by the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NSEP) through a joint venture (B. Y. M. Rodell et al., 2004). The soil moisture is very important in the study of water resources because it controls a different number of processes such as biogeochemical, ecological, hydro-climatological, hydro-meteorological on various spatial and temporal scale (Chen et al., 2013).

The GLDAS data has be used by a lot of researchers to study the unsaturated zone storage in areas where in situ measurement are unavailable. In this research the GLDAS NOAH data set was used to obtain the state variables (i.e. soil moisture, snow water equivalent, canopy water). It incorporates satellite acquired and ground based data into the modeled land surface to generate the state variables and flux variables (B. Y. M. Rodell et al., 2004). The Global land surface fields provided by GLDAS is mostly used in estimation of terrestrial water storage changes, weather and climate prediction and in water resource applications (Ferreira, Andam-akorful, He, & Xiao, 2014).

In the past years, several Land Surface Models (LSM) were developed with the purposes of simulating the transfers of energy, momentum and mass between the atmosphere and Land surfaces. The examples of LSMs include the Community Land Model (CLM), GLDAS Mosaic, Noah,, Variable Infiltration Capacity (VIC), and the Catchment Land Surface Model (Koster, Suarez, Stieglitz, & Goddard, 2000). The higher increase in innovation and improvement of concept in Physics resulted in an improved capability of simulating the LSMs with high resolution. The GLDAS data version is the monthly 1-degree by 1-degree on the global gridded with various storage components (Tangdamrongsub, Ditmar, Steele-dunne, Gunter, & Sutanudjaja, 2016). The estimated TWS from GLDAS is the sum of the four soil layers, total canopy water and snow water equivalent.

The calculated TWS from the GLDAS state variables is used to isolate the groundwater component from the total water storage of GRACE (Famiglietti et al., 2011).

3. STUDY AREA AND DATA DESCRIPTION

3.1. Study area

Turkey is geographically located in southeast of Europe with an approximation of 77.95 million ha of land cover. About 28 million ha of the area is categorized as cultivable land. Turkey consists of 26 basins and Fırat (Euphrates) basin yields about 31.6 km3 of water resource per year (Tosun et al., 2007). The Euphrates river is the main river in the basin, which arose from Karasu and Murat tributary rivers. It is estimated to be 2800 km in length and meets Tigris river in Iraq.

The study area for this research in Fırat Basin, which is the catchment of the Euphrates river and it is located in the eastern side of Turkey as shown in figure 3.1. The study area is located between 4090840.928 to 4875905.115mE and 4361741.211 to 4886682.455mN with an approximate area of 199,850 km^2. The study has an elevation ranging from 312 m to 4032 m above sea level. The surface water flows from the high altitude regions to the lower ones in the southern direction.

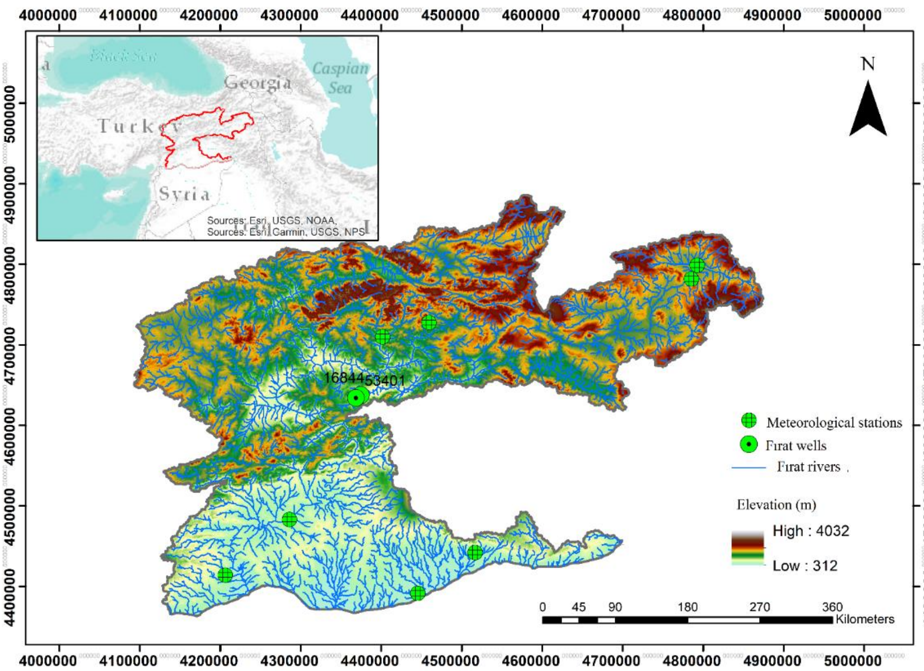


__Figure 3.1:__ The location of the study area (Fırat basin in Turkey)

3.2. Geological setting and Structural geology

The Fırat basin is located in a region comprising a very complex geology and also dominated by active seismic activity. The detailed mapping of this region was carried out by Brinkman (2009). The oldest rock formation in this region is of Precambrian age consist of metamorphic schist, are mostly located in the middle of the basin. The younger rock formation in this basin consists of sedimentary rocks i.e. limestone, mudstone, marl, and shale. The quaternary aged unit includes volcanic, sedimentary rocks and recent deposits of alluvium which are mostly found along river banks and lakes. These alluvium deposits consist of clay, silts, sand and gravel layers. The stratigraphic units found in Fırat basin ranges from permo-Triassic Keban Metamorphites to Plio-Quaternary Palu Formation (Kalender & Aytimur, 2016).

The Keban Metamorphites outcrops are mainly observed along the banks of the Euphrates river. On a regional scale, the Keban Metamophites comprise marbles, recrystallized limestone, metaconglomerate, calc-schist, and calc-phyllite in Fırat basin (Kalender & Hanelci, 2004). The Upper Cretaceous Elaziğ Magmatic Complex is composed of various types of volcanic and plutonic rocks. In the basin, the recrystallized limestone of permo-Triassic Keban Metamorphites overlies the magmatic rocks (Mehmet Turan, Aksoy, & Bingol, 1995). The simplified geological map of the study area is shown in figure 3.2.

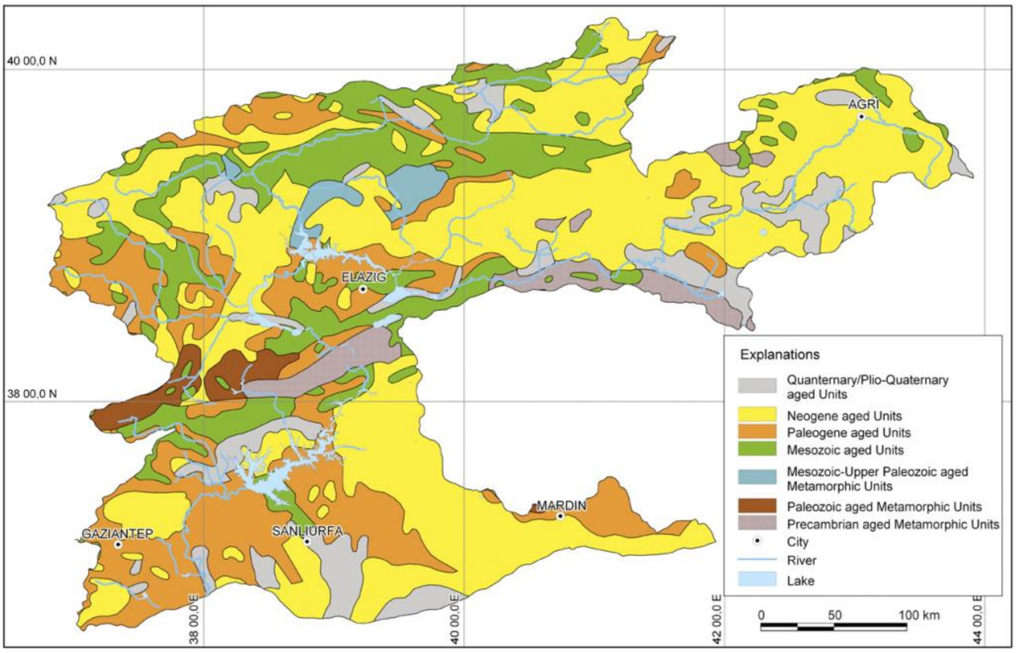


Figure 3.2: *The geological map of Fırat basin* (Tosun et al., 2007).

The southeast Anatolian ophiolite belt consists of the Late Cretaceous Kömürhan Ophiolites, which are formed as the result of suprasubduction activity in the southern Neo-Tethys (Beyarslan & Bingol, 2010). The Upper Paleocene and Lower Eocene massive limestones, are referred to as Seske Formation. This formation is mainly characterized by carbonate and interbedded clastic rocks. The Seske formation is observed around the Karakaya Dam Lake. The andesitic and basaltic rocks and limestone, conglomerates, sandstones, and marl made up the Middle Eocene Maden Complex (Yilmaz, Yiğitbaş, & Genç, 1993). And the Middle Eocene Kırkgeçit Formation is composed of marls, marine Conglomerates, limestone (M Turan & Bingöl, 1991).

The conglomerate is at the bottom, followed by marls and on top is the limestone. Another formation found in the basin is the Alibonca Formation, which was deposited after closure of Neo-Tethys Ocean in Mesozoic time period. The unit is made up of sandy limestone and marls, they are mainly observed in the Keban Dam Lake area (Türkmen, Aksoy, Kürüm, Akgül, & Inceöz, 1998). Figure 3.3 shows the structural features, seismic zones and earthquake occurrences in the basin. The fault structures also acts as pathways for groundwater recharge.

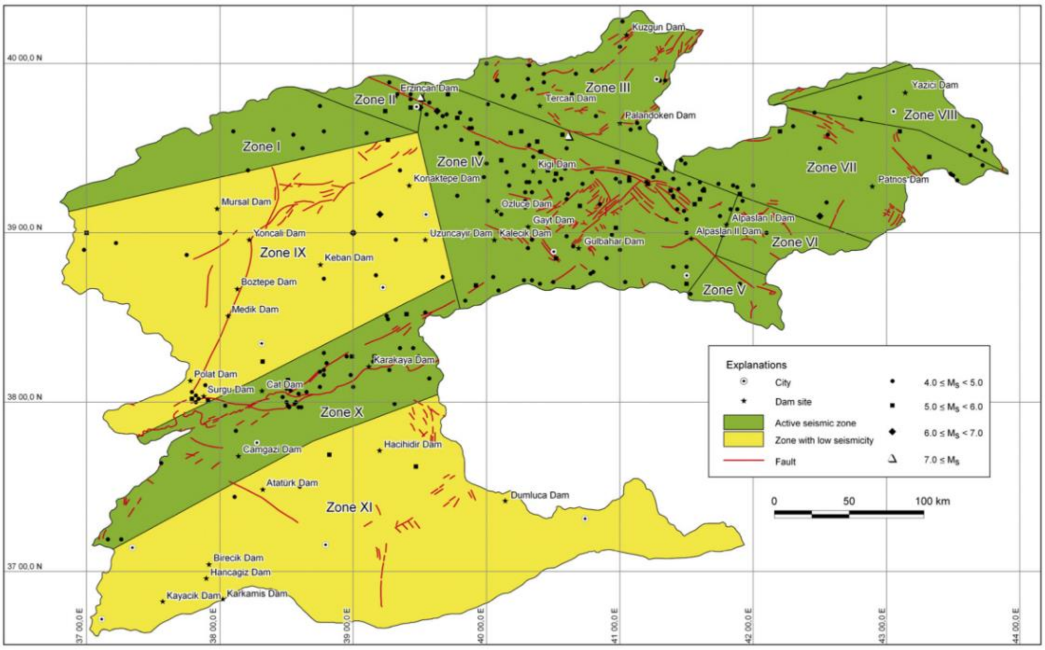


Figure 3.3: *The structural features, seismic zones and earthquake occurrences in Fırat basin for a 100 year period .*

3.3. Description of data

In this research two data types were utilized. All these data cover the duration of 11 years from 2003 to 2014.

3.3.1. Gravity recovery and Climate Experiment (GRACE)

The remotely sensed data include GRACE satellite data and can be divided into 3 levels.

3.3.1.1. Level-1 Data Products

This product comprises of two distinct data products, namely level-1A and level-1B. The level-1A Data Product is formed after applying a non-destructive processing to the level-0 data which is the raw data acquired by the satellite. The level-1A Data can be reversed to level-0, only in the cases of bad data packets. The level-1A Data Product also has the ancillary data product which is essential for further processing to the subsequent data level. The level-1B Data Product results after applying a possibly destructive or non-reversible processing on both level-0 and level-1A data. The jointly processing of the level-0 data, to level-1B is referred as Level-1 Processing. This level product also contains the ancillary data product generated while processing, as well as additional data which is vital for further processing. The accessibility of level-1A is constrained to the public.

3.3.1.2. Level-2 Data Products

The level-2 Data Product consist of gravity fields and other related data derived from processing level-1B Data Product. The spherical harmonic coefficient is the form in which the data product is presented (i.e. a monthly gravity field estimate). The level also has the ancillary data products created through processing. This data product is free and accessible to the public (Wei, 2011).

3.3.1.3. Level-3 Data Products

Unlike the level-2 Data product, the level-3 data is very convenient for users that are not familiar with the concept of spherical harmonics which require some complex processing and analysis. The Level-3 Data Product is distributed to the public as the water layer (mass anomalies). There are certain standardized products and tools that are available to the users for visualization and processing. A numerous GRACE data users, collectively put together resources to create and distribute value-added products from GRACE data products and these are GRACE Tellus, CU, Boulder and ICGEM. The products like GRACE Tellus have enabled users to access the time series of mass anomalies in raster format. CU, Boulder works as a tool to calculate error-corrected mass anomalies on a smaller or larger scale. ICGEM offers software resources and tools to calculate physical geodetic and also in the distribution of static Earth gravity model.

The GRACE Tellus Land data product release05 (RL-05), processed by the Center for Space Research (CSR) at the university of Texas, is utilized (Tangdamrongsub et al., 2016) . This is the latest version of GRACE released by CRS. The Gaussian filter has been applied to this data product, which is a 300 km wide. However, the land grid scale has not been applied, users must scale the data before use. The figure 3.4 shows the variables that compose the GRACE Terrestrial water storage.

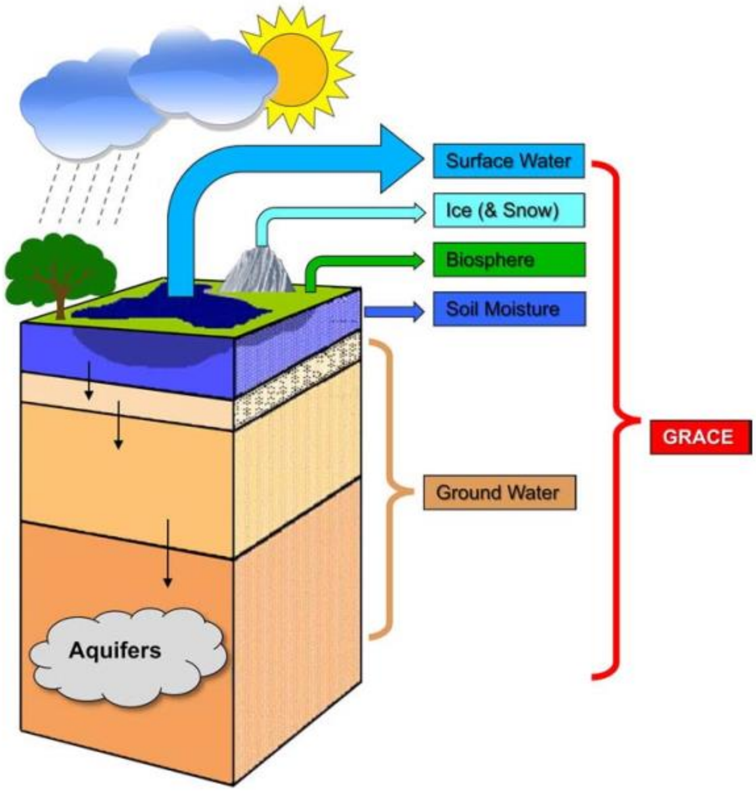


Figure 3.4: *The variables of GRACE Terrestrial water storage* (Cazenave & Chen, 2010)

3.3.2. Climate Hazards Infrared Precipitation with Stations (CHIRPS)

CHIRPS was developed to aid the United States Agency for International Development Famine Early Warning Systems Network (FEWS NET). Unlike other satellites such as NOAA that relies on thermal infrared precipitation products, the calibration of global Cold Cloud Duration (CCD) rainfall estimates in CHIRPS is executed by the Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis version 7 (Huffman et al., 2007).

The data is available to ftp://chg-ftpout.geog.ucsb.edu/pub/org/chg/products/CHIRPS 2.0/global_monthly/. The CHIRPS uses the already existing methods to evaluate and interpolate Precipitation with a high resolution based on infrared Cold Cloud Duration (CCD) observation, over a long period of time. CHIRPS produces unique products by incorporating stations in a two phase process (Funk et al., 2015). The initial rainfall product with 2 day latency is produced in the first phase. The World Meteorological Organization's Global Telecommunication System gauges, data are merged with CCD derived rainfall estimates at every pentad.

In the second phase, the final product is produced with 3 week latency. In this phase the best available monthly station data are combined with monthly high resolution CCD acquired rainfall estimates to yield the similar gridded monthly station products like that of the Global Precipitation Climatology Center (GPCC). The figure 3.5 shows CHIRPS process and validation.

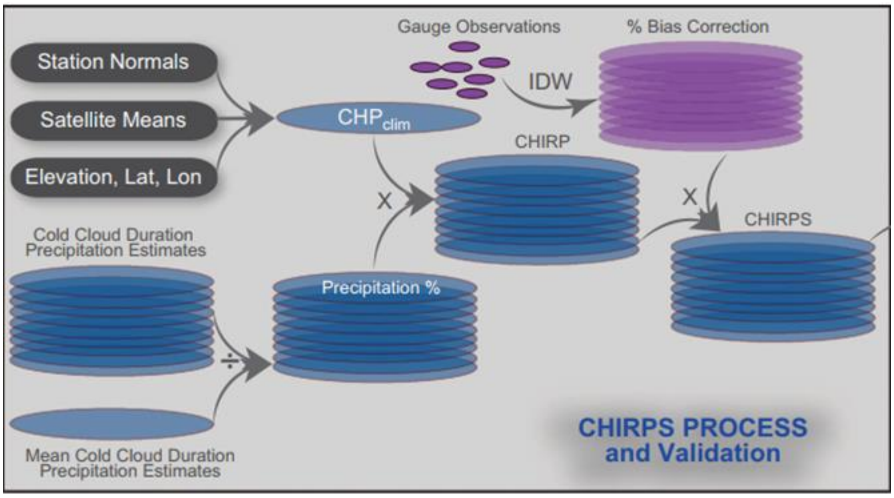


Figure 3.5: *The processing and validation of CHIRPS (Funk et al., 2015)*

3.3.3. Global Land Data Assimilation System

The NOAH land surface model data set used were obtained from http://mirador.gsfc.nasa.gov/, with 1 degree by 1 degree spatial resolution and a temporal resolution of 1 month. The data was distributed to the public by Goddard Earth Science (GES) Data and Information Services Center (DISC) in Network Common Data Format (netCDF), however, it was acquired by NASA's Earth Science Division (Chinnasamy & Agoramoorthy, 2015). The data downloaded encompasses the Fırat Basin over the period of January 2003 till December 2014. The GLDAS NOAH data set can be accessed by any individual at "DISC.SCI" website and its free. The GLDAS state variables used in this research are the total soil moisture, snow water equivalent, canopy water, which consist of 4 layers with the total depth of 200 cm**.** The unit of these data sets is Kg/m^2.

4. MATERIALS AND METHODOLOGY

4.1. Materials

In this research remote sensing data, land surface model and observation wells were used. The Terrestrial Water Storage form 2003 to 2014 are provided by GRACE satellite. And the state variables are provided by GLDAS model. The precipitation data are provided by CHIRPS and temperatures by Meteorological Department of Turkey. Different tools are used in processing the data sets.

4.1.1. Satellite data

GRACE level 3 data product with 1 degree by 1 degree spatial resolution was used. Terrestrial water storage of this data is from 2003 to 2014. The data consist of monthly TWS anomalies and it is derived from spherical harmonic data with an order and degree up to 60. The Gaussian smoothing radius had already been applied to the downloaded data, which was at a half-width equivalent to 300 km, therefore, further smoothening is not required.

The Shuttle Radar Topography Mission (SRTM) provides the Digital Elevation Map (DEM) of the entire globe, the data set can be downloaded from http://srtm.csi.cgiar.org/. The data can be accessed in either ArcInfo ASCII and GeoTiff formats. In this research a GeoTiff format of DEM was downloaded in order to delineate the basin of the study area. The DEM has a resolution of 90 m, mosaiced in 5 deg * 5 deg and provided in WGS84-datum geographic coordinate system. The downloaded GeoTiff format data is imported in ArcMap for processing. The data in and around the study area are extracted, the hydrology tools under Spatial Analyst Tools are used for drainage, basin extraction. The created Basin polygon is used for masking in the processing of data.

4.1.2. GLDAS Model data

The 'wget' software is used to download the Global Land Data Assimilation System (GLDAS) from January 2003 to December 2014. In each monthly GLDAS data constitute 25 variables. The data covers from 60 deg S to 90 deg N on the world map. The state variables (soil moisture, snow water equivalent, canopy water storage) are all derived from these files. The extraction of the state variables is done by the Panoply netCDF viewer which is available at https://www.giss.nasa.gov/tools/panoply/download/.

Table 4.1: *GLDAS land surface variables used in the research.*

No.	GLDAS State Variables	Unit	Symbol	Sampling
1	Four layer Soil Moisture	Kg/m^2	SMSA	Monthly mean
2	Snow Water Equivalent	Kg/m^2	SWE	Monthly mean
3	Plant Canopy Surface water	Kg/m^2	CWS	Monthly mean

4.1.3. Ground Observation data

In this research two in situ measured types of data was used, namely the temperature and groundwater level data. The monthly temperature data were obtained from the Turkish State Meteorological Services. The temperature data consist of monthly maximum and minimum temperature from 2003 to 2014. The data were obtained from 10 precipitation stations, the stations fall within the Fırat basin and outside. The groundwater level data were obtained from Turkish General Directorate of State Hydraulic Works. The institute was established in December 18, 1953 under the Ministry of Energy and Natural resources. The main purpose of this institute is to develop water and land resources in Turkey. Its mandate covers planning, design, construct and operate dams, hydroelectric power plant, domestic water and irrigation schemes. The study area has a limited number of observation boreholes, hence the groundwater level data used are from boreholes within the basin. The monthly well measurements from well 53401 and 16844 are used from 2003 to 2014 (Figure 3.1).

4.1.4. Processing tools

- Open Office
- Ilwis
- ArcGIS
- Panoply netCDF viewer software
- Excel
- Wget an open source network utility to retrieve files from the World Wide Web.

4.2. Methodology

4.2.1. General

The most common method to measure Terrestrial Water Storage (TWS) and its changes is by use of in situ measurements like soil moisture stations, boreholes, and lake level measurements. These methods have a good accuracy, but are costly to be executed in a network of measuring station on the regional level. In order to study the terrestrial water storage and its changes on a regional scale, GRACE and GLDAS data used. The GRACE TWS data is composed of surface water, groundwater, soil moisture, permafrost, snow and ice and canopy water (Biomass) (M Rodell et al., 2001). And GLDAS NOAH model provides storage values of various land state variables and fluxes.

In this research, the estimated TWSC will be compared with the SMSC of GLDAS data. However, it is not possible to validate the GRACE and GLDAS data due to large spatial coverage. GRACE monthly surface mass anomaly values are used to compute the TWS anomalies and averaged over the Fırat basin. The other storage components averaged over Fırat basin are GLDAS surface state variables. Therefore, for the purpose of comparison and studying the trend, meteorological and hydrological data are employed. Later on the GWSC is computed from the TWSC and SWSC.

The methodology flowchart is shown in the figure 4.1.

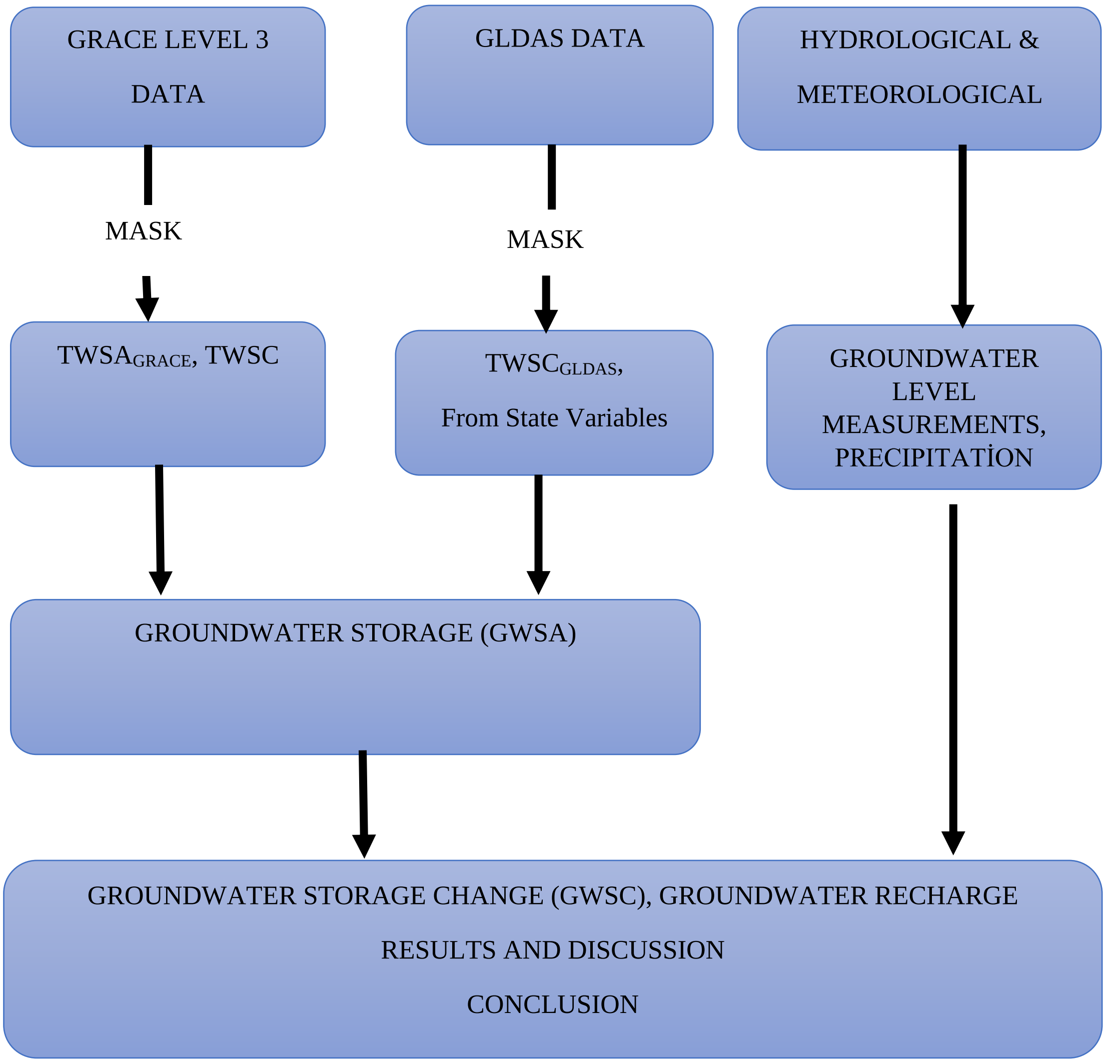


Figure 4.1: *The methodology flow chart of this research*

4.2.2. Data preparation for masking

The global GRACE monthly mass anomalies are downloaded, but they are in form of 1 degree by 1 degree regular grid shape in ASCII format. Each point represents the central point average over the 1 degree grid. The GRACE monthly mass anomalies are filtered using excel. The reason for filtering is to remove the unwanted data and to keep 1 degree by 1 degree regular grid shape over the area of interest. However, this process is not necessary for GLDAS dataset. The data format of GLDAS surface state variables is also ASCII and are 1 degree by 1 degree regular grid shape. Therefore, both the dataset is converted into "dbf" format using open office. Further on, the "dbf" files are converted into point map using Ilwis software. Lastly, these point maps are extracted into "Arcview shape file", a format supported by ArcMap for further processing of the data.

4.2.3. Data masking for the study area

All the converted data sets are imported into ArcMap for processing. In order to mask the previously explained data set for the Fırat Basin the following procedure is used:

- ❖ Point map 1 degree by 1 degree grids of GLDAS and GRACE data sets are crossed with the Fırat Basin shape file.
- ❖ The 1 degree by 1 degree point map is converted into a raster map by inverse distance weighting method.
- ❖ The "Extract by mask" tool is used to extract the raster maps created from GRACE and GLDAS data over the Fırat Basin using Fırat shape file, for each month.

4.2.4. Terrestrial Water Storage Change from GRACE

GRACE provides an indirect estimate of mass anomalies near the Earth's surface by measuring temporal variation in gravity field, which can be used to estimate changes in TWS. The monthly mean terrestrial water storage anomalies are provided as equivalent water height in GRACE level 3 product. The data used in this research is the Release-5 of (GRACE-RL05) averaged from January 2003 to December 2014. The GRACE-RL05 is the latest data product processed by the CSR and it is more accurate than previously released products (Bettadpur, 2012). The signal in this data can be attributed to changes in soil moisture, groundwater and surface water. The masking technique is used to study the water storage variation in the study area.

GRACE data is vital to long-term variation and month-to-month variation study of terrestrial water storage. The month to month variations in water are estimated from the GRACE terrestrial water storage as the difference between the two observations. And these two distinct observation points are measured with an interval of approximately 30 days. The TWSC estimate is an average change in TWS from one month to the other consecutive month (Syed, Famiglietti, Rodell, Chen, & Wilson, 2008). In this research the TWSC estimates from GRACE is calculated from the equation 4.1. The short time variation in Terrestrial water storage can be understood by TWSC. However, this method of subtraction two months to estimate TWSC increases the uncertainty of TWS by $\sqrt{2}$ times (Matthew Rodell et al., 2004).

$$TWSC_N = TWS_N - TWS_{N+1} \qquad \textbf{4.1}$$

Where: TWS is terrestrial water storage and N indicates the GRACE measurement period or month.

The components of the water balance are summed up as shown in equation 4.2, it is based on the principle that the flow in and flow out of the system must always balance.

$$TWSC = GWSC + SWC + SMSC + SWEC + CWSC \qquad \textbf{4.2}$$

Where TWSC denotes the terrestrial water storage change, GWSC is the change in groundwater storage, SWC is the change in surface water, SMSC is the soil moisture storage, SWEC is the snow water equivalent and CWSC is the canopy water storage change.

The Surface water component in GLDAS-LSM is considered as the intersection of the water table and land surface (Winter, 1999). However, the surface water is omitted from the equation because it is considered as the extension of the groundwater except in flood situations.

The GRACE measurements are taken nearly at monthly intervals. Therefore, for missing monthly measurements like June 2003, the values can be estimated using a simple averaging of two months. The linear interpolation method is used to estimate values from previous and next months of the required month as shown by equation 4.3 (Landerer, Dickey, & Güntner, 2010).

$$TWS_N = \frac{1}{2}[TWS_{N+1} + TWS_{N-1}] \quad 4.3$$

Where TWS_N is the TWS of Month N with missing measurement values, TWS_{N-1} is the TWS For the previous month of known measurements, TWS_{N+1} is the *TWS* for the next month with known measurement values.

4.2.5. Estimation of Terrestrial Water Storage Change from GLDAS

In this research, GLDAS 1 degree by 1 degree, monthly NOAH land surface model are used in the Fırat Basin. GLDAS land surface state variables (soil moisture, snow water equivalent and canopy water storage) can be used to compute the TWSC for an Area. However, TWSA at monthly or longer timescales is likely to be dominated Soil moisture and GWSA in the Fırat Basin. The other components have negligible effect on Terrestrial water storage. And the interannual variations in biomass were shown to be negligible (M. Rodell et al., 2005).

The Terrestrial water storage change is calculated as shown in equation 4.4.

$$\mathbf{TWSC_{GLDAS} = SMSC + SWEC + CWSC} \quad \mathbf{4.4}$$

Where, *TWSC* is the change in total water storage, SMSC is change in soil moisture change, SWEC is change in snow water equivalent change and CWSC is the change in canopy water storage (Biomass).

4.2.6. Estimation of Groundwater Storage

The Terrestrial water storage in Fırat Basin is mostly influenced by soil moisture, groundwater, snow water equivalent and plant surface water. Hence, the GWSA for any basin can be calculated as shown by equation 4.5, using the method of K. W. Seo, (2006). The GWSA is obtained by subtracting the sum of the state variables from the TWSA of GRACE (Feng, Shum, Zhong, & Pan, 2018).

$$\mathbf{GWSA = TWSA_{GRACE} - (SMSA + SWE + CWS)} \quad \mathbf{4.5}$$

Therefore, equation 4.6 can be manipulated to calculate the GWSC:

$$\mathbf{GWSC = TWSC - (SMSC + SWEC + CWSC)} \quad \mathbf{4.6}$$

4.2.7. Estimation of Groundwater Recharge

The water table fluctuation method was developed around 20th century for groundwater recharge estimation from groundwater table fluctuation and since that time, the application of this method has been popular among researchers. Groundwater recharge rate can be computed by multiplying the change in head over a specific time interval by specific yield;

$$\mathbf{R = S_y \frac{\Delta h}{\Delta t}} \qquad \textbf{4.7}$$

Where R is GR with units in (mm year^{-1}), h is the height of the water table in (mm), and S_y is the specific yield in (%).

The Water table Fluctuation method is more advantageous over other methods because it requires no assumptions on the movement of water through the unsaturated zone. It can be applied to different recharge mechanisms such as direct recharge from irrigation or precipitation, or indirect recharge from flood channels (Healy & Cook, 1979).

In this study, WTF method is used to estimate total groundwater recharge. The period during which the total recharge exceeds the steady-state is referred as a recharge episode (Nimmo, Horowitz, & Mitchell, 2015).

They are two types of WTF methods, the difference between the two is the inclusion of the unrealized recession. The recession processes such as evaporation, discharge to rivers continues as the water table rises due to recharge. In order to obtain the total recharge from the curve, an assumption can be made that the unrealized recession is negligible, the second way is estimating and correcting it for every episode, the third approach utilizes the functional relationship between the water level and the decline rate (Nimmo et al., 2015).

But, $\Delta GWSA = S_y \times \Delta h$, Therefore, the total recharge can be calculated from the graph by equation 4.8:

$$R = \frac{\Delta GWSA}{\Delta t} = \frac{Sp - Sl}{\Delta t} \qquad 4.8$$

Where S_P is the peak of the rise and S_l is the GWSA extrapolated from the antecedent curve to the time of peak.

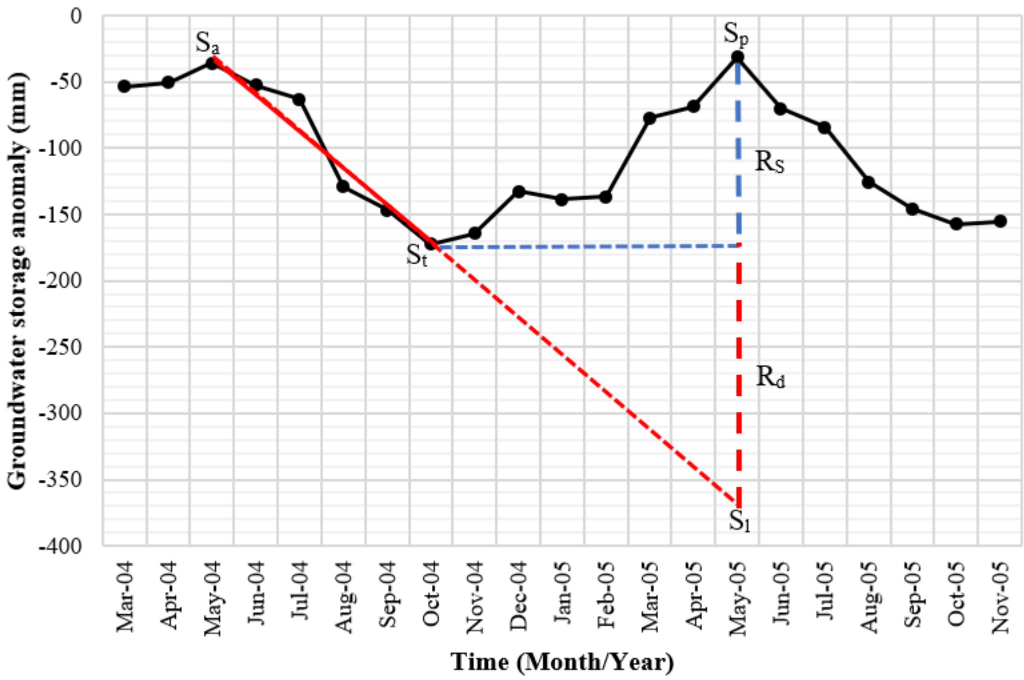


Figure 4.2: *The conceptual diagram showing the groundwater storage anomaly (GWSA) from 2004/03 to 2005/11 and the proposed method for groundwater recharge estimation.*

The calculated recharge is the sum of the recharge that balances the discharge (R_d) and the recharge due the increase in the water storage (R_S).

The antecedent recession curve obtained by fitting a line on the GWSA curve from the peak in the previous year at Sa to the trough of decline St, and then obtain the linear equation was extrapolated to the time of the peak (Sp -Sl) as shown in figure 4.2. The unrealized recession is represented as the dash line from St to Sl.

5. RESULTS AND DISCUSSIONS

5.1. Terrestrial water storage and its change from GRACE

Area averaged monthly mean of eleven years of GRACE terrestrial water storage is plotted for Fırat Basin in figure 5.1. The linear trend line fitted to the time series by least square estimate method shows an overall decrease in the TWSA at a rate of -13.37 mm $year^{-1}$. The 6 order polynomial trend fitted to the data shows a gradual increase in the anomaly values from 2004 to 2006, afterwards a decline in TWSA is observed from 2007 to 2008, another increase is in water mass anomaly is observed from 2009 to 2013 and a further decrease in 2014. From the time series, it can be seen, there is an overall depletion in the terrestrial water storage in the entire Fırat basin.

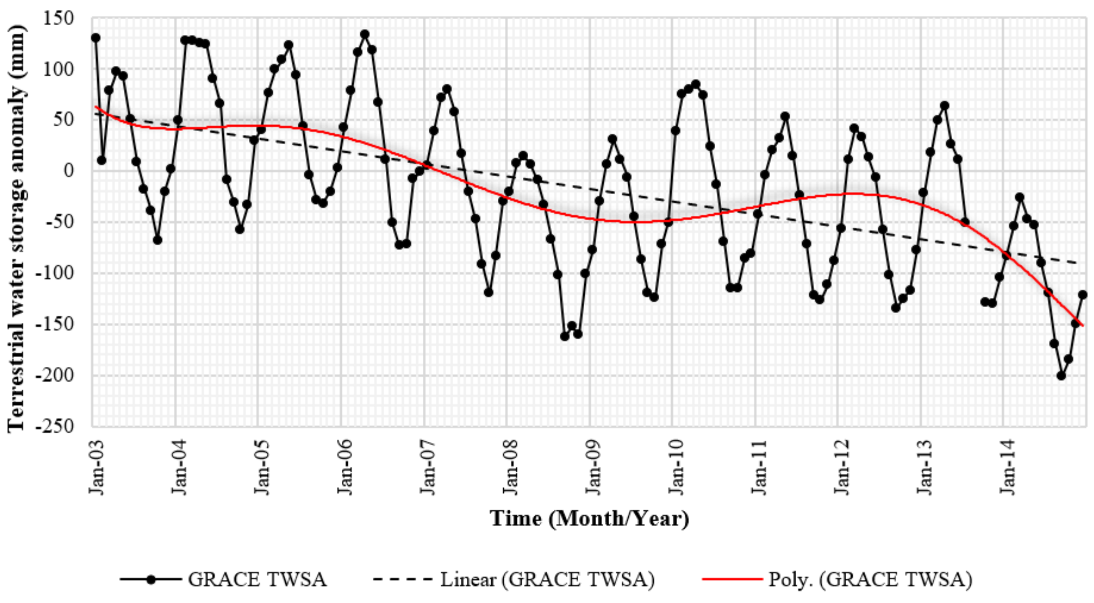


Figure 5.1: *Monthly mean Terrestrial water storage anomaly derived from GRACE data.*

Figure 5.2 shows the TWSC derived from GRACE. The scatterplots of the results does not show a clear pattern in TWSC that can be compared to the seasonal variation in terrestrial water storage of the basin. The reason is due to high uncertainties of terrestrial water storage of GRACE with a comparison to the less hydrological process in the area of study. If the maximum displacement shift (Amplitude) of the hydrological variation in the basin is smaller than the known uncertainty limit of GRACE estimate, then the TWS anomaly measured by GRACE Satellite will be associated with errors. These errors will be transferred to the determined TWSC estimates and will even be magnified. The reason is that the uncertainties in TWSC will gain by $\sqrt{2}$ times the uncertainties in Terrestrial water storage (Matthew Rodell et al., 2004).

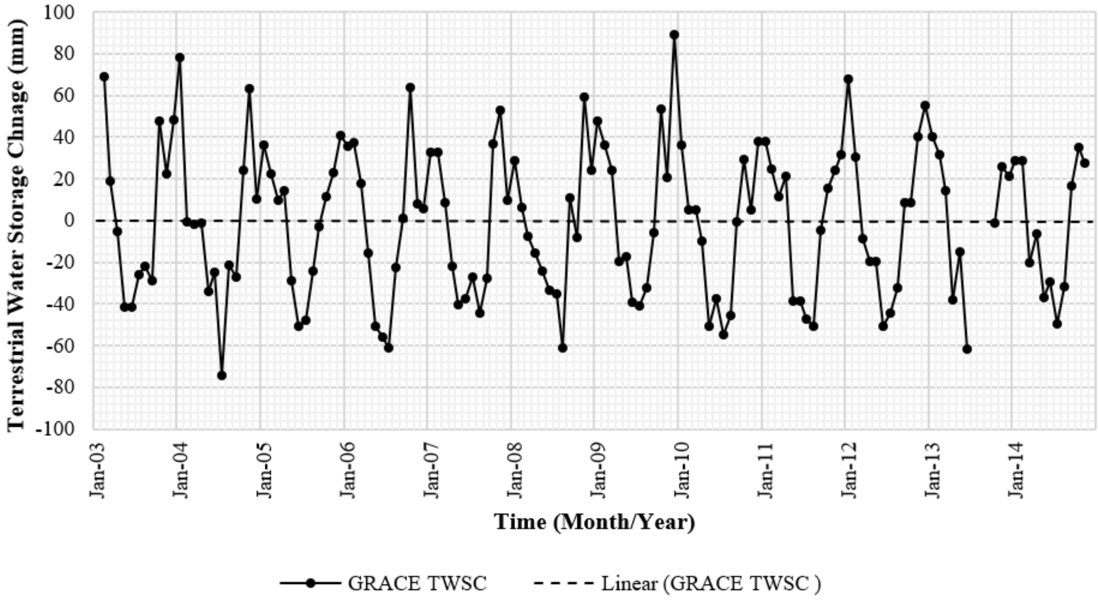
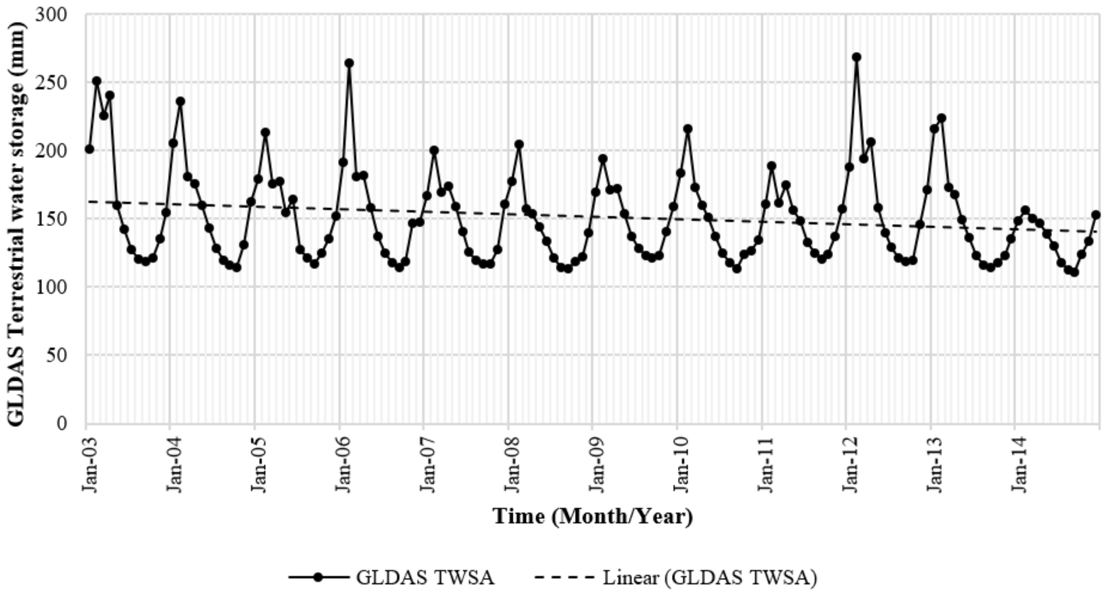


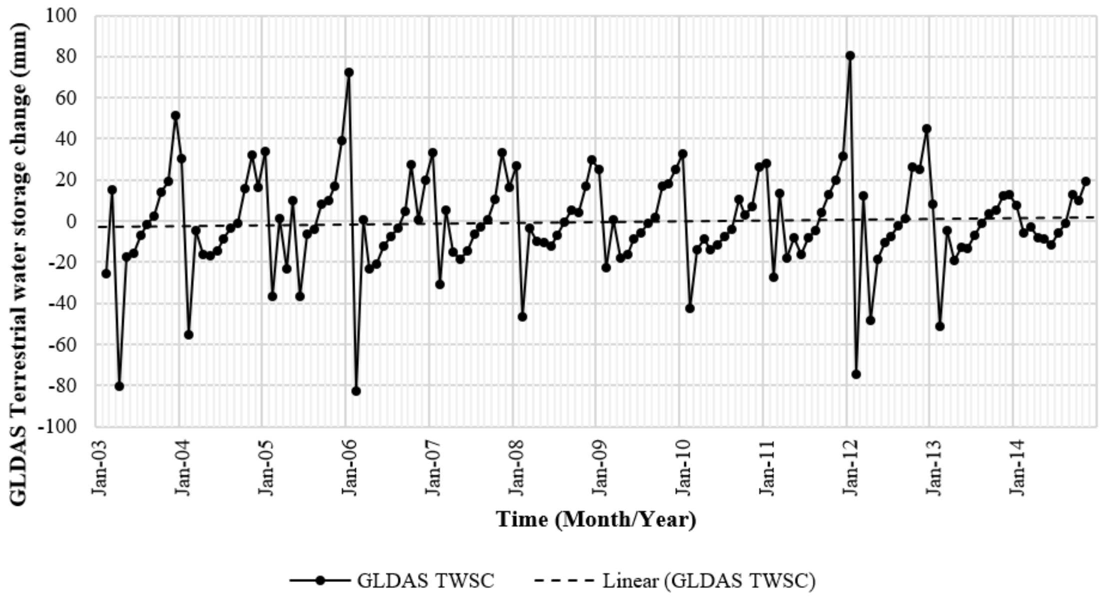
Figure 5.2: *Terrestrial water storage change derived from GRACE data.*

5.2. Terrestrial water storage and its change from GLDAS

Figure 5.3 (a) shows the time series of terrestrial water storage obtained from the GLDAS state variables. The TWSA is obtained by summing up the monthly state variables i.e. soil moisture, snow water equivalent and canopy water. The TWSA shows a declining trend indicating loss in storage amount. The linear trend fitted to the TWSA shows an annual decrease of -3.0 mm year^{-1} from 2003 to 2014 in the entire basin. Figure 5.3 (b) shows a TWSC derived from TWSA of the GLDAS state variables. The terrestrial water storage change is calculated by taking the difference from two sequential monthly values i.e. next month minus previous month. The results in the figure show a variation in TWSC due to seasonal events. As shown in figure 5.3 (a), during the winter, the TWSA peaks and during summer the TWSA are at the lowest point. This implies that the hydrological variation is best predicted by the GLDAS state variable as compared to the GRACE TWSA.



(a)

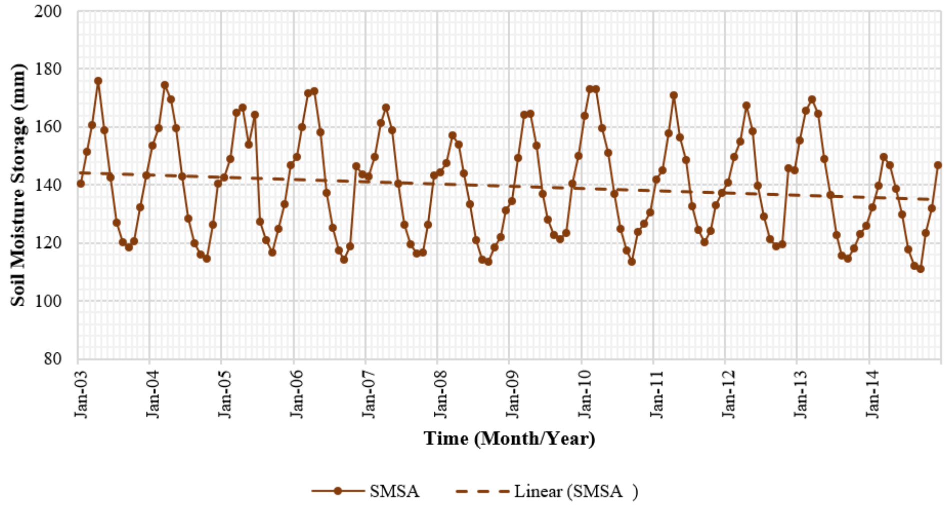


(b)

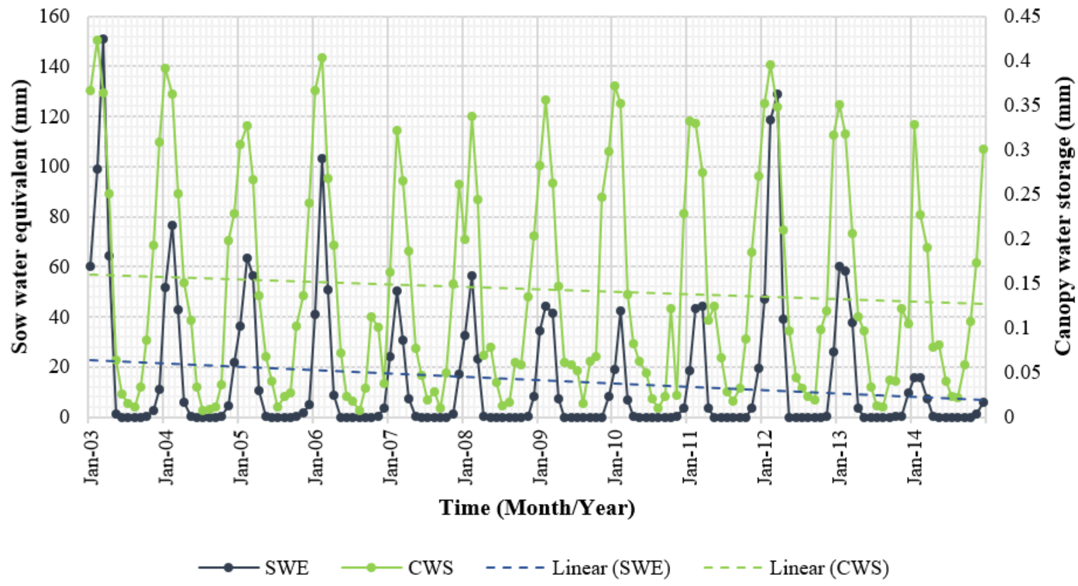
Figure 5.3: *Monthly TWSA (a) and TWSC (b) from GLDAS-LSM consisting of soil moisture, canopy water, snow water equivalent state variables*

5.3. Global Land data Assimilation System state variables

Figure 5.4 (a) shows the average monthly soil moisture storage for the period of 2003 to 2014. The linear trend fitted to the time series shows a declining trend at a rate of -0.79 mm year^{-1}. The seasonal cycle is reflected in the scatter plot, in which the peaks imply higher precipitation and trough implies the dry seasons. Figure 5.4 (b) shows the time series of canopy water and snow water equivalent with the trends -0.88 mm year^{-1} and -1.67 mm year^{-1} respectively.



(a)



(b)

Figure 5.4: *The monthly mean of SWSA (a), SWE and CWS (b) with the trends, averaged in the Fırat basin.*

The figure 5.5 below shows the comparison between the GLDAS state variables. The storage changes of the state variable are calculated by subtracting the succeeding month from the preceding one, for each variable. The figure below shows the monthly changes of all the state variables used in this research, we can see clearly that the peaks of SMSC, CWSC and SWEC are commensurate with each other.

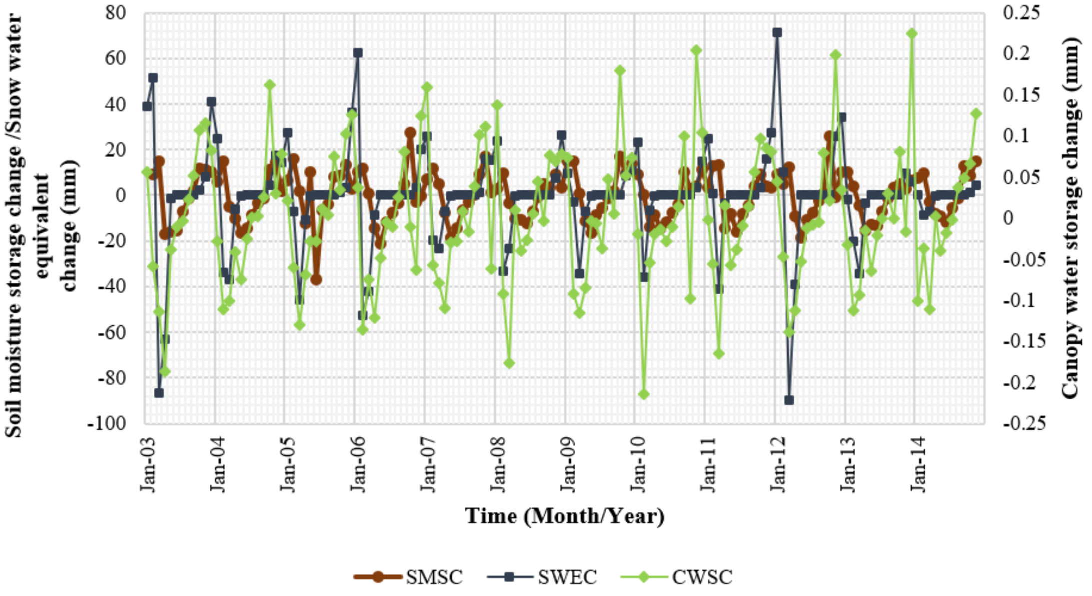


Figure 5.5: *The monthly mean changes of state variables from GLDAS*

5.4. Comparison of GRACE and GLDAS TWSCs

A time series plot of TWSC as derived from GRACE and state variables of GLDAS is presented in figure 5.6. From the plot trends, it is clearly observed that the TWSC estimates from GRACE and GLDAS agree well for the period of 2003 to 2014, despite the difference in the amplitude. This difference in amplitude can be explained by components included in the water balance equation. The variation in monthly GRACE-TWSC is higher than the GLDAS derived TWSC, this is because of the seasonal effects of groundwater storage, which is well detected by GRACE and not by the state variable of GLDAS-LSM. The loss of forest cover in an area can result in an increase in the water table due to a decrease in evapotranspiration. Although the loss in vegetation decrease the evaporation, the groundwater recharge can be enhanced man-made water delivery infrastructures, leading to increase in GWS.

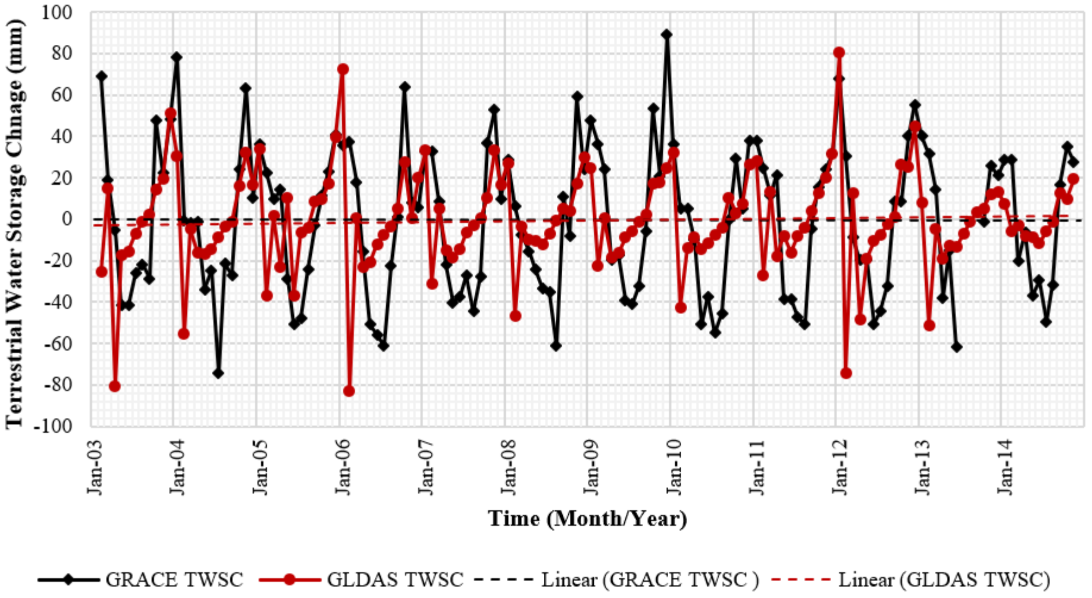


Figure 5.6: *The comparison of monthly variation of TWSC from GRACE and GLDAS.*

The comparison between the GLDAS state variable derived TWSC and GRACE TWSC is carried out in order to further explain the observed differences. The estimation of groundwater storage change is a function of TWSC and GLDAS state variables, thus the correlation and accuracy of two TWSC are important as an accurate measure. The evaluation of the monthly TWSC from GRACE and state variables of GLDAS is presented in the figure 5.7. The time series, scatter plot has the same trend.

In addition, the seasonal cycles from the both GLDAS and GRACE TWSC show the similar pattern as can be seen by the peaks and trough. The comparative analysis shows a lag in changes because it takes time for the state variables to impact the TWSC. This implies that the determined groundwater storage and GWSC for these components is reliable. From figure 5.7, it can be deduced that the changes in soil moisture are less as compared to that of TWSC from GRACE.

This is due to less storage loss in the unsaturated zone of the soil. However, the changes in the canopy are high due to exposure to the environmental factors such as temperature, human interference with the forest cover. The results show that the changes in the average monthly-seasonal analysis of both GRACE TWSC and soil moisture generally higher in the dry season and lower in the wet seasons. The overall storage change in figure 5.7 shows positive for the wet season and negative for the dry seasons.

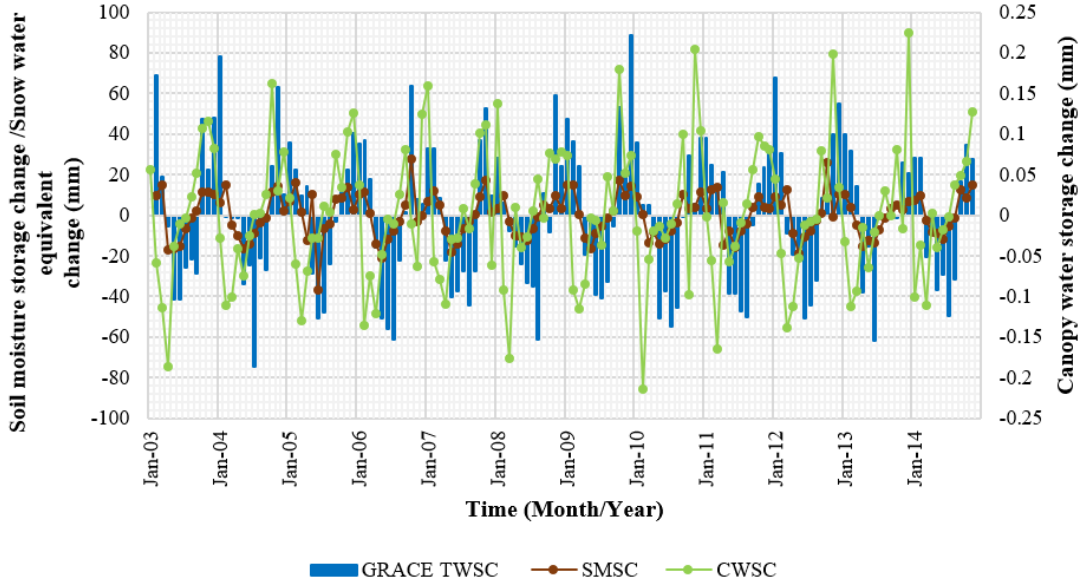
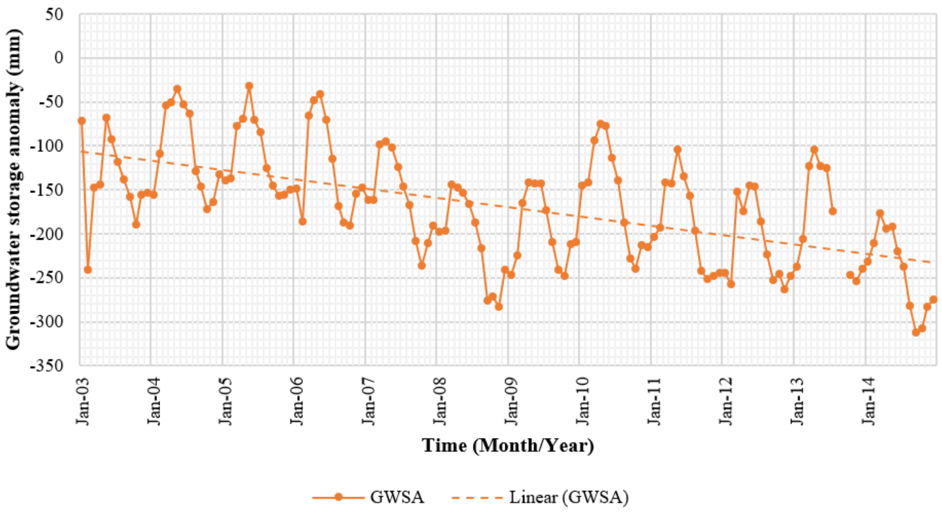


Figure 5.7: *The comparison of TWSC estimated from GRACE and SMSC and CWSC derived from GLDAS-LSM.*

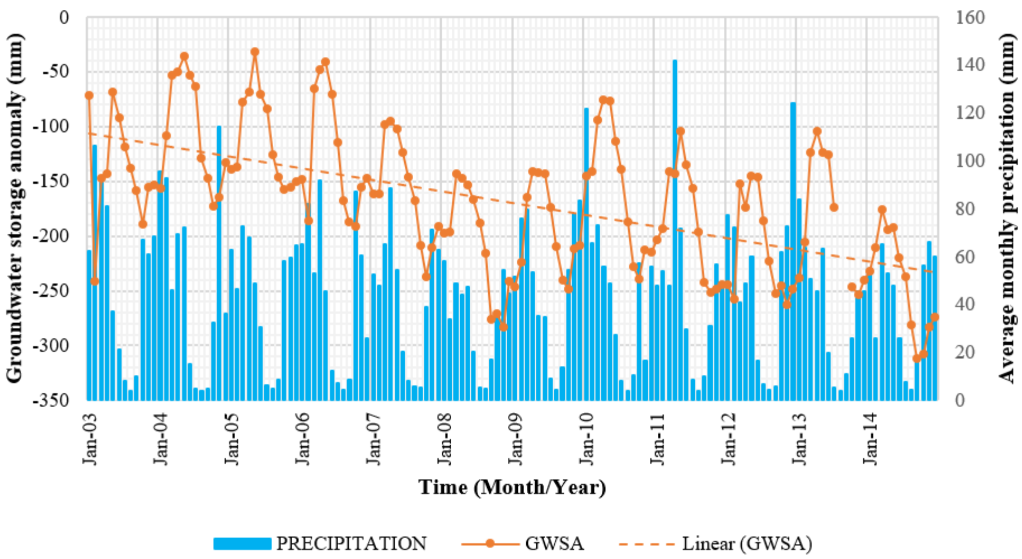
5.5. Estimated groundwater storage from GRACE and GLDAS state variables

In order to determine the groundwater variation, the 144 monthly GRACE model and GLDAS data set for the period of 2003 to 2014 were used. Figure 5.8 (b) shows the temporal variation of the monthly precipitation averaged over the Fırat basin from 2003 to 2014. The seasonality in the groundwater is still available as in figure 5.8 (a) and (b), the time series shows decreases in the groundwater at rate of -12.40 mm year^{-1}. The seasonality of the groundwater is as a result of precipitation which occurs from October to may in the form of rain, snow. High precipitation mainly occurs during the wet season (October – May) accounting for 90 % of the total precipitation and low precipitation in dry season (June - September) which only accounts for 10 % of the annual precipitation. The average annual precipitation over Fırat basin varied from 413 mm year^{-1} to 591 mm year^{-1} from 2003 to 2014.

In some the studies conducted in other regions of the world, the similar seasonality was observed in TWSA, SWSA, and GWSA (Strassberg, Scanlon, & Rodell, 2007a). The precipitation highs and lows matches TWSA and SWSA as shown in figure 5.8 (b). However, a lag of about 3 months was noted in the time series plot of groundwater storage. The Lag is as the result of long time duration taken for surface water to percolate to the root zone.



(a)



(b)

Figure 5.8: *Monthly groundwater storage anomaly (a) showing declining trend and a comparison of GWSA with monthly average precipitation (b) in the entire study area.*

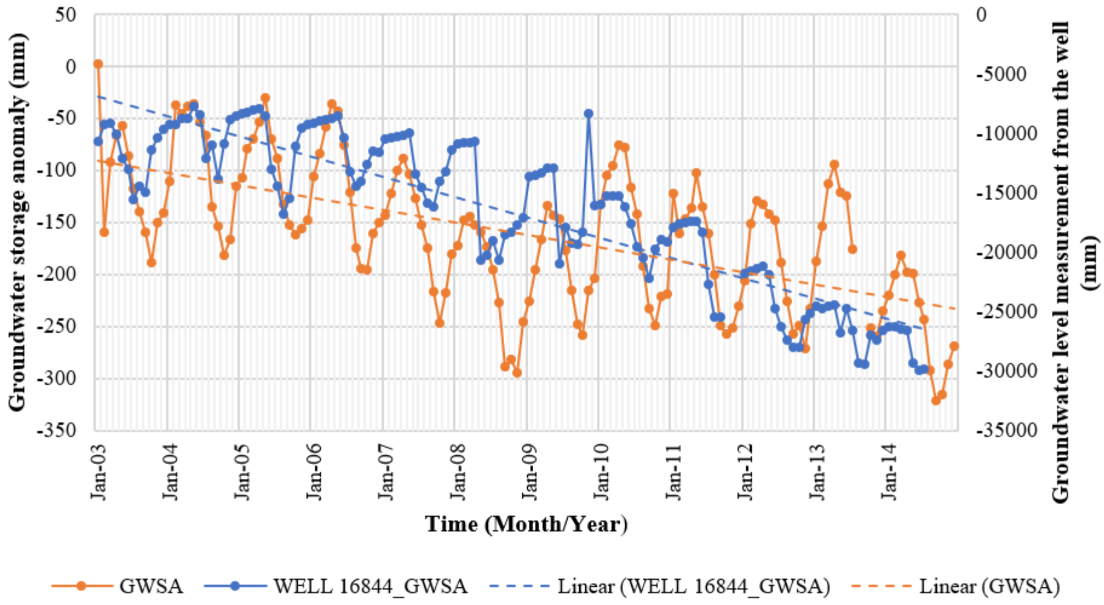
5.6. Groundwater storage estimation and comparison with in situ measurements

Following equation 4.5, the groundwater storage anomalies were determined as a component after subtracting canopy water, snow water equivalent and soil moisture storage from the TWS of GRACE. However, validation of the estimated Groundwater storage, proves to be challenging due to lack of adequate boreholes in the study area. In order to validate the reliability of the estimated GWSA, two borehole data sets were used.

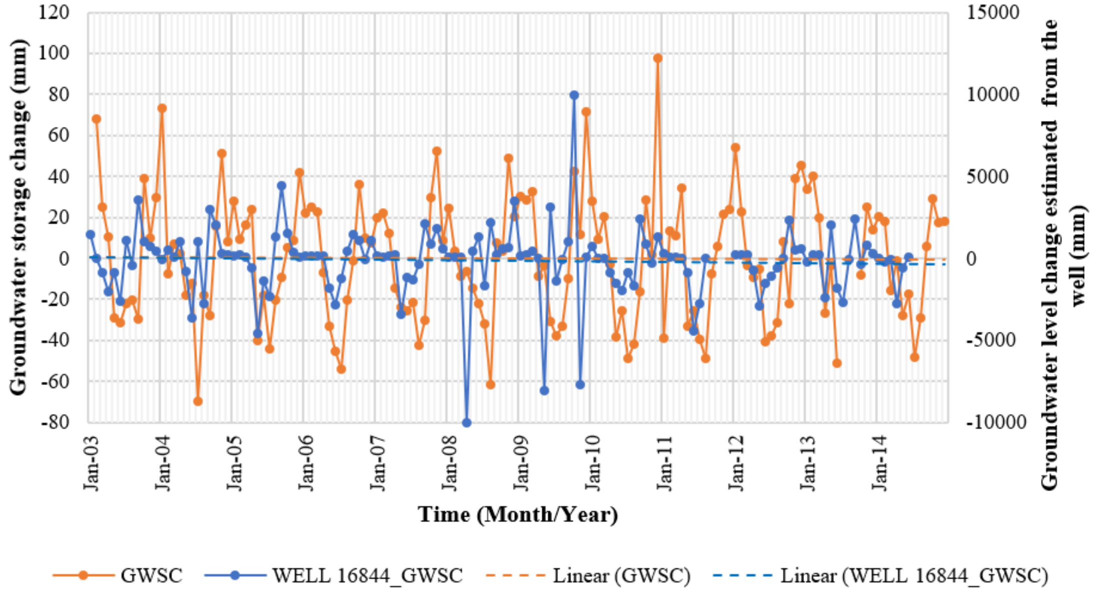
The wells used are Merkez yazıkonak(16844) of 100 meters depth and Merkez kuyulu (53401) of 75 meters depth. Merkez yazıkonak and Merkez kuyulu well are situated on 874 m and 898 m altitude above sea level respectively. Using extraction by points, the values of both GWSA and GWSC are extracted from the raster surfaces, taking into consideration the location of the wells. Figure 5.9 (a) shows the estimated monthly groundwater storage anomalies and the groundwater level measurements of well number 16844. Both the seasonality and decline of groundwater are clear in figure 5.9 (a), especially from the year 2007. The trends in the estimated groundwater and groundwater level measured from the well are -11.68 mm $year^{-1}$ and -1567 mm $year^{-1}$ respectively.

The measured groundwater level variability is consistent with estimated groundwater storage. The peaks and trough in both the time series plots match perfectly, hence showing a season cycle. Figure 5.9 (b) shows the comparison of the groundwater storage changes from the estimated and calculated from well number16844 monthly values. The groundwater level change from the well 16844 shows a significant decreasing while the groundwater changes estimated from the GRACE and GLDAS do not show a clear trend. Figure 5.10 (a) shows the time series of monthly groundwater storage from GRACE-GLDAS and measured groundwater levels from well number 53401.

The general trend of both the time series reflects the decline in the groundwater storage at that particular location. The trends in groundwater storage and trend of the groundwater level is -11.05 mm $year^{1}$ and -2374 mm $year^{-1}$. Figure 5.10 (b) shows the comparison between the estimated groundwater storage and calculated from the well number 53401. However, the comparison between the estimated groundwater storage changes and the changes from measured well levels shows a similar long term trend. The peaks and the trough of the plots matches with a slight variation. The discrepancy between the measured groundwater level and the estimated GWSA can be as a result of the errors in GWSA variations introduced by the spatial aggregation of point well measurements.



(a)



(b)

Figure 5.9: *Comparison of estimated GWSA with measured GWL from well No. 16844 (a) and the Groundwater level change (b).*

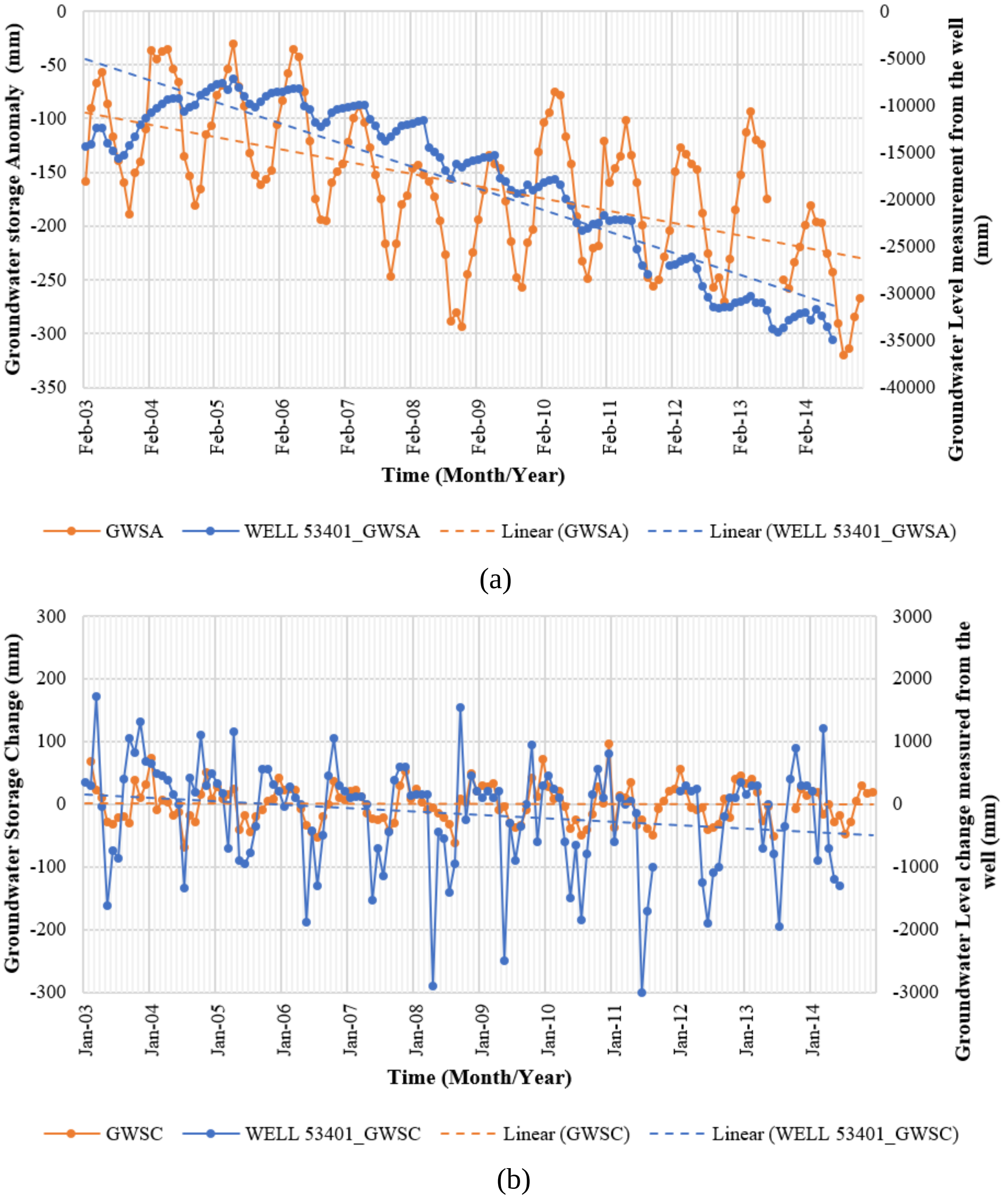


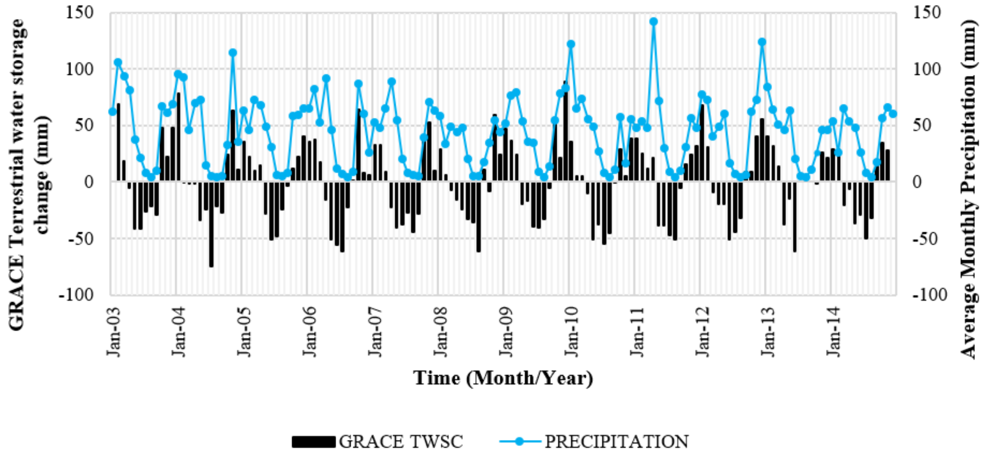
Figure 5.10: *Comparison of estimated GWSA with measured GWL from well No. 53401 (a) and the Groundwater level change (b).*

5.7. The Precipitation variation with TWSC and GWSC

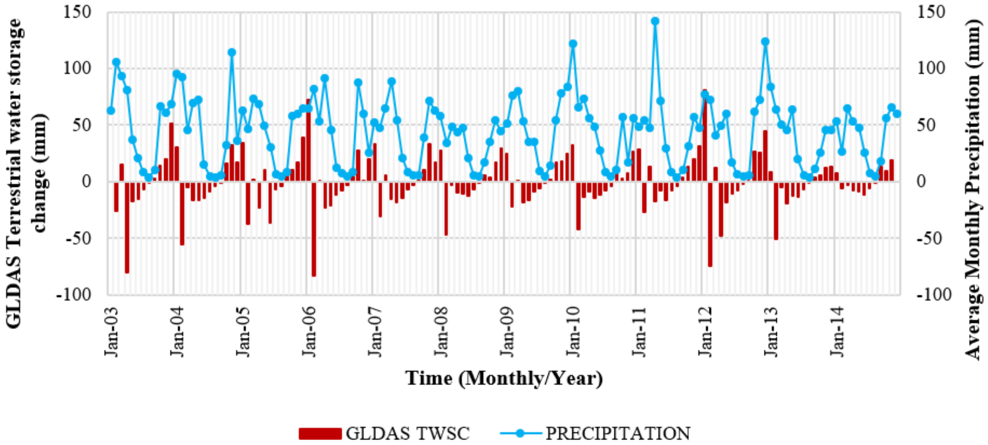
Precipitation is an important parameter for water cycle and it plays a vital role in groundwater recharge. Thus to further validate the obtained results, the average monthly precipitation variations are compared with the estimated groundwater storage change, Terrestrial water storage changes derived from both GRACE and GLDAS-LSM over the entire Fırat basin. Figure 5.11 (a) shows a seasonal and monthly time series of GRACE TWSC and the averaged monthly precipitation in the basin exhibiting a clear seasonal amplitude and phase changes.

The precipitation variation with GLDAS TWSC also shows the similar patterns as can be observed in figure 5.11 (b). However, a lag is observed in TWSC gain with respect to monthly precipitation. The results of figure 5.11 (a) and 5.11 (b), with a precise analysis show that precipitation is the main hydrologic contributor in the basin. Figure 5.11 (c) shows the groundwater storage change in comparison to the precipitation, which determined as the difference between GRACE TWSC and GLDAS TWSC. Generally, like in other water basins, the net recharge causes a rise in the groundwater level in the wet season, and in the dry season we expected the groundwater level to fall. The fall in the groundwater storage is due to evaporation or discharges to the Euphrates river and wetlands.

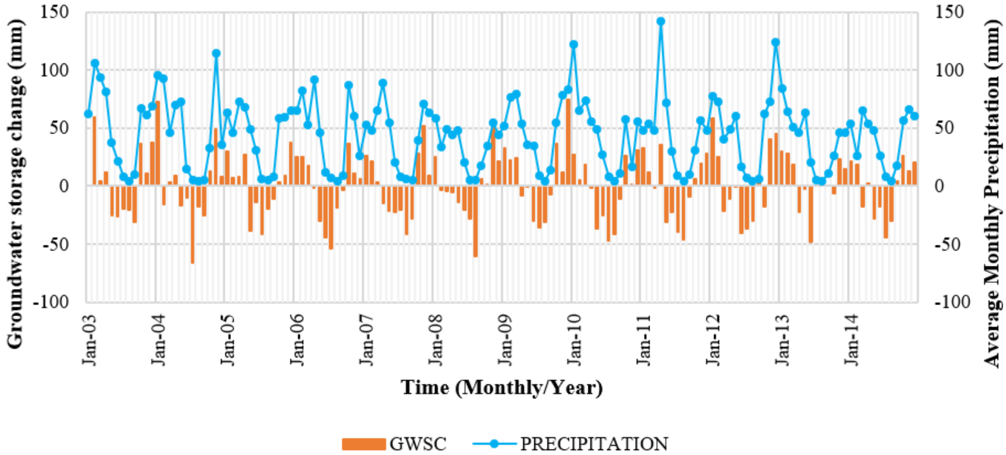
However, the seasonal fluctuation in the groundwater storage variations in response precipitation mainly depends on the size, type and other physical properties of aquifers as well as the recharge from other sources such as made infrastructures. The changes in annual precipitation can result to larger variability in the water storages (Milly, 2010). Precipitation is one parameter that controls the water storages in the Fırat basin. In as important as rainfall is to groundwater recharge, more frequent and heavy rainfall hinders the infiltration capacity of the soil, hence increasing surface runoff. However, in semi-arid and arid areas, the rainfall variability may enhance groundwater recharge due to the fact that high intensity rainfall is capable of infiltrating quickly before evaporating.



(a)



(b)



(c)

Figure 5.11: *Comparative evaluations of results between average monthly precipitation in the basin and the calculated: (a) GRACE TWSC, (b) GLDAS-LSM, and (c) groundwater storage change.*

5.8. Groundwater recharge rate comparative with annual Precipitation.

Figure 5.12 shows the comparison of groundwater recharge rate and annual precipitation averaged over the Fırat basin from 2003 to 2014. There is pronounced variability in annual precipitation histogram, characterized by intense precipitation in the year 2012 and the lowest in 2008. And there is an obvious trend in the groundwater recharge rate, however the estimated annual recharge varied greatly as shown in figure 5.12. The trend in annual recharge shows a decline from 2005 to 2008, thereafter, the basin gained in groundwater storage with the highest recharge in the year 2011.

This increase in annual groundwater recharge is due an increase in the precipitation in the previous year's wet seasons. But from 2008 to 2014 the recharge rate shows a negative trend. The annual recharges for the year 2005 and 2011 are much higher as compared to their annual precipitation, this could be due the residual effect from the increase in previous years of high precipitation.

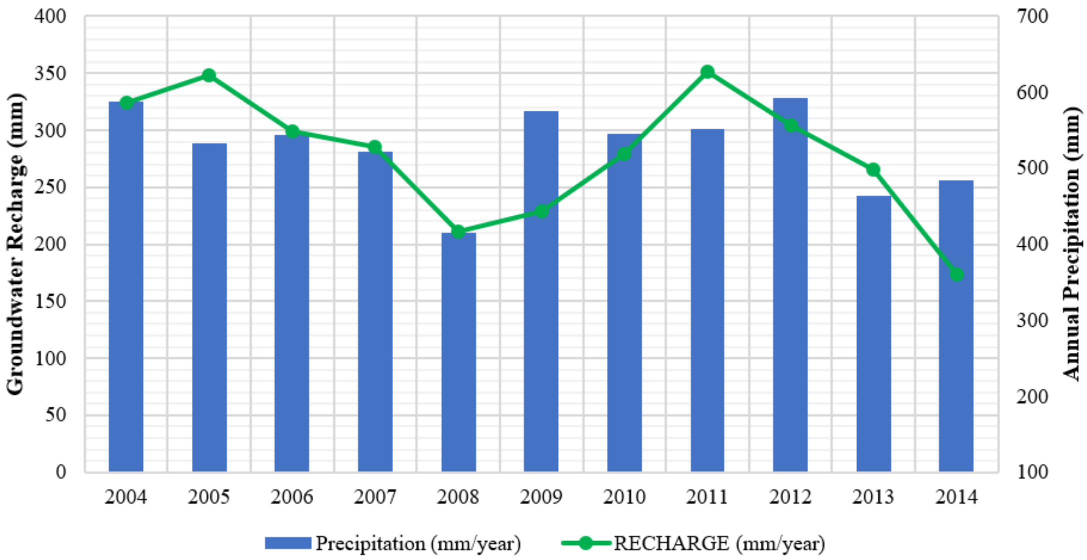


Figure 5.12: *Comparative evaluation of estimated groundwater recharge and annual precipitation in the basin.*

There was a recharge season in each year from 2003 to 2014 as can be shown in figure 5.12. The linear equation was fitted to the recession curve (S_a-S_l) according to figure 4.2. The GWSA monthly mean points in each recession curve ranged from 5 to 9 as shown in table 5.1. The annual recharge in Fırat basin ranges from 174 to 351 mm year^{-1}. The averaged annual groundwater recharge in 11 year period over the entire Fırat basin was 279.26 mm year^{-1}.

Table 5.1: *The variables used to estimate groundwater recharge from groundwater storage, annual recharge and precipitation.*

Time (Year)	**S_p**	**S_l**	**S_t**	**N**	**R_s**	**R_d**	**Recharge (mm/year)**	**Precipitation (mm/year)**
2004	-35.76	-360	-189.15	6	153.39	170.84	324.24	587.66
2005	-31.57	-380	-172.39	6	140.82	207.61	348.43	532.45
2006	-40.89	-340	-157.15	6	116.26	182.85	299.11	543.74
2007	-94.72	-380	-190.98	6	96.26	189.02	285.28	521.25
2008	-143.55	-355	-236.72	7	93.17	118.28	211.45	413.50
2009	-142.24	-370	-282.84	9	141.60	87.16	228.76	573.75
2010	-75.39	-355	-248.04	7	172.65	106.96	279.61	545.07
2011	-103.91	-455	-239.24	6	153.33	215.76	351.09	550.68
2012	-145.47	-450	-251.21	5	105.74	198.79	304.53	590.96
2013	-104.36	-370	-262.97	7	158.61	107.03	265.64	463.20
2014	-176.25	-350	-253.33	6	77.08	96.67	173.75	482.58

Note: S_p is the peak of the rise, S_l is the extrapolated values from the antecedent recession curve at the time of the peak. S_t is the value of the lowest point in the previous year of the GWSA time series graph. N is the number of points used to fit the recession curve. R_s is the change in the groundwater storage or Net recharge, R_d is the recharge that balances discharge in the basin.

The obtained net recharge rate varied from 77.08 to 172.65 mm year for 11 year period and the average was 126.45 mm year^{-1}. During the winter, late fall and spring periods the groundwater recharge is high, because the plants are dormant and the evapotranspiration and evaporation are at the lowest. However, during summer months when the temperatures are high, the evapotranspiration rate exceeds the moisture from precipitation resulting in negligible recharge to the aquifers and groundwater levels decline.

The GR can be partially explained by the variability of annual precipitation, as shown in figure 5.13. And there is a linear relationship between groundwater recharge rate and the annual precipitation with a correlation coefficient of 0.33. This indicates that recharge is regulated by precipitation to some extent in the Fırat basin. Many similar researchers reported higher correlation between groundwater recharge and precipitation, with $R^2 > 0.7$ (Turkeltaub, Kurtzman, Bel, & Dahan, 2015). The recharge rate of any basin can be affected by soil texture, in areas mostly dominated by sand the recharge is higher because of lower runoffs. (Allison, Gee, & Tyler, 1994). In areas of silt formation, precipitation can be held by and later consumed by evapotranspiration, hence infiltration to the root zone is negligible.

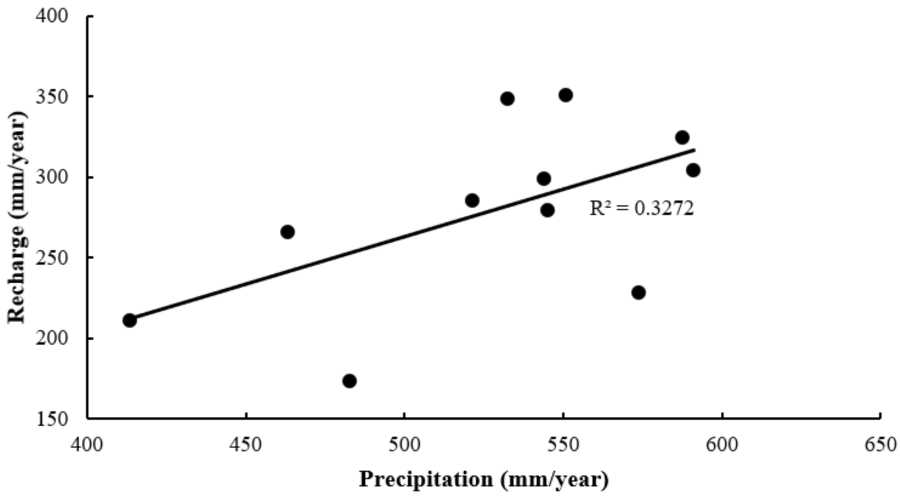


Figure 5.13: *The annual recharge in comparison with annual precipitation. R^2 is estimated to be 0.33 and the black line is the regression line of all the points.*

The R^2 of the recharge and precipitation can be lower if spatial variability is induced. The $R^2 < 0.3$ was obtained in several studies from different countries (Wu et al., 2019). The variability of groundwater recharge rate can be affected by different factors such as climate, soil and geology, vegetation and land use and surface topography. There are different kinds of pathways that promote recharge in the basins. These pathways are mostly caused by old root channels and macropore like fractures in the rocks as well as sink holes and other geological structures. These pathways channels the water to the aquifers faster as compared to the soil matrix (Allison & Hughes, 1983). The deep rooted vegetation also could reduce or eliminate the recharge in an area (Li, Si, & Li, 2018). It is important to reduce the uncertainty groundwater recharge estimations, this can be achieved by accurately measuring precipitation, irrigation, evapotranspiration, soil moisture content (Min, Shen, & Pei, 2015).

5.9. Evaluation of TWS with Meteorological variables

5.9.1. Temperature

Figure 5.14 shows the averaged minimum and maximum temperature spatial map of Fırat basin from 2003 to 2014. The temperature dataset was obtained from 10 meteorological weather stations, some stations fall on the outside of the study area. The month temperatures measurements are interpolated into average monthly temperatures.

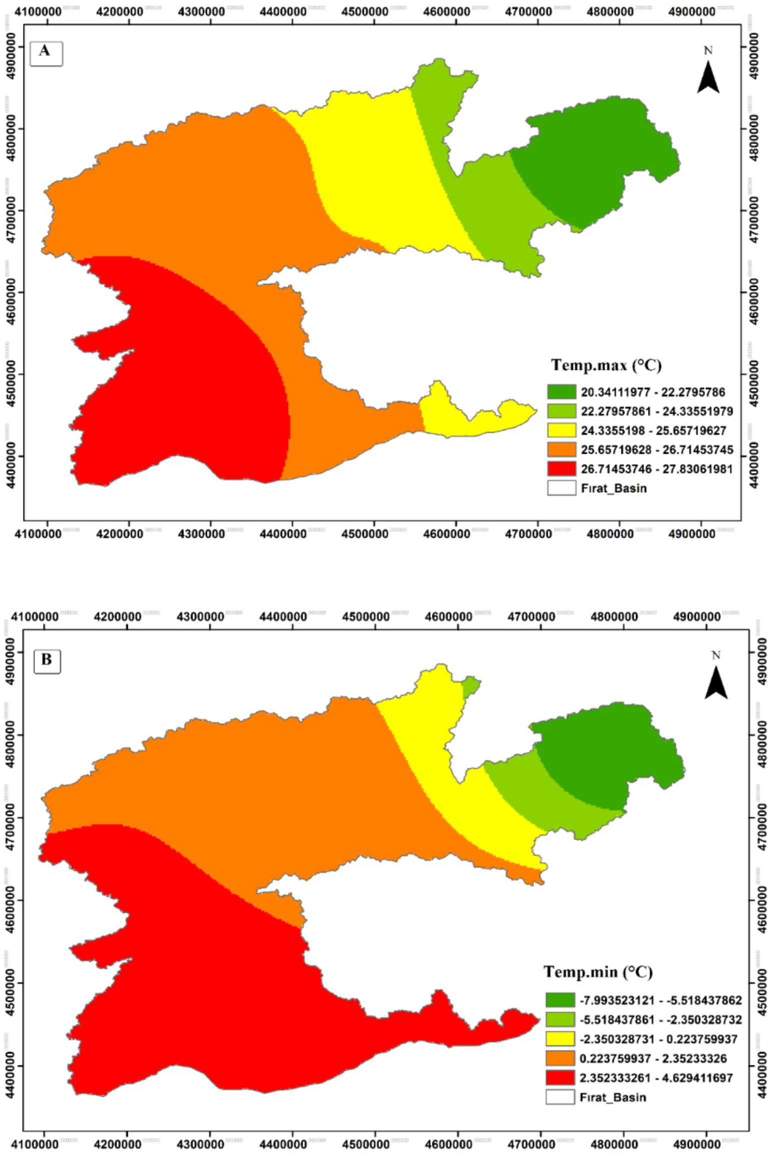


Figure 5.14: *Mean of maximum (A) and minimum (B) temperature from 2003 to 2009 interpolated from 8 meteorological weather stations.*

Thereafter, the spatially interpolated average monthly temperatures are summed up into average annual temperature using the inverse distance weighting (IDW) method in the ArcGIS software. From figure 5.14, it shows that the maximum and minimum temperature in the study area decreases from east (27.83 °C and 4.63°C) to the west (20.34 °C and -7.99 °C) respectively. The mean temperature of the study area from 2003 to 2014 is 26.69 °C. The calculated annual maximum and minimum temperatures are shown in table 5.2.

Table 5.2: *Annual minimum and maximum air temperature for Fırat Basin*

	Annual minimum air temperature					**Annual maximum air temperature**				
Time (year)	**Min (°C)**	**Max (°C)**	**Range (°C)**	**Mean (°C)**	**Std. (°C)**	**Min (°C)**	**Max (°C)**	**Range (°C)**	**Mean (°C)**	**Std. (°C)**
2003	-10.27	6.48	16.75	0.99	3.92	19.25	28.43	9.18	25.13	2.16
2004	-9.96	5.82	15.78	0.26	3.67	19.91	28.84	8.94	25.79	2.16
2005	-9.05	5.97	15.02	1.25	3.52	20.62	29.19	8.57	25.97	1.98
2006	-7.26	5.39	12.65	1.69	3.05	20.99	29.03	8.04	26.46	1.96
2007	-7.18	4.11	11.29	0.29	2.47	19.83	26.17	6.34	24.75	1.72
2008	-9.63	2.78	12.41	-0.38	3.14	22.31	28.00	5.95	26.20	1.48
2009	-7.27	3.51	10.78	0.51	2.27	19.00	26.21	7.21	24.45	1.90
2010	-4.37	8.07	12.43	2.68	2.27	22.31	28.74	6.43	27.03	1.66
2011	-8.12	5.65	13.77	0.93	3.04	19.99	25.97	5.97	24.44	1.54
2012	-8.19	6.53	14.72	1.70	3.14	19.74	27.11	7.37	24.51	1.83
2013	-8.69	6.43	15.12	2.27	3.40	19.56	30.98	11.43	25.89	2.35
2014	-6.37	5.97	12.33	1.61	2.81	20.43	31.71	11.29	25.80	2.66

Figure 5.15 shows the results of mean annual minimum and maximum temperatures of the Fırat basin from 2003 to 2014. The figure shows the variation in both minimum and maximum temperature of each year. The ranges and the standard deviation of the annual temperature are shown in table 5.2. The highest mean maximum and minimum temperature is observed in 2010 as compared to other years. While the lowest mean minimum temperature was in the year 2008. The same year also received lowest precipitation. The temperature has a high influence on the terrestrial water storage, this is due to its effect on evaporation and transpiration rate. The higher the temperature results in the increase in evaporation rates ,which can cause high precipitation in an area. The lowest terrestrial water storage was also observed in 2008.

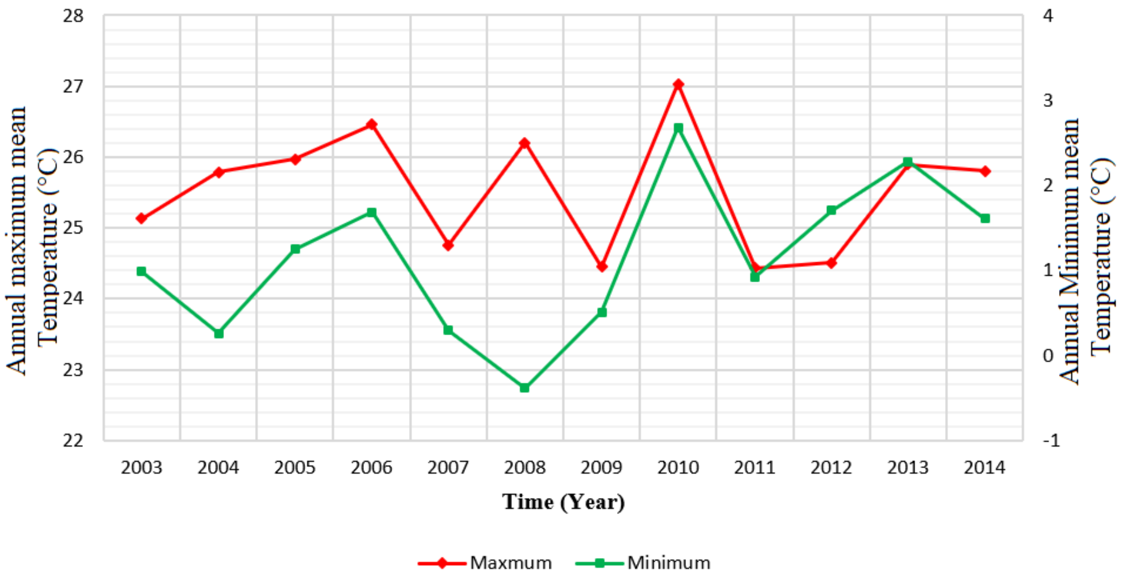


Figure 5.15: *The Mean annual minimum and maximum temperature from 2003 to 2009 averaged in the entire Fırat basin.*

5.9.2. Precipitation

The spatial map of the average precipitation from 2003 to 2014 is obtained from CHIRPS monthly global precipitation data. The annual precipitation of each year is calculated by averaging the monthly data in the Fırat basin. The average annual precipitation from 2003 to 2014 is calculated using the raster calculator after interpolation by inverse distance weighting in ArcGIS software. Figure 5.16 shows the annual precipitation averaged from year 2003 to 2014 from the monthly precipitation of CHIRPS dataset. The averaged interpolated results shows that the annual precipitation decreases from North-eastern to South-western direction. The average annual precipitation in the basin ranges from 280 mm to 960 mm. The maximum precipitation is observed in the north-eastern of the Fırat basin.

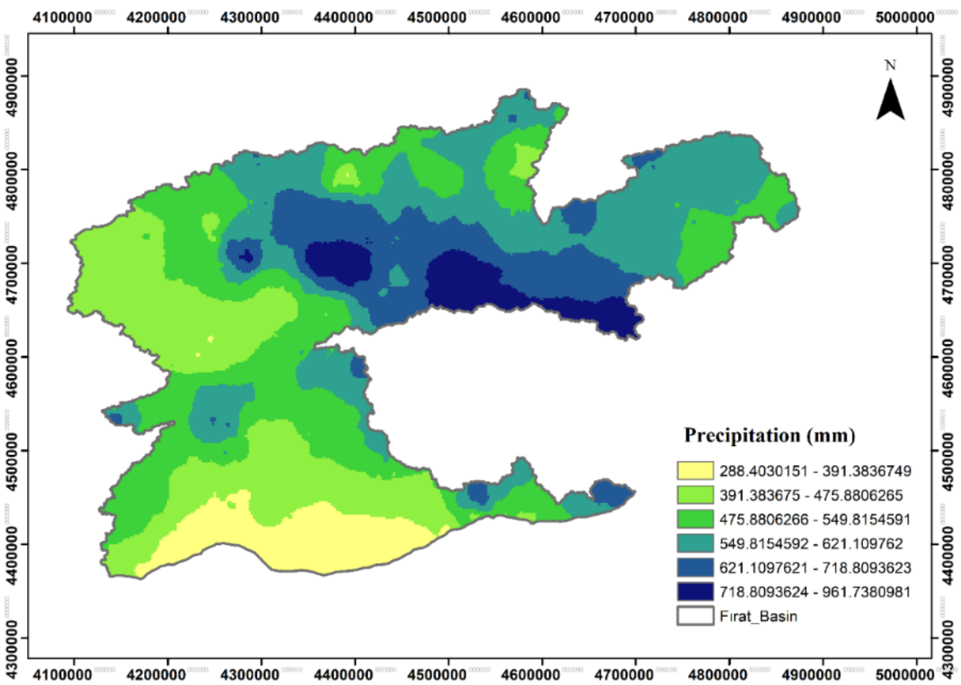


Figure 5.16: *The mean annual precipitation from 2003 to 2014 interpolated from CHIRPS dataset.*

Table 5.3 shows the result of the mean annual precipitation average on Fırat basin from 2003 to 2014. The mean annual precipitation for the entire duration of the study area from 2003 to 2014 in the Fırat basin is 535.43 mm. The annual precipitation in 2008 was the lowest and also lower than the mean precipitation of the study area. The terrestrial water storage of 2008, 2014 are the lowest as compared to other years. The years also recorded the higher maximum temperatures, according to the temperature analysis.

The maximum temperature of 2008, 2013 and 2014 are 26.20 °C, 25.89 °C and 25.80 °C respectively. The temperatures are above the mean temperature of the study area which 25.54 °C. The low precipitation and higher mean temperature resulted in the loss of terrestrial water storage in the basin. The groundwater recharges in these years are also the lowest. The mean annual precipitation trend in the basin shows a declining amount of precipitation from 2003 to 2008 as shown in figure 5.17. From 2009 to 2012 the annual precipitation in Fırat basin recorded an increase and a slight decrease in the year 2013.

Table 5.3: *Annul minimum, maximum and the mean precipitation from meteorological stations over the entire Fırat basin*

		Annual Precipitation			
Time (year)	**Min (mm)**	**Max (mm)**	**Range (mm)**	**Mean (mm)**	**Std. (mm)**
2003	286.15	1256.32	970.16	620.37	141.68
2004	297.91	1122.44	842.53	587.66	123.89
2005	223.04	967.45	744.41	532.45	133.92
2006	242.32	1053.72	811.40	543.74	135.67
2007	260.80	941.27	680.47	521.25	115.31
2008	172.24	810.62	638.38	413.50	106.98
2009	252.35	1076.74	822.87	573.75	125.97
2010	206.68	1010.26	803.57	545.07	128.06
2011	252.35	994.04	741.69	550.68	116.78
2012	338.09	1078	739.91	590.96	110.78
2013	270.24	861.84	591.60	463.20	85.19
2014	287.87	848.60	560.73	482.58	82.43

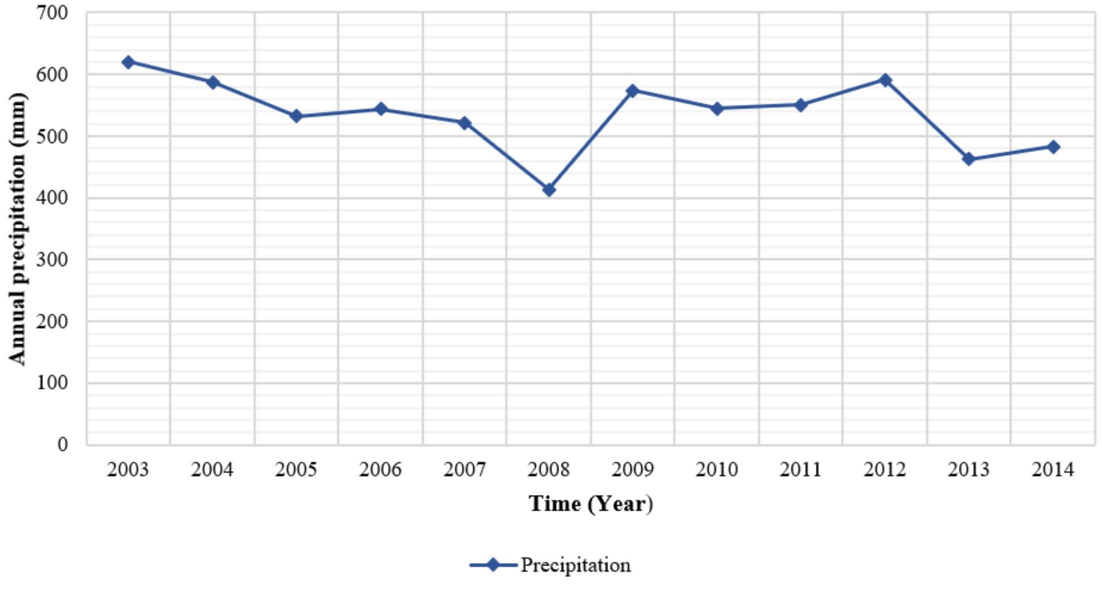


Figure 5.17: *Mean Annual precipitation from 2003 to 2014 averaged from CHIRPS dataset.*

6. CONCLUSION

In this research GRACE satellite and GLDAS data are used to estimate the regional groundwater storage and recharge in Fırat basin. The other data sets used in this research are CHIRPS and in situ measurement of air temperature and groundwater levels. An area averaged monthly of eleven years of GRACE terrestrial water storage shows a declining trend at the rate of -13.37 mm year^{-1}. However, the GRACE time series shows a distinct trend of terrestrial water storage loss from 2003 to 2008 and a gain from 2009 to 2013. From the time series graph, it is clear there is depletion of in the terrestrial water storage in the observed period.

The terrestrial water storage is also estimated from GLDAS state variables, by summing up the monthly state variables. The TWSA obtained from GLDAS also shows a declining trend indicating a loss in total water storage. The state variables include four soil moisture, snow water equivalent and canopy water storage. The GLDAS terrestrial water storage shows a decline in the storage at a rate of -3.0 mm year^{-1}. However, the comparative analysis of the TWSC and precipitation show a lag, this is due to the delay in state variables to impact the TWSC.

In order to determine the groundwater variation, 144 monthly GRACE and GLDAS data sets are used. The groundwater storage in Fırat basin is estimated by subtracting GLDAS TWSA from GRACE TWSA. The estimated groundwater storage time series shows a decline trend in the groundwater at the rate of -12.40 mm year^{-1}. The time series of groundwater storage also show a seasonality, in agreement with precipitation which occurs from October to may in the form of rain, snow. In order to validate the estimated groundwater storage the comparison with groundwater level measurement is carried out.

The study area has very limited number of wells, hence two groundwater level measurements are used in this research. Using well locations, the values of estimated groundwater storage are extracted from the spatial interpolated map. Later, the time series are prepared, both the time series of the extracted values to points and wells show a declining trend in the groundwater. The peaks and trough of both groundwater level measurements and estimated match.

There is seasonality in monthly precipitation and GWSC, exhibited by seasonal amplitude and phase changes. Precipitation is one parameter that controls the water storage in the basin. The groundwater recharge is estimated from the groundwater storage graph. There is a long-term trend in the groundwater recharge. The trend in the annual recharge shows a decline from 2005 to 2008, thereafter, a gain is observed up to 2011 followed by another decline. The annual recharge can be partially explained by precipitation as indicated by correlation coefficient of 0.33. The highest groundwater recharge is observed in the year 2011.

In conclusion reliability of GRACE and GLDAS for estimating groundwater storage and recharge is demonstrated in this research. The result shows that GRACE satellite data and the GLDAS land surface model can be used to estimate groundwater storage and recharge for long term and short term trend in Fırat basin. This research has the demonstrated the potential of GRACE and GLDAS estimate the storage in areas that lack observation wells and inaccessible. GRACE satellite data is the aggregate of the water storage components, differentiating each individual component is not possible. Therefore, the land surface models provides the information, but a certain level of uncertainty is associated with these data sets. In order to get a perfect closure of the groundwater variation in Firat basin, in situ hydrologic data is still important.

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