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ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRNMENTAL ENGINEERING
GEODESY AND GEOMATICS PROGRAM (SPECIALIZATION, GEODESY)

SPATIAL AND TEMPORAL VARIATION OF GROUND WATER STORAGE BY USING GRACE SATELLITE MISSION, A CASE STUDY OF EAST AFRICA

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR MASTER OF SCIENCE IN GEODESY AND GEOMATICS, (SPECIALIZATION IN GEODESY)

BY:

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JUNE, 2022

ADDIS ABABA, ETHIOPIA

DECLARATION

I, the undersigned, declare that the thesis titled "Spatial and Temporal variation of Groundwater storage by using GRACE satellite mission, a case study of East Africa" carried out under the supervision of Dr. Tulu Besha Bedada was my own work and has not been presented for a degree in any other university and that all source of material used while compiled this research have been fully acknowledge.

Tolosa Dejene Tadesse	____________________	_______________
Name of Candidate	Signature	Date

As a master research advisor, I hereby certify that I have read and evaluated this MSc thesis prepared under my guidance.

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APPROVAL SHEET

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The undersigned have examined the thesis entitled "Spatial and Temporal variation of Groundwater storage by using GRACE satellite data, a case study of East Africa " presented by Tolosa Dejene , a candidate for the Degree of Master of science in Geodesy and Geomatics, and hereby certify that it is worthy of acceptance.

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ABSTRACT

The Gravity recovery and climate experiment (GRACE and GRACE FO) satellite mission is very important to monitor Groundwater storage variation where there is a limitation of in situ data and limit of policies for sharing data like East Africa. In this study, GRACE and GRACE FO and GLDAS data were carefully processed and filtered by Gaussian smoothing methods to reduce noise. This study correlates GRACE derived TWSA data with water balance (P-ET-R) over 2008 to 2019 (means, twelve years) period and strong correlation(r = 0.75, rmse = 2.198) were obtained. GLDAS land surface model is used to get soil moisture and plant canopy surface water that reduced from GEACE/GRACE FO derived TWSA to obtained Groundwater storage change of the study area. In addition to that, Global land data assimilation system version 2.2 groundwater storage change was used. To analysis Groundwater storage change, the study area was classified according to river basin in the study area. Therefore, three basins were considered for the area and correlation coefficients were individually determined to measure the strength between the two data analyzed. Accordingly, GWSA of GRACE-GLDAS and GLDASv2.2 have a correlation coefficient value of ***0.88, 0.975*** *and* ***0.906*** *for Nile, Jubba-Shebelle, and Lake Rudolf basins respectively. The largest yearly ground water depletion occurs in February, 2008 to February, 2010 during millennium drought by average rate of -****9.2*** *mm per year in Jubba Shebelle basin and February, 2009 to June, 2010 by* ***-17.98*** *mm per year in Nile basin and June, 2008 to December 2009 by* ***-12.16*** *mm year for Lake Rudolf basins due to decreasing of rainfall.*

Keywords*: Ground water storage, GRACE, GLDAS, TWSA*

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LIST OF ACRONYMS

GRACE	Gravity Recovery and Climate Experiment
GRACE FO	Gravity Recovery and Climate Experiment Follow On
GLDAS	Global Land Data Assimilation System
GPCC	Global Precipitation Climatology Center
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
TWS	Terrestrial Water storage
TWSA	Terrestrial water storage Anomaly
NCEP	National Centers for Environmental Prediction
GWS	Ground water storage
GWSA	Ground water storage Anomaly
GPS	Global positioning system
CABLE	Community Atmosphere Biosphere Land Exchange model
RMSE	Root mean square error
PCSW	Plant canopy surface water
SDC	Science Data System
RDC	Raw Data Center
JPL	Jet Propulsion Laboratory
GFZ	GeoForschungs Zentrum Postdam
CSR	Center for space research
CRI	Coastline Resolution Improvement
WMO	World Meteorology Organization
LSM	Land surface model
SM	Soil moisture
P	Precipitation
ET	Evapotranspiration
R	Runoff water
r	Correlation coefficient

CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

In many parts of the world, groundwater is the principal source of freshwater (Rodell et al., 2009a). However, in many places, groundwater is being consumed in an unsustainable manner, resulting in a reduction in the amount and quality of the resource. Even in many developed countries, rules that regulate the usage of groundwater are not well defined (Livingston & Garrido, 2004). Lack of regulations is largely attributable to insufficient knowledge of groundwater supplies and rates of recharge. When compared to surface water reservoirs such as ponds, lakes, and rivers, groundwater recharge responds slowly to weather conditions in many regions (Livingston & Garrido, 2004). Because of geology and physical characteristics of the underlying soil. Increased agricultural techniques in arid and semiarid nations have resulted in major increases in groundwater extraction in recent decades (Llamas, 2005). Subsidies for electric power to farmers in various nations have fostered, and groundwater resources are being overexploited due to low pumping costs. Despite rising groundwater withdrawals, government agencies' involvement in groundwater planning, control, and regulation remains limited (Llamas, 2005; Rodell et al., 2009a). While government organizations in many countries manage surface water irrigation, farmers operating independently of one another frequently jointly increase and thereby abuse groundwater supplies. As a result, agricultural exploitation of groundwater resources is frequently attributed to a widespread lack of awareness of groundwater supplies and long-term consequences of groundwater withdrawals (Llamas, 2005; Rodell et al., 2009a). Finally, a lack of quantitative understanding of groundwater supplies may be contributing to human abuse of the ostensibly "infinite" resource in many parts of the world.

Because of limited hydrological data management, groundwater system monitoring in the East of Africa has been poor, similar to other developing countries. Groundwater is the principal a constant supply of clean water in several parts of East Africa, and there is no significant alternate source of water, particularly in the semiarid region. The amount of terrestrial water is limited in dry and semiarid regions, and rain is scarce. As a result, a great quantity of ground water is pumped out of the area. On other hand, the limited amount of recharge to ground water is expected because of scarce precipitation and the limited extent of terrestrial water leads to minimum rate of percolation being exist. Therefore, to manage such kind of problem using remote sensed data is the best means of handle hydrological information in order to monitoring ground water storage dynamics and to store other ancillary information for further analysis.

The Gravity Recovery and Climate Experiment (GRACE) satellite mission's remote sensing data could be used to estimate groundwater storage on an infinite and huge scale around the world, providing a new possibility for groundwater storage evaluation (Rodell et al., 2007). Despite the fact that the GRACE satellite program now offers global-scale data for the identification of temporal gravity changes (Tapley et al., 2014). These temporal gravity changes are not a direct measure of groundwater storage. Through the constantly improving algorithms, a relationship between temporal gravity changes and groundwater storage fluctuations would have to be created (Watkins et al., 2015).

The GRACE satellite data is used to create an integrated assessment of monthly terrestrial water mass shifts a footprint of around 450 x 450 km. To identify how various components of terrestrial water storage (TWS), such as groundwater storage, relate to the total relative monthly change (i.e., TWS) provided by GRACE, observed data and hydrological models must be employed in conjunction with GRACE data (Bonsor & Shamsudduha, 2018).

GRACE data show an in-depth correspondence to in-place groundwater data (to within 10%) e.g. in (Famiglietti et al., 2011) in areas where changes in terrestrial water mass are dominated by groundwater storage, and GRACE data can be directly related to the groundwater mass where long-term depletion is occurring e.g. in (Famiglietti et al., 2011)in areas where long-term depletion is occurring. (Wahr et al., 2004) GRACE data, in combination with other remotely sensed datasets, could be used to discover and describe groundwater storage changes in data-poor regions (rainfall and soil moisture).

This study is aimed to monitor spatial and temporal change of groundwater storage from GRACE. Terrestrial water storage change was derived from GRACE satellite mission and other surface water like soil moisture, plant canopy surface water was extracted from GLDAS. The other data used in this study was Ground water storage change extracted from Global land data assimilation system version 2.2 which is used to correlate with GRACE/GLDAS GWSA to evaluate how strong relation between the two variables. In this study, GPCC precipitations were also used in the water balance evaluation and to evaluate the estimated GRACE groundwater storage behaviors relative to precipitations. In this research, data of 12 years was used and analyzed for all variables. At the end spatiotemporal change of Groundwater storage of East Africa were monitored.

1.2. Statement of the problem

Increasing demand for the delivery of water in arid and semi-arid areas has increased use of groundwater, which leads wide range of depletion. Due to the growth of population, the rate of extracting groundwater to consumption is increasing from time to time as a result the storage of groundwater is being highly depleted even in global context. (Khalid et.al., 2015; Yin et al., 2020) In different part of East Africa especially in arid and semi-arid region since there is scarce of water, Groundwater is pumped for different purpose like freshwater and for irrigation without knowing its variation and storage. Lack of proper estimation of groundwater storage variation is the main reason why groundwater exploitation and management have serious problems compared to surface water in the country. The lack of data on groundwater storage changes makes it difficult to establish and implement appropriate water management plans. Because of the fact that monitoring networks are frequently restricted and it is difficult to generalize point-based observations, significant groundwater storage variation problems in the research region have insufficient information on geographic and temporal variability in groundwater storage. This study monitors timely information on spatiotemporal variation of Groundwater storage of the study area.

1.3. Objective of the study

1.3.1 General objective

The main objective of this study is to monitors spatial and temporal variability of groundwater storage of East Africa from 2008 to 2019 by using Gravity Recovery and Climate Experiment (GRACE/GRACE FO) satellite data.

1.3.2 Specific objective

- To identify spatial distribution of Groundwater storage change of the study area from GRACE data.
- To analyze temporal variability of groundwater storage over East Africa from GRACE data in between 2008 to 2019.

1.4. Research question

- What is the spatial distribution of Groundwater storage variation of East Africa from 2008 to 2019?
- What is the temporal variability of Groundwater storage of East Africa from 2008 to 2019?

1.5. Significance of the study

The significance of this study gives information on Groundwater storage variation both spatially and temporally. This information is utilized in groundwater management to progress toward sustainable groundwater usage and to draw attention to this unseen water resource before it is depleted, causing significant economic, environmental, and social disruption. Another significance of this study were, it used for ongoing research.

1.6. Limitations of the study

The present study uses GRACE and GLDAS data to monitor Groundwater storage variation of the study area. But, since there is inaccessibility of data like in situ groundwater in the study area, it’s limited to use only GRACE and GLDAS data with precipitation.

1.7. Thesis organization

The thesis contains five chapters. Chapter one discusses the background of the study, objectives and significance of the study. Chapter two discusses previous study on GWS change using GRACE/GRACE FO satellite mission, and also explain about GLDAS, GPCC precipitation. Chapter three discusses the methods and materials used in the study. In addition to this, it discusses the study area and data processing. Chapter four contains results and discussion. The result obtained from the data analysis was discussed. Finally, in Chapter five based on the results obtained and the discussion made in chapter four, a conclusion and recommendations were formulated.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

This chapter discusses an overview of groundwater storage change and previous work using GRACE data for GWS change analysis.

2.2. Gravity recovery and climate experiment (GRACE)

2.2.1. GRACE Satellite mission

The American National Aeronautics and Space Administration (NASA) and the German Aerospace Center (Deutsches ZentrumfürLuft- und Raumfahrt-DLR) launched the GRACE satellite gravity mission on March 17, 2002. The GRACE satellite constellation is made up of two co-orbiting spacecraft. The GRACE twins are in orbit around Earth at a distance of 137 miles (220 kilometers), orbiting at a low average height of roughly 450 kilometers, and with an inclination of 89.5 degrees. As the duo travels around the globe, places with somewhat stronger gravity (higher mass concentration) influence the lead satellite first, drawing it away from the following satellite. As the satellites travel over the gravity anomaly, the following satellite is dragged toward the leading satellite.

Although the shift in distance between the satellites would be unnoticeable to the naked eye, GRACE's very precise microwave range equipment is designed to detect it. An accelerometer, which is placed at the center of mass of each satellite, measures non-gravitational accelerations so that only gravity-induced accelerations are taken into account. GPS is a system that can be used in conjunction with GRACE to determine location. The satellite's exact position over the planet is determined to within a centimeter or less by GPS receivers. All of the data from the satellite was used to create a monthly picture of the earth's average gravity field, which shows how mass, mostly water, moves around the planet. Each satellite's payload also included a three-axis accelerometer that measures dynamic effects such as conservative forces, such as solar and Earth radiation pressure, as well as air drag. Change in distance and inter-satellite distance changing rate were utilized to estimate variations in the geo-potential along the twin spacecraft' route after non-gravitational factors were removed. Changes in inter-satellite distances recorded during the orbit reflect variations in Earth's gravity caused by density heterogeneities and topography (Frappart & Ramillien, 2018).

The GRACE project then estimates gravitational coefficients and other dynamical orbit characteristics using least squares estimation to optimize the fit between a predicted orbit (based on gravitational potential) and the observations.

One issue with using GRACE data for this aim is that gravity coefficients for long wavelengths are substantially more accurate than for short wavelengths; as a result, they must be filtered and so replaced average water storage over some spherical disk (Bryan, 1998).

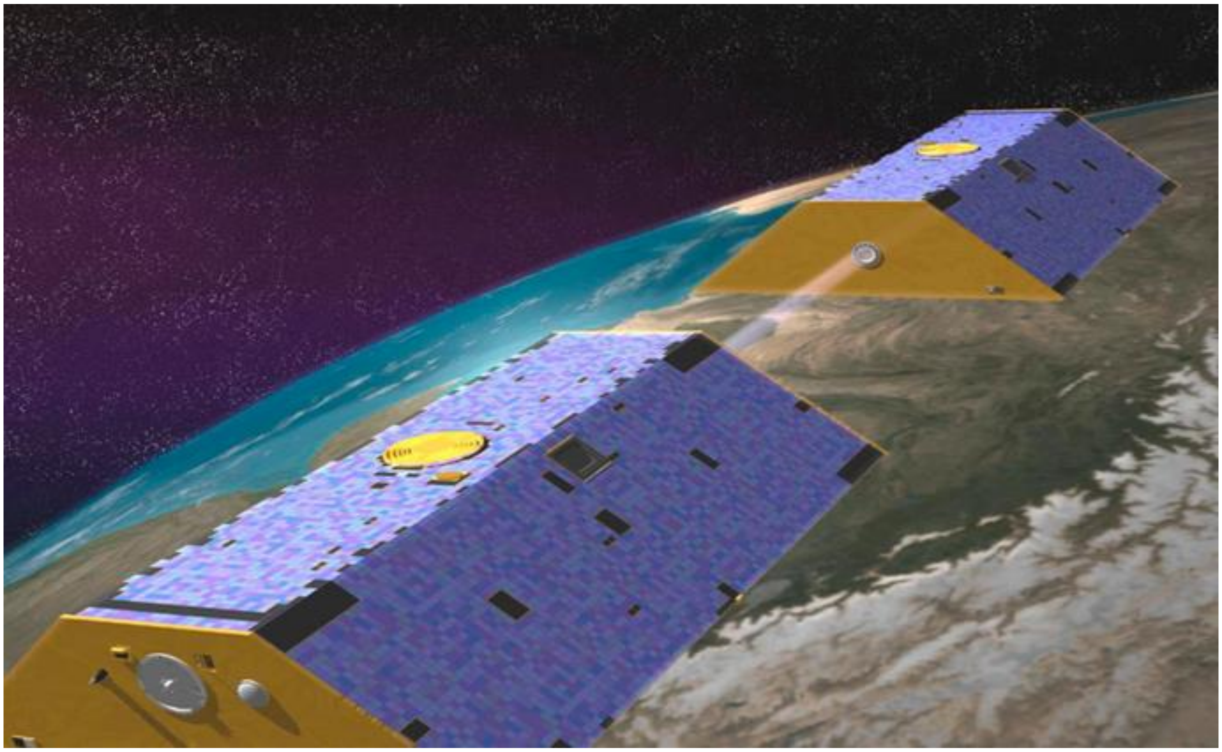


Figure2. 1 shows GRACE twin satellites orbiting the earth surface (source: jpl.nasa.gov)

Satellite instrumentation: The following component is carried by the two satellites: (Thomas, 1999). Antenna for sending and receiving intersatellite transmissions in the k/ka band, For receiving GPS signals, an upward facing L1/L2 band microwave is used. For processing both the GPS signal and the down converted k/ka signal, JPL developed a black jack GPS receiver. A k/ka inter satellite signal down converter The transmitter for producing k/ka transmission signals, The GPS and k/ka systems are driven by an ultra stable oscillator (USO). In addition, each GRACE satellite has a high-precision three-axis accelerometer for measuring non-gravitational forces, and the Stellar Camera ASSEMBLY (SCA) establishes the spacecraft's orientation in relation to a fixed star.

2.2.2. Data frame and accuracy of GRACE data

The GRACE science data center (SDC) produces the level 1 product and level 2 solutions generated from GRACE mission measurements through three official processing locations they are as follows: The Center for Space Research (CSR) is based in Austin, Texas. The GeoForschungsZentrum (GFZ) in Potsdam, Germany, and the Jet Propulsion Laboratory (JPL) in Pasadena, California. The editing, correction, and compression of GRACE Level 1A data, additionally the production of Level 1B data files, are all handled by the Level 1B data processing software system. Raw data (Level 0) collected on-board the GRACE spacecraft are sent to the ground and converted into Level 1A by reformatting and calibration of the Level-0. This process is non-destructive, which means that all level-0 is retained and at their original rates.

In addition to reformatting, the level 1A program gathers data into 24-hour and 30-hour data files centered on noon each day (Landerer, 2021). The following items are included in the Level 1A data: For spacecraft attitude determination, quaternions from two star cameras on the two spacecraft (4 sets of quaternions). Data from each spacecraft's GPS, as well as data from the on-board navigation system and dual-frequency GPS. Data from each spacecraft's accelerometer (angular and linear accelerations). KBR (K-band ranging) readings from each spacecraft, as well as spacecraft and science instrument housekeeping data

The Level 1B method edits and time-tags the Level 1A SCA quaternions, GPS, accelerometer, and housekeeping data while converting the Level 1A KBR data into dual-one-way range, range-rate, and range-acceleration data. These figures were used to create the monthly gravity field model or level 2 products, which are measured in geoids height (Bryan, 1998).

Other research groups may be able to get level 2 GRACE solutions by employing spherical harmonic coefficients (global techniques) or spatial grids (local or regional approaches) with temporal resolutions ranging from one day to one month (Frappart & Ramillien, 2018). Level 2 GRACE product Solution generated utilizing one-day dynamic arcs spanning the stipulated data span as a weighted combination of GPS double differences for each satellite and inter-satellite K-Band Range-Rate. For each double difference observation, the GPS data weight was limited to 2 cm. The appropriate weighting was permitted for the K-Band range-rate (Bettadpur, 2018).

The mass change data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission is now accessible as noisy spherical harmonic coefficients that have been reduced as much as feasible (band-limited). Filtering is thus an unavoidable step in the post-processing of GRACE Fields in order to extract useful information regarding mass redistribution in the Earth system. Varieties are frequently assigned to the spatial resolution of a band-limited spherical harmonic spectrum and also to a filtered field, according to prior studies. In addition, it is now standard practice to correct filtered GRACE data for signal degradation caused by filtering (or convolution in the spatial domain). Because these correction approaches are similar to deconvolution, the spatial resolution of corrected GRACE data must be examined (Vishwakarma, 2018).

Based on Land Surface Model (LSM) outputs, an early research predicted a measurement accuracy of a few millimeters of equivalent water height (EWH) in terms of mass surface density (and for a reference water density of 1000 kg/m^3) over regions of 400 km by 400 km. The presence of noise at the shorter wavelengths was predicted to influence the TWS retrieval (Bryan, 1998). Furthermore, when the area diminishes, spectral truncation errors grow. The changes in TWS may be observed if they exceeded 1.5 cm of EWH across an area of 200,000 km² based on LSM outputs and the projected accuracy of the GRACE land water solutions(Rodell et al., 2004). For a drainage area of 400,000 km², the GRACE land water solutions were projected to be accurate to within 0.7 cm EWH, and 0.3 cm for a drainage area of 4,000,000 km² (Swenson & Wahr, 2003). The spatial resolution of today GRACE products is a few hundred kilometers (around 200 km for the Mascons solutions and the regional solutions and 330 km for the releases 03 to 05 for a typical degree of truncation of 60). At the Equator, errors expected to occur to be roughly 40 mm, decreasing to 15 mm in the Polar Regions.

2.2.3. GRACE Total water storage anomaly

The GRACE satellite has supplied monthly estimates of global gravity fields since 2002, which are then processed into vertically integrated Total Water Storage Anomalies(TWSA)

(Syed et al., 2008) that can be used to evaluate the behavior of a variety of hydrologic factors counting lake and reservoir storage (Awange et al., 2008; Becker et al., 2010; Hassan & Jin, 2014; Swenson & Wahr, 2009; Wang et al., 2011) and groundwater storage (Castle et al., 2014; Rodell & Famiglietti, 2002; Rodell et al., 2009b; Rodell, Chen, Kato, et al., 2007; Voss et al., 2013; Yeh et al., 2006). The Gravity Recovery and Climate Experiment (GRACE) data provide a new opportunity to gain a direct and independent measure of water mass variations on a regional scale. GRACE and its successor, GRACE Follow-On, measures total water storage of the continent. They are designed to measure the changes in the attraction of gravity of the earth that is resulted from the changes of the Earth's mass. When the GRACE twin satellites move on their circle, one taking after the other, the mass alter underneath the satellites changes the difference in altitude between the two satellites slightly. Therefore, this alter is analyzed and prepared to form month to month worldwide maps of alter and redistribution on the earth mass close the surface. This change in mass of the earth is mostly due to the water movement on the surface underneath the surface of the earth (Smith, 2019). GRACE satellite utilized for the outcome of monitoring the spatiotemporal change of the water cycle at expensive scale rapidly. For regions larger than 200000 km², the TWS changes with intervals on month and longer time scale can be checked, and the exactness can reach 1.5 cm and above (Jiang et al., 2014).

In 2014 the review on GRACE data application shows that GRACE presents a novel way for studying terrestrial hydrology that may be used in other fields, utilized in order to improve the monitoring outcome of the spatiotemporal alter of the water cycle at a large scale rapidly. The paper also discuss a description of GRACE datasets and latest applications of GRACE data: including Changes in terrestrial water storage evaluation, hydrological components of groundwater and evapotranspiration (ET) retrieving, droughts analysis, and glacier response of global variation (Jiang et al., 2014).

GRACE data was combined with Hydrological data that like GLDAS data to obtain estimate of changes in Ground water storage by subtracting surface water from the GRACE total water storage results (Joodaki & Wahr, 2014).

2.3. Hydrological models

2.3.1. Global land data assimilation system (GLDAS)

A Global Land Data Assimilation System (GLDAS) has been developed jointly by scientists at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) in order to produce such fields. GLDAS takes use of a new generation of ground- and space-based observation technologies to use data to restrict the modeled land surface states. Constraints can be used in two different ways. Land surface models (LSMs) can be forced with observation-based meteorological fields to prevent biases in atmospheric model-based forcing. Second, observations of land surface states can be utilized to limit unrealistic model states via data assimilation techniques (Rodell et al., 2004).

Using complex land surface modeling and data assimilation techniques, GLDAS is a NASA project that will absorb satellite and ground-based observational data sources and construct optimum fields of land surface states and fluxes (Aeronautics, 2019; Rodell et al., 2004).

GLDAS' high-quality global land surface fields enable a variety of present and prospective weather and climate forecasting, water resource applications, and water cycle studies. GLDAS is a huge library of worldwide surface meteorological data modeled and observed, parameter maps, and, output, including 1-degree and 0.25-degree resolution Noah, CLM, VIC, Mosaic, and Catchment land surface model simulations from 1948 to the present. NASA GLDAS-2 is now available and may be used for a variety of investigations.

GLDAS-2.0, GLDAS-2.1, and GLDAS-2.2 are the three components of NASA GLDAS-2. GLDAS-2.0 presently covers the years 1948 to 2014, with newer years being added as the dataset becomes available. From 2000 to the present, GLDAS-2.1 is forced using a combination of model and observation data. Data assimilation is used in the GLDAS-2.2 product suites, whereas the GLDAS-2.0 and GLDAS-2.1 products are "open-loop" (i.e., no data assimilation). For various GLDAS-2.2 products, the forcing data, as well as the Data Assimilation observation the source, variable, and scheme are all different. On January 1, 2000, the GLDAS-2.1 simulation began with the same circumstances as the GLDAS-2.0 experiment. GLDAS-2.0 includes a daily data product from Catchment Land Surface Model F2.5 (CLSM-F2.5) and four data products from Noah LSM. The atmospheric analysis fields from the (NOAA)/ (GDAS) were used to drive this simulation (Aeronautics, 2019), These GLDAS-2.0 Noah products were previously available in the GES DISC archive, however they were reprocessed in November 2019 with updated Princeton meteorological forcing data and the improved Noah-3.6 LSM. GLDAS-2.1 data products are now available in two production streams: one (the primary production stream) is forced using combined forcing data including GPCP version 1.3, while the other (the secondary production stream) is processed without it (the early production stream). Due to the 3-4 month delay of the GPCP Version 1.3 data, the GLDAS-2.1 data products are first developed without it, and are labeled as Early Products, with 1.5 month latency. Once the GPCP Version 1.3 data is ready, the GLDAS-2.1 data products are processed in the main production stream and removed from the Early Products repository. Two CLSM-F2.5 items, two VIC-4.1.2 products, and four Noah-3.6 goods are now part of the GLDAS-2.1 main production stream. The GLDAS-2.1 collection now includes the Catchment and VIC model data items. The Noah products were publicly accessible in the GES DISC archive until January 2020, when they were reprocessed using the updated Noah-3.6 LSM. All GLDAS Version 001 (GLDAS-1) products are replaced by the GLDAS-2.1 main production stream. The GLDAS-1 forward stream will terminate in March 2020, and all GLDAS-1 devices will be retired in June 2020.

GLDAS-2.2 is a new addition to the GES DISC archive, containing a primary product from CLSM-F2.5 with Data Assimilation for the Gravity Recovery and Climate Experiment (GRACE-DA) from February 2003 to the present. GLDAS-2.2 will be accessible in two production streams, similar to GLDAS-2.1: one with GRACE data assimilation outputs (the primary production stream) and one without GRACE-Data Assimilation.

2.3.2. GPCC Precipitation

The World Meteorological Organization requested the establishment of the Global Precipitation Climatology Centre (GPCC) in 1989. (WMO). As a German participates to the World Climate Research Programme, it is managed by Deutscher Wetterdienst (DWD, German National Meteorological Service) (WCRP). The GPCC's mission is to conduct a worldwide study of daily and monthly precipitation on the earth's land surface using data from in situ rain gauges (Schneider et al., 2010; Schneider & Wetterdienst, 2021). The goal of the GPCC is to meet user needs, particularly in terms of gridded precipitation analysis accuracy and product availability timeliness. Over example, the WCRP Program Global Energy and Water Exchanges (GEWEX) seeks high geographic resolution and accuracy for the previous two decades, but GCOS and the IPCC (Intergovernmental Panel on Climate Change) place a premium on long-term homogenous time-series in the context of climate change. Data processing and analysis cut-off dates ensure that things are supplied on time. The GPCC analysis deliverables are created using the same quasi-operational data management and analysis technology. They range in terms of the number of stations (data sources) included and the amount of quality control undertaken, depending on the needs (Becker et al., 2013; Rudolf et al., 2010; Schneider et al., 2014; Schneider & Wetterdienst, 2021). The GPCC's many products are utilized by a variety of institutions across the world, particularly in the context of WMO, WCRP, and other water and climate-related research and monitoring operations he updated GPCC Precipitation Climatology (V.2020) covers the years 1951 to 2000 and includes normals from about 84,800 stations. The climatology is made up of normals gathered by WMO, supplied to GPCC by nations, or computed from monthly data time series accessible in its database (Rajeevan et al., 2006; Rubel & Kottek, 2010; Wild et al., 2008). All precipitation data received is kept in the data bank individually for each data source (CLIMAT, DWD-SYNOP, CPC, National, Regional Projects, CRU, FAO, and GHCN), along with metadata and quality indicators (Becker et al., 2013; Rubel & Kottek, 2010; Rudolf et al., 2010; Schneider & Wetterdienst, 2021; Wild et al., 2008). The comparison of data from various sources is a useful tool for quality control and evaluation of the data that will be used for analysis.

This data base is used to create all goods, which are created by selecting data based on data quality and product parameters. GPCC's near real-time monitoring of terrestrial monthly precipitation is based on data from various sources, which are reviewed and integrated to increase geographical coverage and data quality (Rudolf et al., 2010).

Its data may be downscaled using proper methodologies and is valuable for large-scale hydrological applications, research of climate trends and extremes, drought monitoring, and rainfall probability estimates.

2.4. Groundwater storage change

Water is an essential human requirement; therefore, it must be carefully managed and maintained. Ground water, in particular, has been used for a broad range of purposes, resulting in depletion of ground water both globally and nationally; as a result of population expansion, ground water extraction is increasing. On the other hand, the amount of ground water recharge and loss has been a dynamic character in the spatiotemporal aspect, posing a difficulty in managing it accurately. Groundwater has provided the majority of global water development in recent decades. Currently, an estimated 70% of the world's population relies on groundwater for basic residential water supplies. In 51% of nations, yearly groundwater extraction exceeds 100 m^3 per capita. In rural economies in India, South Asia, China, North Africa, and the Middle East, groundwater has generated miracles of faster agricultural productivity (FDRE Ministry of water Resources, n.d.). Groundwater is critical for East Africa's economic growth, as well as to complement current surface water resources in supplying drinking water to its people and mitigating the impacts of climatic variability. There are still a lot of unanswered questions in groundwater knowledge, capability, and management systems. There are notably huge gaps in our understanding of very shallow aquifers (less than 30 meters) and deep aquifers (FDRE Ministry of water Resources, n.d.). According to the Addis Ababa Environmental Protection Agency, the groundwater wall is estimated to be around 1000. This demonstrates that groundwater extraction is abundant; consequently, a model of how the quantity of recharge and loss changes is required to fill the gap shortage.

As demonstrated by (Chen et al., 2016; Famiglietti et al., 2011; Scanlon et al., 2015), it is conceivable to simulate ground water dynamics from earth mass redistribution with probable worldwide validation. GRACE data have been highly utilized to process long-term groundwater storage variation in a variety of locations around the world, including India, the United States' High Plains Aquifer and Central Valley, the Middle East's North China Plain, and Australia's southern Murray–Darling Basin (Chen et al., 2016).

According to various studies, GRACE time-variable gravity solutions' 13-year record provides a revolutionary means of measuring water mass movement and redistribution in the global water cycle, as well as a unique tool for monitoring Changes in long-term groundwater storage at continental to global scales. Finally, they could show that uncertainty in GRACE low-degree spherical harmonic coefficients should have a little impact on GRACE groundwater estimations, because groundwater depletion scales are often much lower than the length scales of such harmonics. GRACE time variable gravity measurements will continue to offer great potential for improving understanding of the world's water cycle, as well as monitoring and quantifying long-term variability in groundwater resources globally, thanks to the long record (now 13 years) of GRACE statistics and improvements in data quality and data processing methods (Chen et al., 2016).

The study presents a nonparametric way to use GRACE's forecasting capability that is reasonably simple. The utility of a newly published, gridded GRACE product as a substitute for regularly monitored in situ water level measurements, which have shown an excellent drop in coverage, was investigated. Groundwater agencies, particularly in semiarid areas, are interested in observing groundwater table changes in order to manage aquifers sustainably. PRISM monthly precipitation, maximum and lowest temperatures, and GRACE TWS were employed as inputs in the nonparametric ANN models used in the experiments. The change in groundwater level is the variable of interest. The wells that were examined are in various geographical and climatic zones across the United States (Sun, 2013).

The GWSA estimations acquired from GRACE derived data gave possibilities to examine groundwater conditions in remote ungauged places as the research worked in the Alberta and Canadian basins between January 2003 and April 2015. They calculated GWSA in the examined basins using two newly published satellite products. The soil moisture and snow water equivalents were calculated using a mix of surface water observations and land surface model calculations. In general, the GRACE predictions correspond well with the observed estimates, meaning that GRACE data might be utilized to monitor groundwater storage in the region at a near-continuous rate in the future. The GWSA patterns show depletion in a number of basins dominated by anthropogenic groundwater removal, whether from irrigation or home and industrial uses, as the author illustrated. In the Athabasca River basin, a GWSA depletion rate of 0.20 cm per year has been found (Bhanja et al., 2018).

Groundwater depletion patterns in the northwest Indian state of Gujarat (surface area of 196 030 km^2) were shown using Gravity Recovery and Climate Experiment (GRACE) satellites and simulated soil moisture fluctuations from land data assimilation systems.

GRACE produced results highly correlated with well data when compared to direct measurement data from in situ measurement. GRACE data is a useful technique for complementing and interpolating observed regional groundwater well data and improving groundwater storage calculations, according to the findings. GRACE data may be utilized in conjunction with available observed well data to better define geographical and temporal changes in groundwater depletion and recharge, demonstrating that it is beneficial to enhance quantitative evaluations and hence management of groundwater supplies. Finally, he believes that GRACE/GLDAS and recorded groundwater level have a positive association, bolstering the methodology as a feasible method for establishing multiyear correlations (Chinnasamy & Hubbart, 2013).

GRACE data are utilized to track monthly variations in total water storage over the center East, according to a research conducted in the Middle East by the broad agreement between well data and GRACE-minus-SSCR Estimations for Iran lend some credence to the overall trends of GRACE-minus-SSCR Groundwater time series for Middle Eastern locations other than Iran. In addition, the data for eastern Turkey, Iraq, and northern and southern Saudi Arabia were smoothed GRACE-minus-SSCR. From February 2003 to December 2012, the data show a substantial, negative association in total water storage over western Iran and eastern Iraq. In addition, the data for eastern Turkey, Iraq, and northern and southern Saudi Arabia were smoothed GRACE-minus-SSCR. From February 2003 to December 2012, the data show a substantial, downward trend in total water storage over western Iran and eastern Iraq. Other Middle Eastern locations lost groundwater between 2003 and 2012, according to the GRACE-minus-terrestrial model results. Groundwater loss rates in Iraq, eastern Turkey (east of 35 longitude), northern Saudi Arabia, and southern Saudi Arabia (north and south of 25 latitude), respectively, are estimated to be 263 Gt/yr, 567 Gt/yr, 663 Gt/yr, and 562 Gt/yr. To monitor such high variability of ground water satellite based estimation with dense ground wall is a good approach to validation (Joodaki and Wahr, 2014).

GRACE indicates distinct seasonal TWS responses of 1-5 cm/year for all African basins, with the exception of the Congo, North Kalahari, and Senegal basins, which exhibit greater seasonal TWS corresponding to approx. 11-20 cm/year. Seasonal GWS derived by integrating GRACE TWS and LSM outputs differs from in situ groundwater recharge measurements from various basins, underlining the need for better depiction of the recharge process in LSMs and, as a result, additional in situ piezometry data (Bonsor & Shamsudduha, 2018).

These findings highlight the importance of future LSM refinement in order to understand groundwater recharge processes, as well as the significant uncertainty in calculating seasonal groundwater storage fluxes using GRACE GWS anomalies and LSMs. Finally, they came to the conclusion that seasonal groundwater behavior is often investigated by combining TWS from different GRACE products with rainfall and land use information. Interpreting TWS from an ensemble of GRACE products using a typical statistical technique may also be used to infer long-term groundwater reaction (Bonsor & Shamsudduha, 2018; Rodell et al., 2004).

2.5. Summary

The main aim of this study was to monitor Groundwater storage change of East Africa by using GRACE satellite mission to give information on Groundwater storage variation both spatially and temporally as this information is utilized in groundwater management to progress toward sustainable groundwater usage. Different study monitors GWSA in different area by using GRACE and other geodetic technique. In East Africa GWSA were also monitored by excluding some country in Horn of Africa like Ethiopia, Djibouti, Somalia and other. In addition to this Global land data assimilation system version 2.2 were not used in the study. Therefore, this study fill the gap observed in the study area.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Description of study area

The study area is located between 27.5˚W and 55.5˚ E Longitude and -12.5˚ S and 20.5˚ N latitude. This sub-Saharan African area has the most vulnerable populations to water scarcity. Due to climate change, population expansion, and development, water scarcity is predicted to worsen in a number of countries within the region (Meigh et al., 1999; Falkenmark, 1997; Fischer & Heilig, 1997; Wallace, 2000).

Direct infiltration from precipitation and favoured channels replenish groundwater inside weathered zones and bedrock fissures (Macdonald et al., 2016)

The average annual rainfall in the research region ranges from >2000 mm/yr in Lake Victoria and in hilly areas to less than 200 mm/yr in desert and semi-arid areas (Nicholson, 1996) Rainfall is influenced by a variety of meteorological phenomena, ranging from 200 mm/year in desert and semi-arid countries to the Inter Tropical and mountainous zones (Nicholson, 1996)

In East Africa, groundwater recharge is a consequence of rainfall and occurs across sections of basement aquifers; considerable recharging has been seen during major rainfall events (MacDonald et al., 2010; Owor et al., 2009; Taylor et al., 2013). Groundwater recharge is also geographically varied across the region, with wet and humid areas getting greater recharge than semiarid areas (Gavigan et al., 2009). Groundwater recharge and storage in East Africa may increase in the future if global rainfall model predictions are accurate (Gavigan et al., 2009) as global climate models predict an increase in mean precipitation rates and intensity over East Africa during the twenty-first century (Shongwe et al., 2011) Current groundwater consumption rates and storage capacity, however, are poorly understood. Growing population demand and usage of groundwater (Carter & Parker, 2009) might possibly counteract the effects of increased recharge, resulting in storage reductions, as some portions of this region have already seen (Mogaka et al., 2006).

Because groundwater is the most important source of drinking water for rural populations and municipal and industrial water for urban areas (Wijnen et al., 2012) such decreases have significant social and economic ramifications. This analysis of the groundwater storage change using GRACE was done at largest basin which classified at global scale and assumes that groundwater boundaries are coincident with surface water boundaries. The study area was classified into three basins those are Nile, Jubba Shebelle and Lake Rudolf.

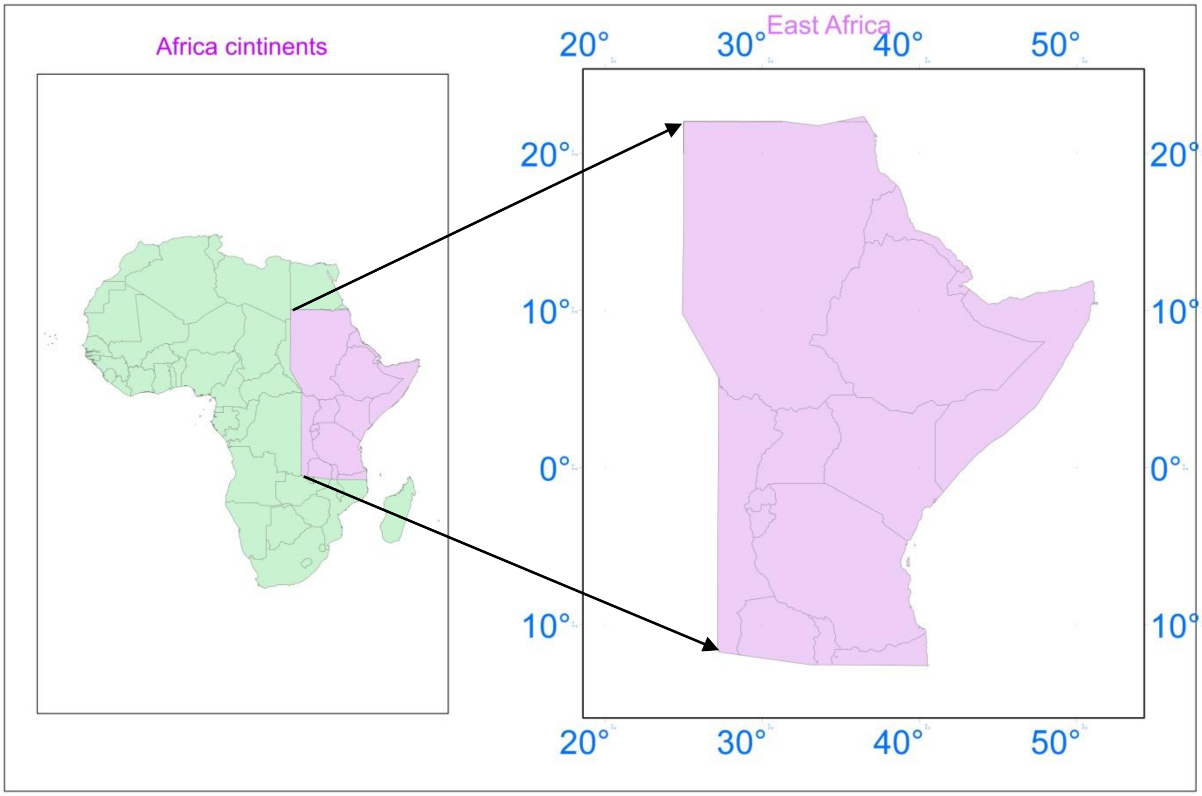


Figure 3. 1 Location map of the study area

3.2 Data

3.2.1. GRACE Data

GRACE data products are derived from a system known as the GRACE Science Data System (SDS). It's a distributed system, the GRACE SDS. The Jet Propulsion Laboratory (JPL), The University of Texas at Austin, and the Center for Space Research (UTCSR), as well as the GeoForschungsZentrum (GFZ), collaborate on system development, data processing, and archiving (GFZ) (Case et al., 2010).

GRACE data packages come in a variety of processing levels, version numbers, and processing levels. The GRACE Raw Data Center (RDC) at DLR in Neustrelitz received, collected, and de-commuted telemetry data to produce Level-0 data products (Case et al., 2010). The Science Instrument and Spacecraft Housekeeping data streams are isolated from the telemetry data from each satellite during each down-link pass and stored in a rolling archive at the RDC. Each Level-0 data product file comprises the unscaled, binary encoded instrument communication packets in addition to the relevant headers. The GRACE SDS collects these data from RDC's rolling archive and saves them in permanent archives at JPL and GFZ's SDS facilities. Non-destructive processing is used to create Level-1A data products from Level-0 data. In order to convert binary encoded readings to engineering units, sensor calibration factors are used. Time linked to the relevant satellite receiver clock time as necessary. The data is reformatted for further processing and editing and quality control flags are added. Except for faulty packets, level 1A data can be reversed to level 0. The auxiliary data products required for processing to the next data level are also included at this level (Case et al., 2010).

This level contains extra data products that are necessary for the following data level's processing. The Level-1B Data Products are the outcome of possibly damaging (irreversible) processing of both Level-1A and Level-0 data. The sample rate of the data is reduced or decreased from prior higher rate levels after time tagging. The level 1B data are obtained from the level 1A and level 0 data after potentially irreversible processing (Case et al., 2010).

The extra data products created during this processing, as well as other data required for subsequent processing, make up the outcome of level 1B data. The gravitational field and related data products obtained from Level-2 processing of prior level data products are included in the Level-2 data products. The auxiliary data products created during this processing are likewise included at this level. Level-2 data is created by applying Level-2 processing to prior level data products. Level-2 spherical harmonics are sent into Level-3 post-processing stages. Spatial sample of one degree in latitude and longitude, about 111 km at the equator, is used in all grids of the data. However, this does not imply that cells in two adjacent grids are independent. Because GRACE and GRACE-FO have a geographical resolution of around 330 km, spatial smoothing has been used. The new GRACE level-3 data packages are available in a variety of data formats to meet the demands of a wide range of users. NetCDF, ASCII, and Geotiff are the available formats (land only). Each monthly

GRACE Tellus grid indicates the monthly surface mass variation compared to a baseline temporal average (usually 2004-2009) (Landerer, 2021).

The spatial sample of the mascon data is 0.5 degrees in both latitude and longitude. This is in contrast to spherical harmonic solutions, which have a spatial sample of 1 degree in both latitude and longitude. The mascon's limits are on Parallels of roughly 0.5-degree increments, which explain the disparity. Despite the fact that the grid is sampled at a precision of 0.5 degrees. The data and error grids are measured in Liquid Water Equivalent Thickness (in meters or centimeters), and the gain factors (scaling factors) are dimensionless and time-invariant. The grids include 360 latitude points (-89.75, -89.25... 89.25, 89.75) and 720 longitude points (0.25, 0.75, 1.25... 359.75) (Landerer, 2021).

For this Study GRACE Mascon data is used for three main reasons as described in the GRACE L-3 data user manual. These are:

- Constrained mascon solutions obtained from geophysical models, unlike unconstrained spherical harmonic solutions, do not need to be de-striped or smoothed, and have less leakage errors than harmonic solutions.
- With the coastal resolution improvement (CRI) filter and the use of state-of-the-art gain factors, the mascon technique provides for a better separation of land and ocean sounds.
- When computing basin averages for hydrological applications, harmonic and mascon solutions are often in accord for large basins; however, mascon solutions typically offer a higher resolution for smaller spatial areas, which is especially important when analyzing secular signals.

3.2.2. GLDAS Data

GLDAS could be a vigorous recreation framework that consolidates in situ ground estimation and fawning based observational information items, utilizing progressed land surface modeling and information absorption methods, with the objectives of creating ideal areas of land surface state for SM, snow and surface temperature, and flux for evapotranspiration and sensible warm flux items, at worldwide scales and high spatial resolution(0.25˚ to 1˚) in real time (Rodell et al., 2004). GLDAS drives four land-surface models, namely NOAH (Ek et al., 2003), Community Land Model (CLM) (Dai et al., 2003), MOSAIC (Koster and Suarez ,1992) and Variable Infiltration Capacity (VIC) (Liang et al. 1994). GLDAS data are exists in spatial resolutions of 0.25˚, 0.5˚, 1˚, 2˚ and 2.5˚ latitude by longitude with temporal resolution of adjustable model time step and output interval.

In this study for the purpose of simplicity, the GLDAS CLM model is used to gets the SM and PCSW at a spatial resolution of 1˚ with monthly temporal resolution.

3.2.3. GPCC Precipitation Data

In the global energy and water cycle, precipitation plays a critical role. Groundwater evaluation and management rely heavily on accurate understanding of precipitation reaching the ground surface. The need to understand climate change and its implications on all geographic and time scales has sparked a lot of interest in long-term precipitation investigations. Many research and monitoring programs have been created and supported by national and international organizations in response to this need (Schneider & Wetterdienst, 2021). The World Meteorological Organization requested the establishment of the GPCC in 1989, and it was founded in 1989 (WMO). As part of Germany's commitment to the United Nations Framework Convention on Climate Change (WCRP), it is run by Deutscher Wetterdienst (DWD, German National Meteorological Service) (Wetterdienst et al., 2021). It was made with the intention of evaluating daily and monthly precipitation on the earth's land surface using data from in situ rain gauges. It's made to fulfill the demands of the users, particularly in terms of gridded precipitation analysis accuracy and product availability timeliness.' In geographic resolutions of 0.25°, 0.5°, 1.0°, and 2.5° latitude by longitude All GPCC products, which are gauge-based gridded precipitation data sets for the whole globe, are available. The database contains data from more than 123,000 different stations, being the largest precipitation database of the world (Wetterdienst et al., 2021).

Data Monthly Product V.2020 is of much higher accuracy compared to the GPCC near real-time products. Therefore, Its used for hydro meteorological model and water cycle studies, in context of UNESCO, GEWEX, and GTN-H (Global Terrestrial Network for Hydrology) (Wetterdienst et al., 2021). For this research Global precipitation climatology center version 2020 of 0.5° by 0.5° spatial resolution with NetCDF format was used.

The GPCC precipitation was used for this investigation because it offered a more consistent water storage shift with GRACE and hydrological signals.

Table 3. 1 Summary of data used in the study

Data type	Data name	Data Access	Spatial and Temporal Resolution, period used
GRACE	TWSA	**http://grace.jpl.nasa.gov/**	0.5°×0.5°,monthly,2008-2019
GLDAS-LSMs	SM+PCSW, Evapotranspiration	**https://disc.gsfc.nasa.gov/**	1°×1°, monthly, 2008-2019
	GWSA from GLDASv2.2		0.25°×0.25°, daily, 2008-2019
GPCC	Precipitation	http://gpcc.dwd.de	0.5°×0.5°, monthly, 2008-2019

3.3. Methods and Data Processing

3.3.1 GRACE TWS data

GRACE Data processing aims to determine the monthly Terrestrial water storage (TWS) of the Study Area. To process and achieve the goal of the study, the Level-3 RL06 V2.0 GRACE mascon solution dataset were downloaded from the NASA website, NASA JPL site https://grace.jpl.nasa.gov, and used. The mascon datasets include mascon file, land mask, mascon placement, and scale factors. This GRACE data was available in NetCDF, ASCII file and Geotiff format. Off this, NetCDF format were used since all other data used for this study was similar format and easy to extract using matlab software. After data was downloaded from official website of NASA, it was extracted with the boundary of the study area and the result is multiplied by gain factors and then, by land mask to separate the land from ocean. GRACE Mascon data have a spatial resolution of 0.5°×0.5°, which was resample to 1°×1° resolution after extracted and processed since the spatial resolution of the other variable used in this study was 1°×1° resolution. Missing data is filled using the cubic spline interpolation approach since the GRACE data misses certain month data. Spline calculates values using a mathematical function that reduces total surface curvature, yielding a flat surface that properly passes across all input points. For gradually variable surfaces, such as elevation, water table heights, or pollutant concentrations, this strategy works well (Spline interpolation). Because the area's total water storage is a softly fluctuating variable, this strategy was chosen. Then, spatial map and time varying series graph of the Terrestrial water storage change of the study area were prepared and Groundwater storage anomalies were derived from it.

3.3.2. SM and PCSW Data from GLDAS and GWSA from GLDASv2.2

GLDAS is hydrological model used to monitors land surface fields at high spatial resolution and in near real time to supply land surface models. Groundwater, soil moisture and plant canopy surface water are the significant contributors to the regional water storage observations. That soil moisture and plant canopy surface water are output from sophisticated land surface models called Global Land Data Assimilation System (GLDAS). To extract and analysis those data, GLDAS_CLSM10_M2.1 dataset were downloaded from NASA/GLDAS official web site, https://disc.gsfc.nasa.gov/datasets and used. GLDAS data was available in Net CDF format which was suitable for extraction. After soil moisture, snow water equivalent and plant canopy surface water was downloaded from official website of GLDAS GES DISC and it was extracted by using matlab software. In this study snow water equivalent changes are expected to be minor and negligible since it contribute less than one percent to total water storage. Then, soil moisture and plant canopy surface water change are subtracted from Terrestrial water storage change obtained from GRACE to get Ground water storage anomaly of the study area. GLDASv2.2 is other model used to simulate Groundwater storage in a global scale. It provides spatial resolution of 0.25˚ by 0.25˚ in both longitude and latitude with daily temporal resolution. These resolutions were resembled to 1˚ by 1˚ spatial resolution and monthly temporal resolution to make similar with other variable used in the study. To determine the monthly GWSA of GLDASv2.2, the mean monthly GWS for each basin was first determined by averaging the monthly values, and then the monthly values were subtracted from the mean monthly GWS to derive the GWSA (Ouma et al., 2015). Then its value was correlated with GRACE derived GWSA to check their relationships.

In all basins Ground water storage change obtained from GRACE-GLDAS and GLDASv2.2 shows same trends. These indicate that the estimated groundwater storage changes are reliable.

3.3.3. Spatial distribution of GWS change from GRACE

Groundwater storage change was isolated from GRACE derived TWS change which other components were obtained from other hydrological model. As explained above, filtered soil moisture and plant canopy surface water were subtracted from filtered Terrestrial water storage to get filtered Groundwater storage change as equation below:

$$\Delta\mathrm{TWS} = \Delta\mathrm{GWS} + \Delta\mathrm{SM} + \Delta\mathrm{PCSW} + \mathrm{SWE} \qquad (1)$$

From equation (1) Groundwater storage anomaly was determined as below:

$$\Delta\mathrm{GWS} = \Delta\mathrm{TWS} - (\Delta\mathrm{SM} + \Delta\mathrm{PCSW})$$

Where, Δ is monthly anomaly, GWS is Groundwater storage, SM is soil moisture, PCSW is plant canopy surface water. In this case, snow equivalent water were minor and ignored in equation (1) as it contribute less than 1% to the TWSA. After that spatial distribution of the Groundwater storage change were analyzed in all over the study area.

3.3.4. Temporal change of GWS

To analysis temporal variation of GWS the study area was classified based on the basin considered in the study area. Accordingly three basins were considered since those basins are all most cover the all study area except at some edge. Thus the considered basin was Nile, Jubba Shebelle and Lake Rudolf basins. Based on the above equation of Groundwater storage change, temporal changes of the considered period were analyzed for all basins. To do so, time graph of each basin were plotted and its decline or increasing rate were determined.

3.3.5. Precipitation from GPCC

Global daily or monthly precipitation data is disseminated by the GPCC in spatial resolutions (from 0.5˚ to 2.5˚, or roughly 50-250 km) for different time periods. In this research Precipitation data was downloaded from GPCC website (http://gpcc.dwd.de) and extracted by using Matlab software with the boundary of the study area. The spatial resolution used for this study was 0.5˚×0.5˚ (55.5km) resolution with NetCDF format and resample into

1˚×1˚ resolution for making similar with other variables used in this study in order to process and analysis. The resample data were smoothed by Gaussian smoothing to remove systematic and random error similar to GRACE for use in the study. GPCC precipitations were used in the water balances evaluation by subtracting Evapotranspiration and runoff discharge by water balance equation as below:

$$\mathrm{WB} = \mathrm{P} - \mathrm{ET} - \mathrm{R} \qquad (2)$$

Where, WB is Water balance, P is Precipitation, ET is Evapotranspiration and R is Runoff discharge, Evapotranspiration and runoff discharge were obtained from Global land data assimilation system.

The water balances obtained from Global precipitation climatology center were used to correlate with GRACE Terrestrial water storage change to evaluate the estimated GRACE groundwater storage behaviors relative to precipitation changes .

3.4. Correlation analysis and trend

In research, correlation analysis is a statistical approach for calculating the link between two variables and measuring the strength of the linear relationship between them.

A positive correlation, a negative correlation, or no correlation might exist between two variables. When two variables have a positive correlation, it suggests they move in the same direction. Increases in one variable lead to increases in the other, and vice versa. When two variables have a negative correlation, the variables move in opposing directions. Increases in one variable result in decreases in the other, and vice versa.

Weak/zero correlation: When one variable has no effect on the other, there is no correlation (Schober & Boer, 2018; Senthilnathan, 2019). Pearson's Product Moment Correlation Coefficient and Spearman's Rank Correlation Coefficient are the two most commonly utilized correlation coefficients in applications (Schober & Boer, 2018; Senthilnathan, 2019). Pearson's correlation coefficient is a statistical tool for determining how strong a linear link between two sets of data is. The Pearson's correlation coefficient (r) is a number that ranges from -1 to +1. A value of 1 shows that the two variables are perfectly linked. The association between the two variables will get weaker as the correlation coefficient value approaches zero. The sign of the coefficient denotes the direction of the relationship; a + sign denotes a positive relationship, while a – sign denotes a negative relationship'. The range of r's value indicates the correlation's strength. A value of r between -0.5 and +0.5 suggests a moderate correlation, a value between -1 and -5 and 0.5 to 1 indicates a high connection, and a value of 0.0 indicates no correlation (Alem, 2020; Senthilnathan, 2019).

The Pearson's correlation coefficient, **r**, is mathematically described as below:

$$r = \frac{n\Sigma(xy) - (\Sigma x.\Sigma y)}{\sqrt{[n(\Sigma X^2) - (\Sigma X^2)][n(\Sigma y^2) - (\Sigma y^2)]}} \qquad (3)$$

Where, n = Number of observations; x = Measures of Variable 1; y = Measures of Variable 2;

Σxy = Sum of the product of respective variable measures; Σx = Sum of the measures of Variable 1; Σy = Sum of the measures of Variable 2; Σx2 = Sum of squared values of the measures of Variable 1 ad Σy2 = Sum of squared values of the measures of Variable 2.

To study Groundwater storage change from GRACE data, the interrelation between different parameters were first visually analyzed. Soil moisture, plant canopy surface water, Evapotranspiration and Runoff from GLDAS, precipitation of GPCC and TWS of GRACE are the variables used in this study. Additionally, GWSA of GLDASv2.2 was used. Data of 2008 to 2019 were used for all variables and their correlation was analyzed using the Pearson's product moment correlation method.

3.5. General work flow of the study

To study spatial and temporal change of Groundwater storage different data were used and analyzed. Monthly Terrestrial water storage is extracted from GRACE. Soil moisture, plant canopy surface water, Evapotranspiration and surface runoff were extracted from GLDAS and Precipitation from GPCC and GWSA from GLDAS V2.2 were extracted and analyzed. In this case, filtered SM and PCSW were subtracted from filtered GRACE TWSA to get GWSA and correlated with filtered GWSA obtained from GLDASv2.2. Those data were processed by using matlab software and their statistical analyses were computed to check the strength of relationship between the data to achieve the objective of the study.

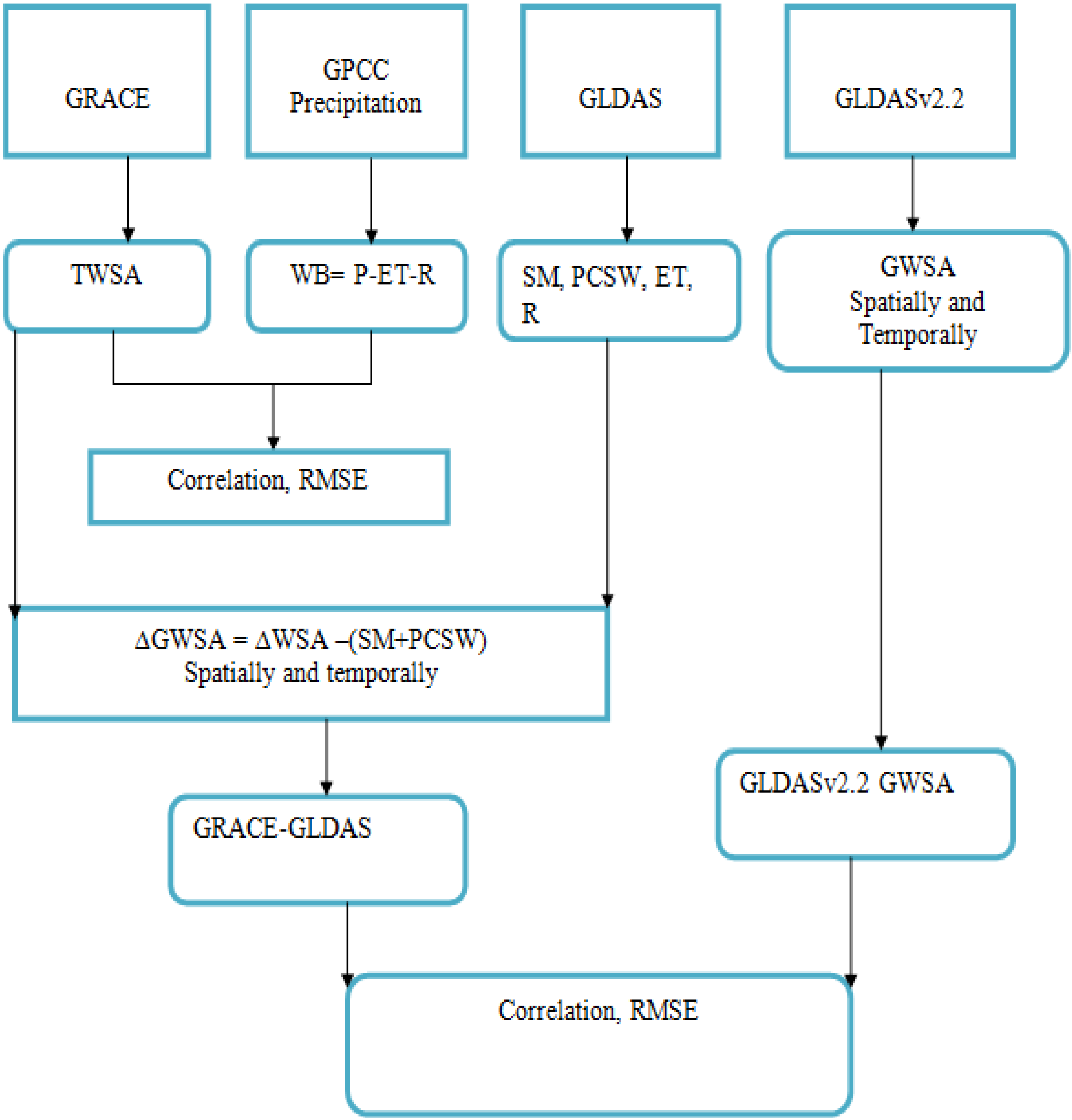


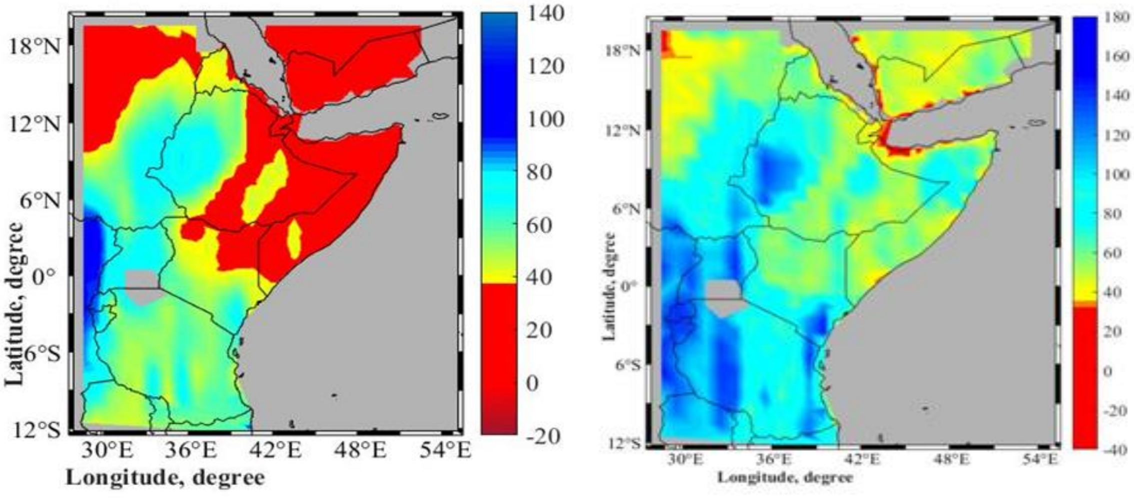
Figure 3.2 General Workflow of the study

CHAPTER FOUR

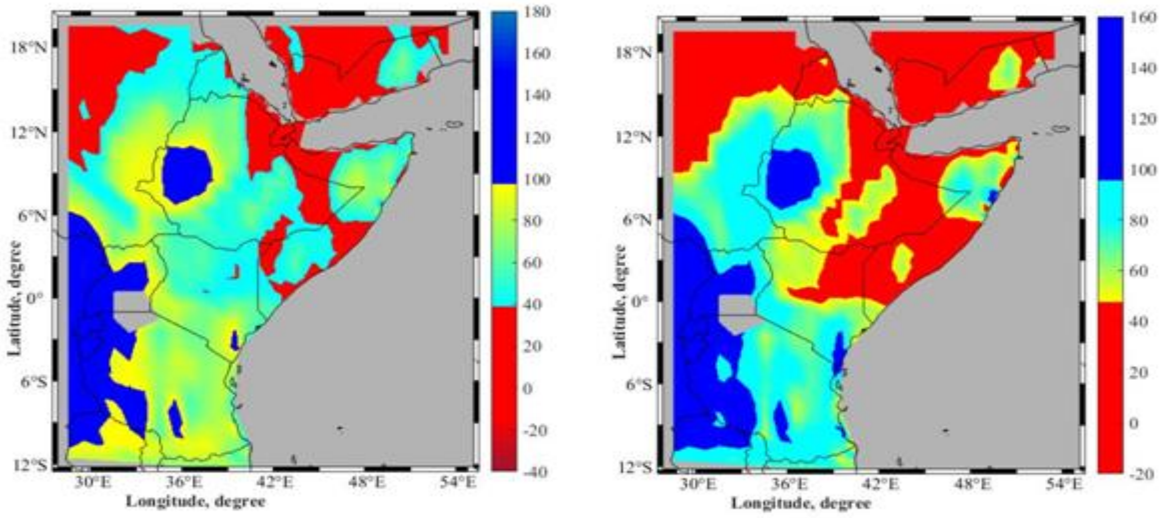
RESULT AND DESCUSION

4.1. Spatiotemporal variation of terrestrial water storage anomalies

GRACE TWS data were utilized to monitor spatiotemporal variety of Groundwater storage. Monthly estimates of terrestrial water storage within the considered region were computed for 12 years (2008 to 2019). In this study Terrestrial water storage variation over the whole study area was obtained from JPL mascon solution from 2008 to 2019 period as shown on the figure (1) below. The result of TWSA from GRACE and water balance which obtained from equation (2) above shows that they are well correlated (r = 0.75, RMSE= 2.97), this explain potential use of GRACE data to estimate Groundwater storage change in East Africa. Figure 4.2. Shows the time series of Total water storage and precipitation change which have similar trends. This indicates that the variation in total water storage and variation in precipitation were related. Both of them were decreasing from 2008 to 2010, followed by increasing in some extent at the middle of 2011 and decreasing at the end of 2011, then rising from 2012 up to 2019 in similar trends.



(a) (b)



(c) (d)

Figure 4. 1 Shows spatial distribution of TWSA derived from GRACE in the study area from 2008 to 2010, 2011 to 2016, 2017 to 2019 and 2008 to 2019 respectively.

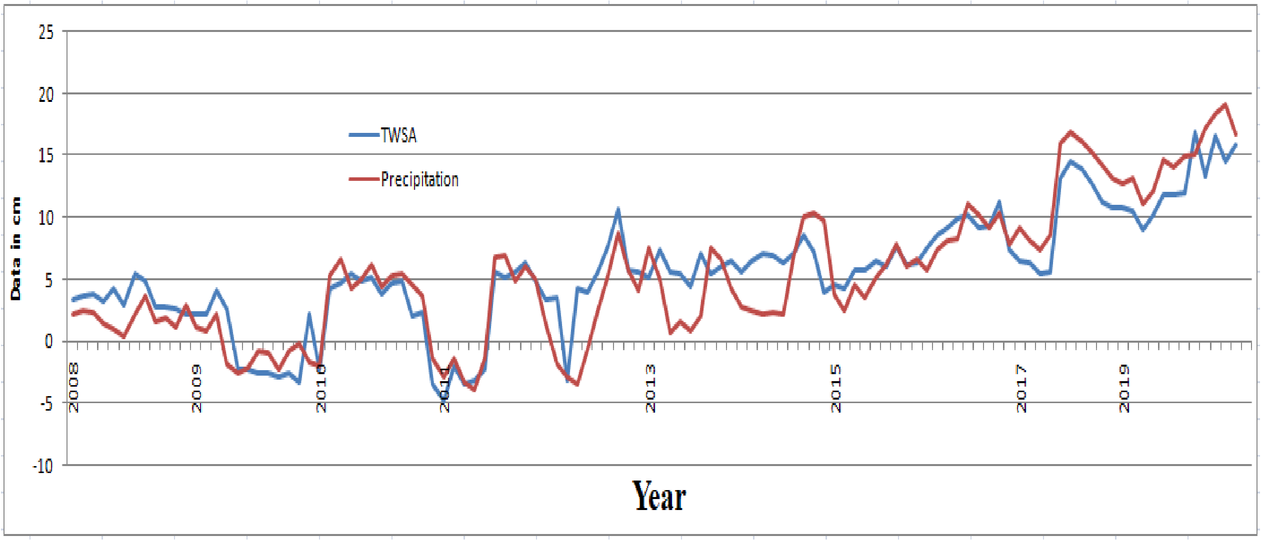


Figure 4. 2 Time series of GRACE derived TWSA and P-ET-R over the whole study area.

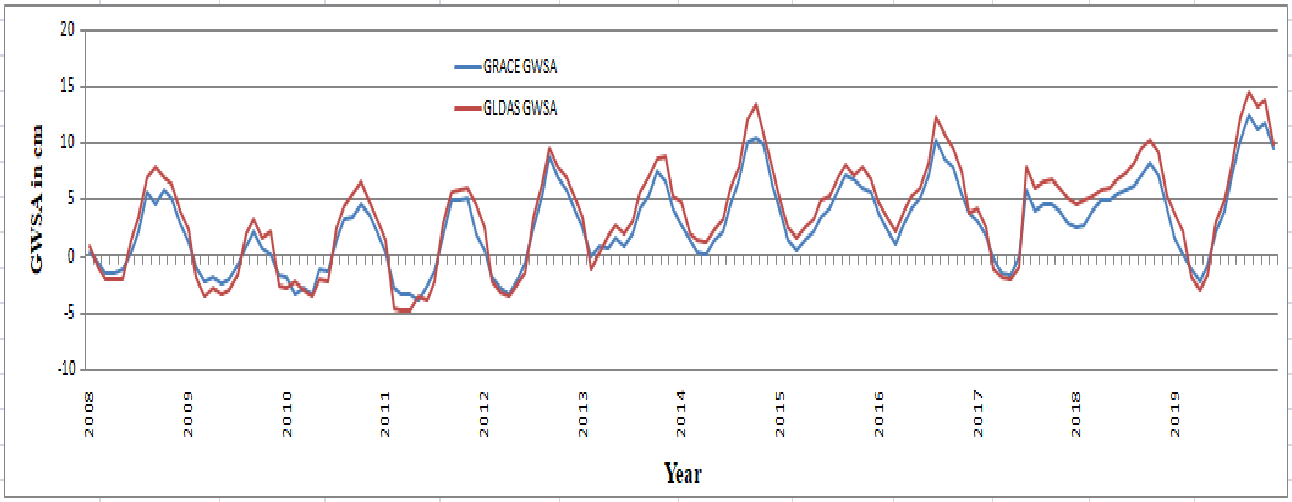
4.2. Temporal variation of GWSA

To study, the temporal assessment of each basin used in the study area, the averaged changes of the GRACE-derived Groundwater storage anomalies and GLDASv2.2 Groundwater storage changes were plotted and dissected. Figure 4.3 shows the monthly GWS changes from GRACE-GLDAS and GLDASv2.2 in different basin (a) Nile basin, (b) Jubba-Shebelle basin and (c) Lake Rudolf from 2008 to 2019. The overall trend of GRACE-GLDAS and

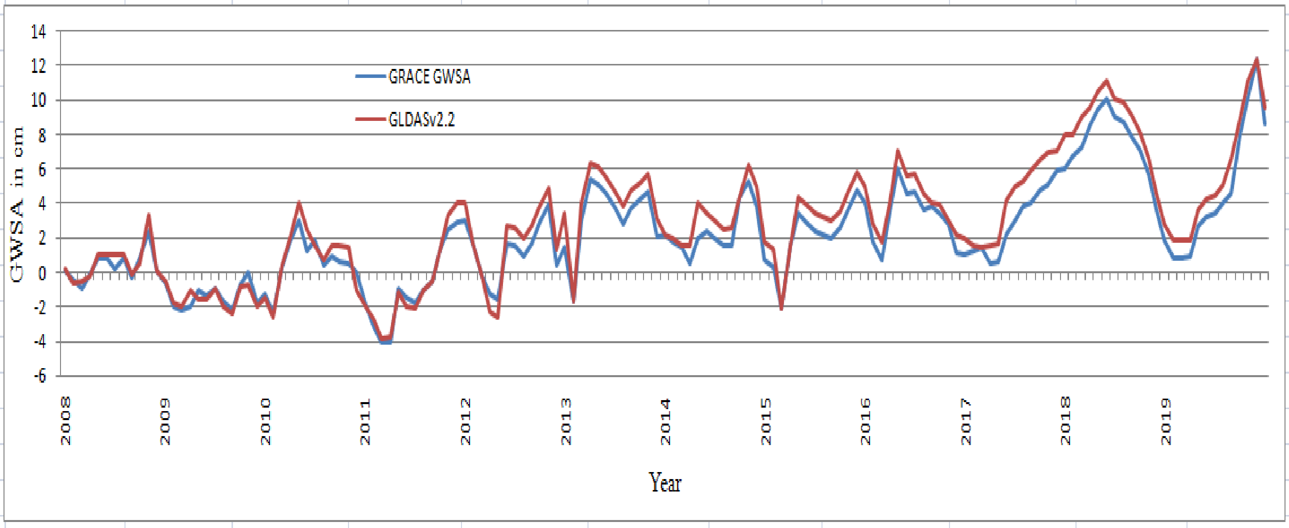
GLDASv2.2 results shows a strong agreement, with the correlation coefficient of 0.88, 0.975 and 0.906 respectively. The RMSE of that basin were 1.98, 0.89 and 1.25 for Nile, Jubba Shebelle and Lake Rudolf basin respectively. As a whole, the study period was classified into three based on the increasing and decreasing rate of GWSA. Accordingly, In Nile and Jubba-Shebelle basin (fig (a&b)) below, there was a loss in groundwater storage from 2008–2010 by increasing in some extent in Nile basin at the middle around August to October in 2009 especially at September. However, the largest yearly groundwater depletion occurs in February, 2008 to February, 2010 during Ethiopian millennium drought, by an average loss of **-9.2** mm per year in Jubba Shebelle basin and February, 2009 to June, 2010 by an average loss of**-17.98** mm per year in Nile basin because of decline of precipitation

The mean of the 12 year groundwater storage changes from February, 2011 to December, 2019 was increased by +2.51 mm per year in Jubba Shebelle basin and July, 2010 to December, 2019 was increased by +3.32 mm per year in Nile basin. This indicates that, the increasing of rainfall is related with increasing of groundwater storage.

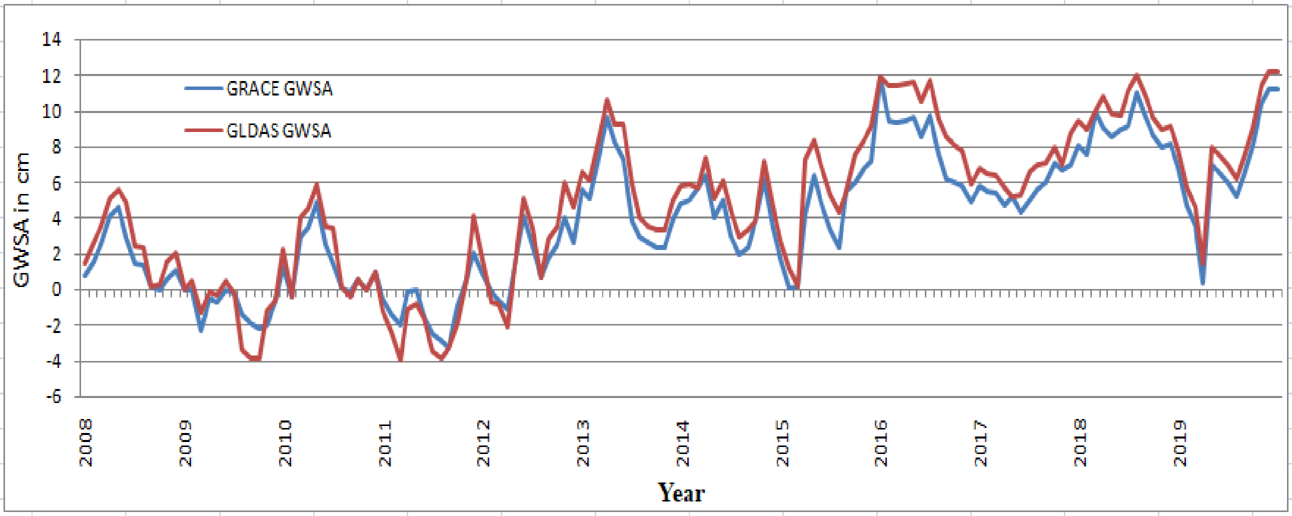
In Lake Rudolf figure 4.3 (c) there was highly decreasing of Groundwater storage change from June, 2008 to December 2009 by rate of **-12.16** mm year−1, followed by an increase in GWSA to December 2010 by rate of +1.657cm per year which is succeeded by other decline up to November 2011 by -1.376 cm per year and increase until the end of 2019 by +5.37cm per year with some lose of Ground water storage.



(a)



(b)



(c)

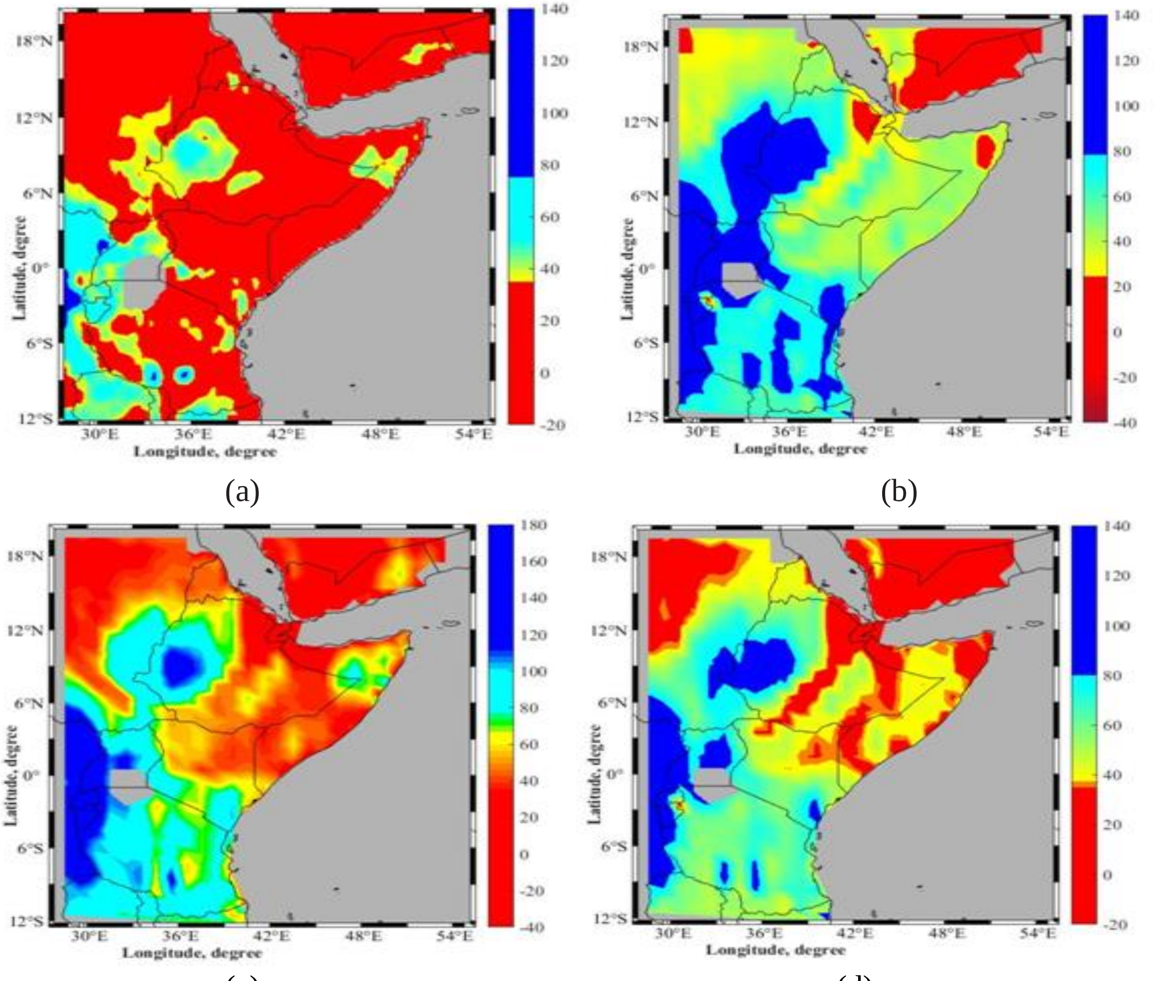
Figure 4. 3 Shows mean monthly Ground Water Storage Anomaly from GRACE – GLDAS and GLDASv2.2 starting from January, 2008 to January, 2020 of Nile (a), Jubba-Shebelle (b) and Lake Rudolf (c) basins in cm per month respectively.

4.3. Spatial distribution of Ground water storage variation

Spatial variety of GWSA can be ascribed to many components counting non consistency of precipitation, groundwater withdrawals, hydro geological properties, and groundwater release. Figure 4.4 shows the spatial distribution of Groundwater storage change of 2008 to 2010, 2011 to 2016, 2017 to 2019 and 2008 to 2019 in fig3a, 3b, 3c and 3d respectively.

In the study period GWSA is declined from 2008 to 2010 in Eastern and south east of Ethiopia, northern part of Sudan, all most all part of Somali except small area at eastern part of the country, all part of Djibouti, North and north east of Kenya and small area of Tanzania at north and south part. The trends from 2011 to 2016 shows rising of Groundwater storage with some lose of water over all the study area. In between 2017 and 2019 there was moderate GWS Anomaly because of medium rainfall registered in the area. But, as a whole GWSA of the study area for the twelve years shows increasing trend with high rising at the middle. Both data used for GWSA analysis were shows strong relationship.

In general, negative Ground water storage trends are concentrated in the whole study area during Millennium drought except some part at western part of Ethiopia, east part of Sudan, Congo, and small part at south Republic of Tunisia and in some extent in Rwanda, Burundi and Uganda because of lack of rainfall in the study area.



(a)

(b)

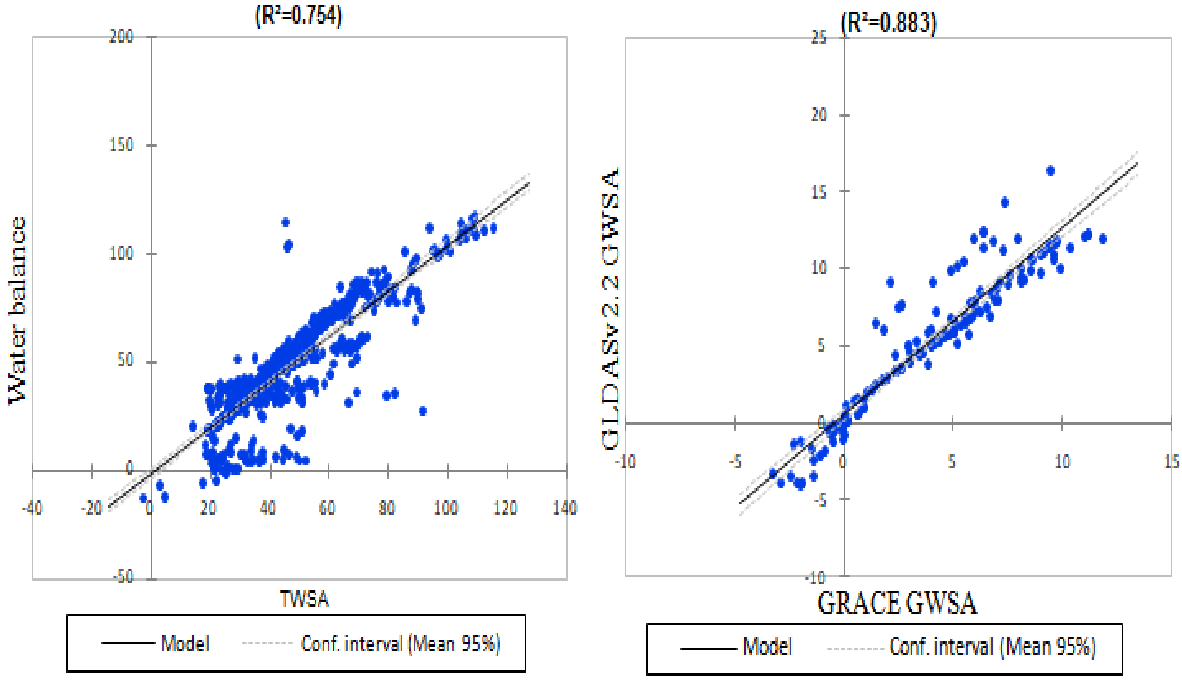
(c)

(d)

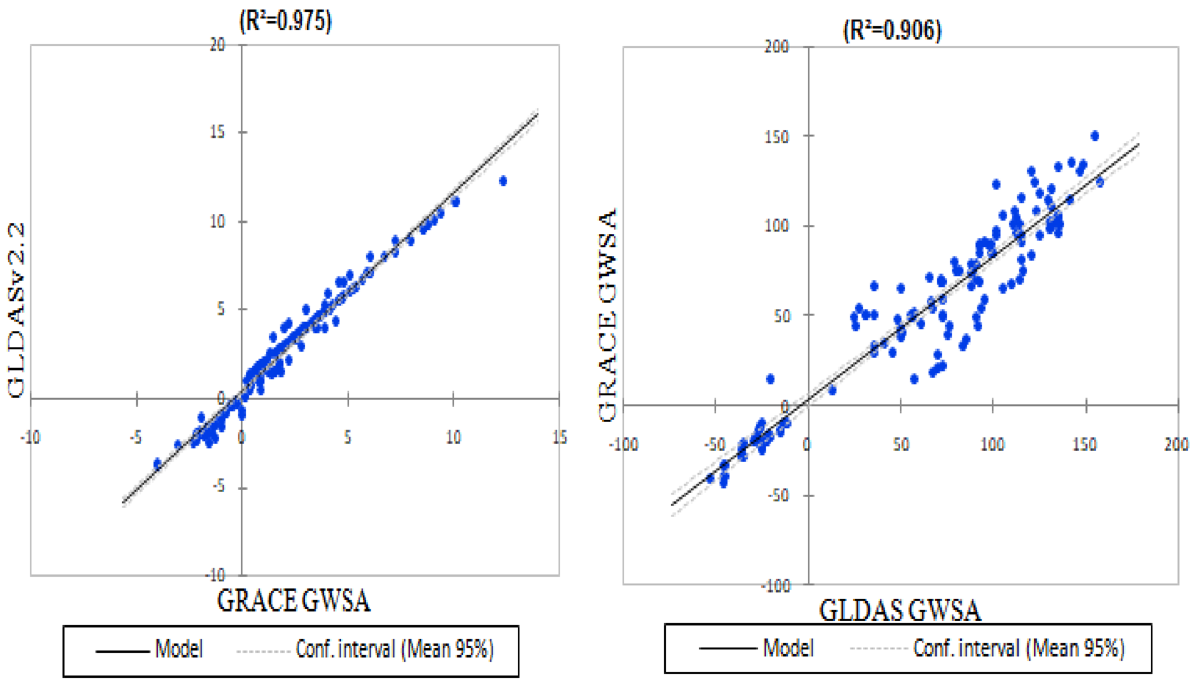
Figure 4. 4 Shows spatial distribution of GWSA derived from GRACE-GLDAS in the study area from 2008 to 2010, 2011 to 2016, 2017 to 2019 and 2008 to 2019 of fig a, b, c, and d respectively.

4.4. Correlation Analysis

The linear correlation coefficients (r) were determined to know the strength linear relationship between the results obtained from GRACE-GLDAS and GLDASv2.2 data. The correlation coefficient values of TWSA and water balance were 0.753 which means strong positive correlation. In this study to analysis Groundwater storage change the study area were classified according to river basin in the study area. Therefore, three basins were considered for the area and correlation coefficient were individually determined to measure the strength between the two methods. Accordingly, correlation coefficient value of 0.88, 0.975 and 0.906 were obtained for Nile, Jubba-Shebelle, and Lake Rudolf respectively. Those values indicate that GRACE derived GWSA and GWSA obtained from GLDAS version 2.2 were strongly correlated. The figure below shows the correlation of the two methods for TWSA derived from GRACE and water balance and correlation of the three basins considered in the study area.



(a) (b)



(c) (d)

Figure 4. 5 Shows correlation between TWSA of GRACE and water balance (a), correlation between GRACE-GLDAS and GLDASV2.2 GWS anomaly of Nile (b), Jubba Shebelle(c), and Lake Rudolf (d) basins respectively.

4.5. Discussions

This study, aimed to monitor Groundwater storage change by using Gravity Recovery and Climate Experiment (GRACE) and Gravity Recovery and Climate Experiment Follow on (GRACE FO) in East Africa. In this, GLDAS which is the sophisticated hydrological model were used to simulate soil moisture and plant canopy surface water. In addition to that, Global land data assimilation system versions 2.2 were used to simulate Groundwater storage change to correlate with GRACE-GLDAS Groundwater storage change. Terrestrial water storage variation derived from GRACE were highly correlated (r=0.75, RMSE=2.189) with Water balance (P-ET-R) derived from precipitation of Global precipitation climatology center. Groundwater storage changes were analyzed in three different basins in the study area. In this study, the largest depletion occurs from 2008 to 2010 by rate of -9.2 mm per year, -17.98 mm per year and -12.16 mm per year for Jubba Shebelle, Nile and Lake Rudolf basins respectively during Millennium drought in the study area because of decreasing rainfall.

Many studies monitor Groundwater storage variation in different basins by using Gravity Recovery and climate experiment(GRACE) and Gravity recovery and climate experiment follow on (GRACE FO) with land surface model in different country. The studies conducted in California, India, Australia, Tasmania, and other country in different basins monitored Ground water storage anomaly by using GRACE/GRACE FO with GLDAS land surface model. The study (Li et al., 2019) conducted research to estimate Groundwater storage anomaly of Murray Darling Basin from 2003 to 2015 using GRACE and Community Atmosphere Biosphere Land Exchange (CABLE) model. In the study, the result showed decreasing trend in south west, east and south of the study area, while increased trend in north and south central. This study correlates GRACE with CABLE and obtains correlation coefficient of **0.94** and lowers RMSE of **15.74**. The result showed increasing trend with the rate of 1.19 mm per year between 2003 and 2015.

Other study (Chen et al., 2016) did in Tasmania, Australia, using GRACE, GLDAS and WGHM and correlate with in situ observation. The study result showed that in situ observation is highly correlated with GRACE-GLDAS (r = 0.64 to 0.85) while correlation with GRACE-WGHM is (r= 0.69 to 088) in eastern part of the study. The study result showed decline during millennium drought (2003 to 2010) at depletion rate of -2.57 mm per year and increased by 3.94 mm per year after 2010. The researchers explained the cause of depletion as decreasing of precipitations. (Bonsor et al., 2010) also studied on Analysis of GRACE satellite mission of the Nile Basin using a groundwater recharge model called ZOOMRD (Zoomable object oriented distributed recharge model to interpret seasonal variation in Terrestrial indicated by GRACE. The result showed that the total annual recharge simulated by ZOOMRD is 0-50 mm/year with semi arid lower catchment and mean of 250 mm per year in some tropical upper catchments. Other study (Rodell et al., 2009b) conducted in Indian state of Rajasthan, Punjab and Haryana from 2002 to 2008 period. The researchers use GRACE to analyzed Groundwater storage change. The results showed depletion by rate of 4 ±1 cm per year because of withdrawals for irrigation and other purpose.

Similar studies have been conducted on monitoring Groundwater storage change in California central valley, Sacramento and San Joaquin River Basins (Famiglietti et al., 2011). The study use GRACE data and precipitation between 2003 to 2010 period. The result showed loosing of water at rate of 3±2.7 mm per year for the study period.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The Gravity Recovery and Climate Experiment (GRACE) and Gravity Recovery and Climate Experiment Follow ON (GRACE-FO) are very crucial in monitoring Groundwater storage variation where there were no availability of in-situ groundwater data and limitation of policies for sharing data. Because Groundwater storage change monitoring is very important in economic and social development of once country especially in arid and semi-arid region. In this research, TWSA was derived from GRACE/GRACE FO and Soil moisture and plant canopy surface water were derived from GLDAS land surface model. In addition, GWSA of GLDAS v2.2 was extracted. Then, all data were filtered by using Gaussian smoothing methods to remove noise. The result of TWSA from GRACE/GRACE FO and water balance (P-ET-R) which obtained from precipitation of Global precipitation climatology center(GPCC) shows that they were well correlated (r = 0.75, RMSE= 2.97), this explain potential use of GRACE data to estimate Groundwater storage change . In this study to analysis Groundwater storage change the study area were classified according to river basin in the study area. Therefore, three basins were considered for the area and correlation coefficient were individually determined to measure the strength between the two methods. Accordingly, correlation coefficient value of 0.88, 0.975 and 0.906 were obtained for Nile, Jubba-Shebelle, and Lake Rudolf basin respectively. Those values indicate that GRACE derived GWSA and GWSA obtained from GLDAS version 2.2 were strongly correlated. The largest yearly ground water depletion occurs in February, 2008 to February, 2010 during Ethiopian millennium drought by an average loss of **-9.2** mm per year in Jubba Shebelle basin and February, 2009 to June, 2010 by **-17.98** mm per year in Nile basin and June, 2008 to December 2009 by **-12.16** mm year for Lake Rudolf basins because of decline of rainfall. Precipitation is a key deriver of Terrestrial water storage change in the research region, and it is utilized to analyze the behavior of Groundwater storage change. It is further concluded that, the GRACE/GRACE FO have good potential to monitor Groundwater storage variation in east Africa where there were limitation of data.

5.2. Recommendations

Gravity recovery and climate experiment(GRACE/GRACE FO) create good opportunity to Monitor Ground water storage change of a country like East Africa which have limitation of in situ groundwater observation and limit of policies for sharing data. Theses study only use GRCAE derived ground water storage change and GWSA derived from Global land data assimilation system version 2.2 of the considered period. Therefore, for further analysis, it is recommended to use other geodetic techniques like satellite radar altimetry since satellite altimetry is used to assess the level of a lake or a major river to determine the storage change of surface water.

This study was limited to use in situ groundwater data since there is no policy to share such data for use. Therefore, The concerned body should give attention to this data for the analysis of this invisible properies.

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APPENDICES

Appendix A: Figure

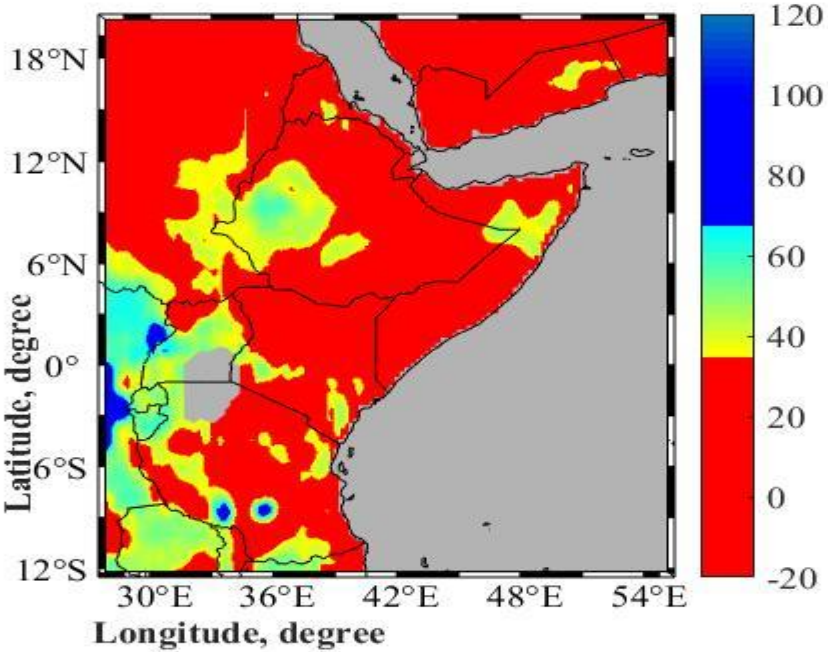

Figure A-1 GWSA obtained from GLDAS from 2008-2010

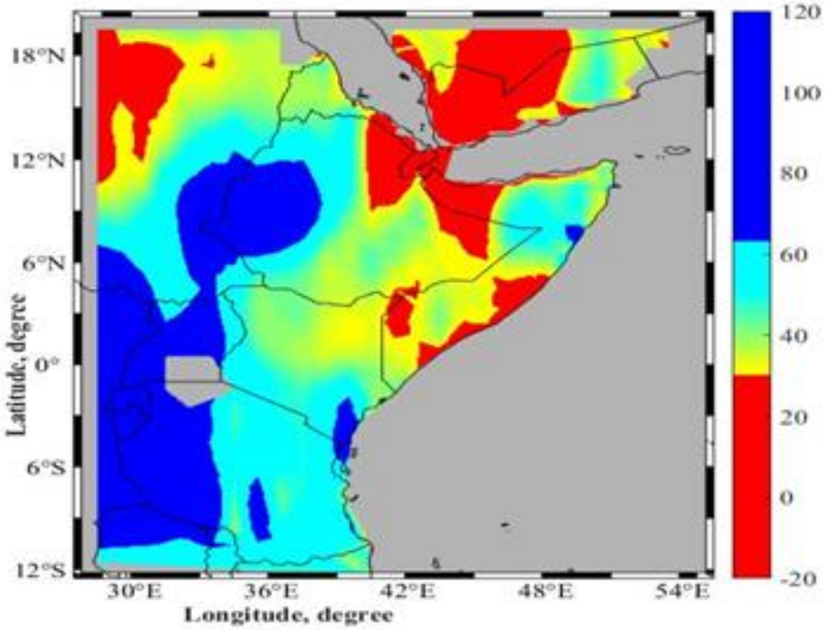

Figure A-2. GWSA obtained from GLDAS from 2011 – 2016

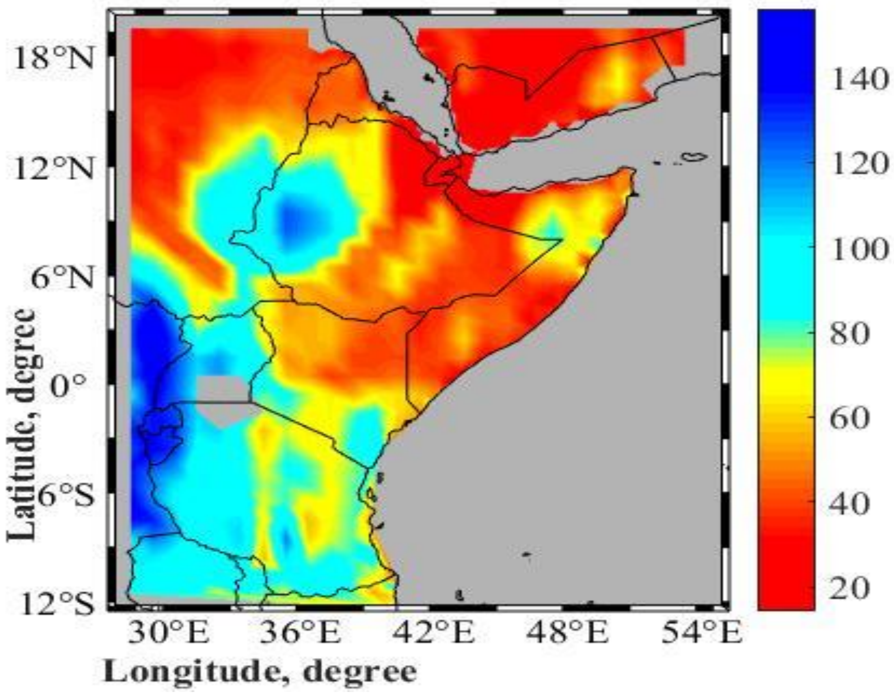

Figure A – 3 GWSA obtained from GLDAS from 2017 – 2019

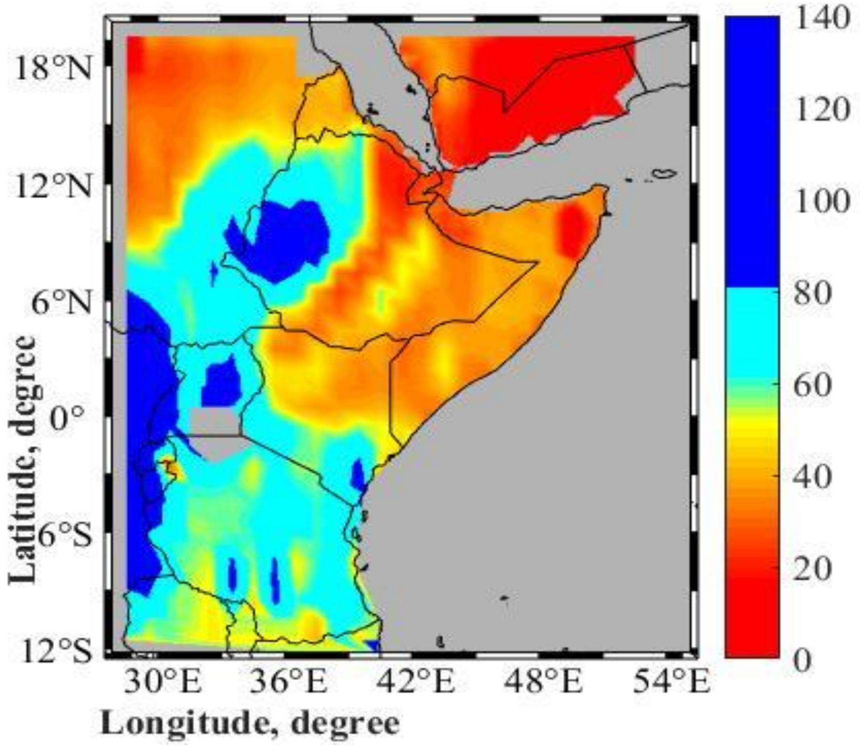

Figure A-4. GWSA obtained from GLDAS from 2008 - 2019