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Groundwater Resource Assessment for West Africa Using Earth Observations and Groundwater Modeling

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A dissertation submitted to the faculty of
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Abstract

Groundwater is a crucial global resource, particularly in semiarid regions where surface water is scarce. As a result, effective groundwater management is essential. However, the challenge lies in a lack of data and information for proper decision-making. This dissertation present studies related to groundwater storage changes and recharge in West Africa, using data from NASA's Gravity Recovery and Climate Experiment (GRACE) mission.

In Niger, this research reveals little change in groundwater storage from 2002 to 2010 but a steep rise from 2010 to 2021, attributed partially to increased precipitation. Groundwater resources in Niger are found to be underutilized, with estimated recharge rates aligning favorably with previous estimates.

In the Volta Basin in sub-Saharan Africa, this research identifies three distinct trends from 2002 to 2022, including increases and decreases in groundwater storage, and correlates these changes with precipitation. The Water Table Fluctuation method was used to estimate recharge rates, which compare favorably with other studies.

For sustainability assessment in water resources planning, groundwater modeling is essential but can be difficult in West Africa due to limited data. The GRACE satellite mission provides valuable data to address in situ data gaps. In the Goulbi-Maradi alluvial aquifer in Niger, the GRACE data was incorporated into a MODFLOW groundwater model, both to provide recharge estimates and groundwater volume changes for calibration. The calibrated model can be used to analyze sustainability for for hypothetical pumping strategies and recharge rates projecting 40 years into the future.

Keywords: GRACE, Groundwater Storage, Groundwater modeling, Recharge, West Africa

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1 *Introduction*

1.1 Motivation

Groundwater is of paramount importance on a global scale, serving as the primary water source for approximately half of the world's population [1,2]. Its significance is particularly evident in agriculture, where it contributes significantly to food production, especially in arid regions with limited water resources [3]. In sub-Saharan Africa, arid and semi-arid regions rely on both surface water and groundwater sources for various purposes. However, surface water sources are characterized by their unreliability and inability to meet the escalating demand, thereby making groundwater sources well-suited for serving the expanding rural population [4]. The Volta Basin, for instance, experiences notable climate and precipitation variations, with most rivers being ephemeral, posing challenges in accessing safe water during dry seasons. Consequently, analyzing water storage and studying changes in groundwater storage become crucial in these regions, especially when streams and reservoirs are distant or during droughts [5,6].

In Southern Niger, which is characterized by high population density, reliance on rain-fed crops and animal husbandry is widespread. However, the adverse impacts of climate change have resulted in reduced productivity and food shortages during dry years. To mitigate these challenges, shallow aquifers serve as the primary source of freshwater, aiding in drought resilience and facilitating agriculture in dry areas [7–9]. Unfortunately, the underdeveloped state of groundwater infrastructure, coupled with limited data availability, hampers effective management of these vital resources [10–12]. Groundwater resource managers face multiple challenges, including climate change, groundwater depletion, and the limited availability of data [1,8–10]. Compounding these issues is the lack of understanding among regulators and the public regarding the repercussions of groundwater depletion, often leading to unregulated access to groundwater [10].

As global groundwater demand continues to rise [9], the evaluation of aquifer utilization and the determination of sustainable withdrawal rates becomes imperative. Recent advancements in remote sensing technologies provide valuable tools and data sets to assess the sustainable yield of aquifers [13]. To address these pressing issues, this research project focuses on estimating storage change and recharge in critical aquifers associated with the Iullemeden and Chad basins in Niger, as well as the Volta basin in West Africa. By doing so, this study aims to enhance groundwater resource management and promote sustainability considerations among managers. Furthermore, to foster a deeper understanding and facilitate the long-term development of groundwater infrastructure in Southern Niger, this research project employs groundwater modeling techniques and leverages remote sensing data.

1.2 GRACE Mission

As previously mentioned, one of the challenges in groundwater management is the scarcity of information, primarily due to the high costs involved in acquiring specialized equipment, conducting extensive fieldwork, and maintaining continuous data recording. However, satellite data presents an opportunity to bridge these information gaps and provide valuable insights. Specifically, this study utilized data from The Gravity Recovery and Climate Experiment (GRACE) to analyze groundwater storage changes in West Africa, estimate groundwater recharge in the region, and calibrate a groundwater model for a significant aquifer in Niger.

GRACE, launched in 2002 by NASA and the German Aerospace Center (DLR), involves two satellites orbiting 220 km apart, measuring changes in Earth's gravitational field through the variation in distance between them [14,15]. These measurements, accurate to 10 μm, enable the quantification of gravitational anomalies caused by mass changes below the satellites on a global scale [14]. The initial GRACE mission spanned approximately 15 years, providing data from 2002 to 2017, and was succeeded by the GRACE Follow-On (GRACE-FO) mission in 2018, which continues to deliver monthly gravitational anomaly data [16–18].

GRACE satellites serve to map global changes in Earth's gravitational field, with water storage being the primary driver of mass changes in most locations, making it possible to monitor global water storage variations [19]. GRACE data captures anomalies in water mass compared to a long-term average, providing valuable insights into changes in water storage, although it does not estimate total water mass [20]. NASA processes GRACE data and offers the total water storage anomaly (TWSa) dataset, widely utilized in hydrological studies, including research on droughts, floods, and regional water storage trends [21–35]. Furthermore, GRACE data has demonstrated its effectiveness in remotely monitoring groundwater storage changes, including in arid and semi-arid areas, without relying on in situ measurements [7,36–41].

To investigate groundwater using GRACE, researchers commonly employ global land surface models to separate groundwater from total water storage [7]. By subtracting surface water storage components calculated by NASA's GLDAS model from the GRACE-derived Total Water Storage Anomaly (TWSA), researchers estimate groundwater storage changes anomaly [7,42,43]. This resulting data and information are valuable for local groundwater managers to assess groundwater use and understand the potential impacts of future development.

1.3 Groundwater Recharge Estimation

A crucial aspect of assessing aquifer sustainability is the estimation of annual groundwater recharge [8,44]. Groundwater recharge serves as a fundamental input in the aquifer's water balance, playing a vital role in determining its overall capacity to support water resources. By accurately quantifying this essential component, we gain valuable insights into the aquifer's capacity and its ability future water demands. In this dissertation, we focused on estimating recharge in two selected areas in West Africa using GRACE data and utilized these values to complete a groundwater modeling study in a significant aquifer located in the South of Niger (Maradi).

While numerous techniques are available to estimate groundwater recharge, the selection process is challenging due to the requirement for detailed information and accurate historical groundwater data. Factors such as the study area, scope, time period, and the reliability of the recharge estimation method need to be considered when choosing an appropriate approach [45–48].

Groundwater level-based techniques, such as the Water Table Fluctuation (WTF) method, are widely recognized for their ability to estimate recharge rates [49]. Developed in the early 1920s, the WTF method analyzes fluctuations in groundwater table levels and identifies the rising portion of the annual fluctuation as recharge [50] This method is suitable for various time scales, requires minimal data, and is cost-effective [51]. While the WTF method typically utilizes observed water level measurements, it can also leverage water level anomalies derived from Gravity Recovery and Climate Experiment (GRACE) data, which is the approach used in this study..

1.4 Groundwater Modeling

Part of this research focuses on developing a groundwater model in the semiarid southern region of Niger, specifically on the southeastern boundary of the Iullemmeden Basin (Figure 1). This region holds significant importance due to its dense population, with an estimated range of 81 to 105 individuals per square kilometer [52]. The local communities heavily rely on rain-fed crops, including sorghum, millet, and cowpeas, as well as animal husbandry, for their livelihoods [53,54]. However, the productivity of these agricultural and husbandry activities has been adversely affected by the impacts of climate change [53,55], resulting in food shortages during dry years [53].

The primary source of freshwater in the region is derived from shallow aquifers located approximately 100 meters below the surface. These aquifers play a crucial role in supporting the local population during droughts, especially for agricultural purposes and providing water access in areas distant from water bodies [56–58]. However, the development of groundwater infrastructure in the region has been limited. While numerous small-scale wells exist for human and animal use, large-scale irrigation practices are not widespread. Furthermore, the lack of comprehensive field data on groundwater in the region poses challenges to the effective study and management of these valuable resources [59–61].

To address these issues and facilitate long-term development planning of groundwater infrastructure in southern Niger, there is an urgent need for sophisticated and well-calibrated numerical models that accurately depict the dynamics of groundwater flow in the region. The implementation of such models would significantly enhance our understanding of the system and enable effective resource management. However, in situ data in the region is severely limited. In this project, GRACE data is used to overcome some of these data limitations. GRACE data was used to estimate recharge rates as described above. Recharge is the primary source of water to the aquifer. GRACE data was also used to determine storage changes vs. time, which made it possible to back-calculate pumping rates in the region and calibrate the model. The model can now be used to predict aquifer response to various pumping strategies and to assess sustainability.

2 *Evaluating Groundwater Storage Change and Recharge Using GRACE Data: A Case Study of Aquifers in Niger, West Africa*

This chapter is composed from a paper entitled *"Evaluating Groundwater Storage Change and Recharge Using GRACE Data: A Case Study of Aquifers in Niger, West Africa"* published in the MDPI Remote Sensing journal [13]. I hereby confirm that the use of this article is compliant with all publishing agreements.

2.1 Introduction

2.1.1 Groundwater and Study Motivation

Groundwater is an important resource; studies estimate it provides approximately 30% percent of global freshwater use and is the primary water source for about half the world population; ~2 billion people [1,2]. Agriculture relies on groundwater, with estimates that groundwater irrigation supports 40–50% of global food production [3]. Globally there are large differences in groundwater use, with use often depending on existing water infrastructure and local climate, with increasing groundwater use in arid regions [62]. Groundwater is especially important in dry, arid regions of the world where other water resources are scarce [7]. Groundwater resources can be stressed due to several factors, with one of the primary concerns being groundwater depletion [9].

Limited groundwater data can make managing groundwater resources difficult [1,8,10] especially over the longer time periods required to evaluate aquifer sustainability [7]. Groundwater monitoring is costly in terms of financial, technological, and time issues as it requires installing multiple monitoring wells and consistently recording, storing, and analyzing water level and quality data over long time periods [7]. Aquifers often have little management because of the difficulty of obtaining data and the lack of understanding by regulators and the public of the impacts caused by groundwater depletion [11,12,63]. This creates what Famiglietti [10] refers to as a "free for all," where, in many jurisdictions, anyone can drill and have unlimited access to groundwater with little or no regulation.

This development of groundwater resources with limited management is often encouraged by local governments. For example, in India, electrical costs for well pumping are subsidized by the government to encourage additional agricultural production [64].

Groundwater demand is increasing, with a 3% annual growth in groundwater use globally from 1990 to 2010 [9]. The ability to evaluate aquifer use to determine if withdrawal rates are sustainable is an important capability. The lack of historical or even current data makes this task challenging, but recent advances in remote sensing have provided data sets and tools that can be used to help evaluate sustainable yield in aquifers. We estimate storage change and recharge for several large aquifers in Niger, West Africa, with areas ranging from 13,000 to 161,000 km^2. This information helps managers better include sustainability considerations in their management.

2.1.2 GRACE Mission and Applications

In 2002, the United States National Aeronautics and Space Administration (NASA), in collaboration with the German Aerospace Center (DLR), launched the Gravity Recovery and Climate Experiment (GRACE) [15]. GRACE uses two satellites that follow the same orbital path about 220 km apart. The distance between the satellites varies in response to variations in the Earth's gravitational field. The satellites measure distance changes between the two satellites to 10 μm w [14,15,65]. As the satellites pass over the Earth, changes in mass affect the lead satellite first, then the following satellite, thus changing the distance between the two satellites. These measurements, along with high precision accelerometer data, are processed to quantify gravitational anomalies (i.e., mass changes) below the satellites as they cover the globe [14]. The first GRACE mission ended after about 15 years, providing data from 2002 to 2017 [18]. In May of 2018, the GRACE Follow-On (GRACE-FO) mission [17] was launched and provides gravitational anomaly data on a monthly basis, similar to the original GRACE mission, up to the present [16,17].

The GRACE satellites globally map changes in the Earth's gravitational field; for most locations, the change in mass that produces gravitational changes is driven primarily by changes in water storage as there are few other changes that affect Earth's mass on this scale. This means that GRACE data can be used to monitor changes in water storage globally [19]. These data cannot be used to estimate the total water mass, but instead, measure variations or changes in water mass compared to a long-term mean which are called anomalies in GRACE usage [20].

NASA processes GRACE data and provides the total water storage anomaly (TWSa) dataset, a measure of the change in water storage at each location globally [31]. These data are widely used, with one highly-cited paper reporting that there were over 150 publications in 2016 on GRACE data processing and applications to hydrological issues [31]. Example applications include drought studies [22,27,29,32,34,35], flood studies [21,23,25,30,33], and other general hydrologic studies involving regional water storage and trends [24,26,28]. Recent work has shown that GRACE data can be used to monitor groundwater storage changes remotely, including groundwater depletion in arid and semi-arid areas [39,41].

2.1.3 GRACE Mission and Applications

While GRACE measures the total change in mass, and by inference, total change in water storage, GRACE data can be used to study groundwater, a subset of the total water storage [7,36,43,66]. Most GRACE groundwater applications use global land surface model results to separate the groundwater component from total water storage [7]. For example, to estimate the groundwater anomaly, researchers subtract the surface water, snow water equivalent, plant canopy, and soil moisture water storage components computed by the NASA's Global Land Data Assimilation System (GLDAS) model from the GRACE-derived TWSa [7,43,67]. This approach, subtracting the land surface model non-groundwater components from GRACE data, has been widely applied using various land surface models [7,12,38,43,66,68–76].

While groundwater data can be derived from the GRACE TWSa, these data, based on our knowledge, are not commonly used outside academia, and are rarely used for on-going groundwater management. Various tools have been developed to access and process GRACE TWSa data but many have limited GRACE TWSa datasets because of their size, and most lack derived groundwater datasets. Nearly all of these tools cater to a scientific or technical experienced user and do not provide the ability to easily support regional analysis required for local groundwater study and management [18,77–81]

We recently published tools designed to allow groundwater managers to easily use GRACE data to estimate groundwater storage changes over time representing aquifer storage in a region [82]. These tools include both a web application and a Python-based notebook interface that accesses GRACE and GLDAS model data, computes the gridded monthly groundwater anomaly, accepts data to define an aquifer extent, and integrates the spatial gridded groundwater anomaly data over time to generate an aquifer storage time history limited to the aquifer region being studied or managed [82]. These data and the resulting information can be used by local groundwater managers to evaluate aquifer groundwater use and better understand the impacts of future development.

2.1.4 Groundwater Recharge Estimation

An important part of analyzing aquifer sustainability is estimating annual groundwater recharge. There are several techniques to estimate groundwater recharge; however, selecting an appropriate method is difficult as most techniques require detailed information, including accurate historical groundwater data [83]. Considerations for selecting appropriate method include scope of the study, the size of the study area, the time period of the study, and the reliability of the recharge estimation method. Both physical and chemical techniques have been used to estimate recharge [48]. The chemical techniques that have been used extensively in our study region are the chloride mass balance (CMB) method and the tritium (3H) peak concentration method [46,48]. However, these methods have disadvantages. The tritium method is not usable when the unsaturated zone is shallow [84] and the CMB method requires a balance between the input and output of chloride concentrations from precipitation and underneath the root area, respectively. This balance often takes years to decades to equilibrate in the vadose zone and up to a century for the saturated zone. This means these techniques only provide appropriate results, and are mostly useful where the climate and land use have not changed significantly recently [84]. Furthermore, these methods rely on in situ measurements and laboratory analysis, both of which are scarce in West Africa.

The Water Table Fluctuation (WTF) method is an alternate approach that does not require chemical data. WTF was developed in the early 1920s to estimate episodic recharge based on fluctuations in the groundwater table [49,50]. WTF analyzes seasonal changes in piezometric head at monitoring wells (or in the aquifer) and categorizes the rising portion of the annual fluctuation as recharge. A few studies have been made to estimate groundwater recharge using the WTF method with water levels derived from GRACE data. For example, Henry et al. [85] analyzed both GRACE and GLDAS data in Mali Africa to estimate the groundwater storage anomaly and annual groundwater recharge from 2002 to 2008 and compared these results to estimates using the WTF method with data from available observation wells. They calculated a recharge value 16.4% and 14.8% of the annual precipitation using GRACE and historical water levels data, respectively. Gonçalvès et al. [86] estimated the recharge in North-Western Sahara Aquifer System employing GRACE monthly records, GLDAS results, and groundwater pumping rates. Their results suggested a recharge rate of 40% contradicting the hypothesis that in that region the recharge is low or even null. Another study that quantified recharge and depletion rates with GRACE data was conducted by Ahmed and Abdelmohsen [87] in the Nubian aquifer in Egypt. Their results indicated that recharge occurs only with a substantial rise in Lake Nasser levels and/or excessive precipitation conditions in the region. Finally, Wu et al. [84] estimated groundwater recharge using the WTF method with GRACE and GLDAS data in the Ordos Basin in China. The results indicated that the groundwater recharge estimated with GRACE did not differ considerably with the values calculated with an environmental tracer.

2.1.5 Causes of Groundwater Storage Change

Long-term water levels changes can be due to change in groundwater pumping, irrigation practices, climatic variations, or fluctuations in precipitation [88]. For example, Leduc et al. [89] concluded that rainfall interferes with the change in the water table in South-West Niger. They found that severe droughts could be interpreted as influencing the decline in the water table at some points between 1960 and 1980. Also, the rise during the 1990s could be an indication of increased recharge due to wetter years. They also argued that groundwater storage increases in recent decades could be explained by land use changes that concentrated surface water runoff into catchments and ponds, thus increasing recharge efficiency.

Scanlon et al. [90] recently reported an increase in total water storage trends in West Africa, particularly in the Iullemeden aquifer. Favreau et al. [91] also reported a continuous rise in the water table in southwestern Niger. Furthermore, Bonsor et al. [92] and Cuthbert et al. [93] showed an increase in groundwater in the Sahelian aquifers (Iullemeden and Chad). Each of these authors at least partially attributed this phenomenon to a change in land use where the clearing of native vegetation enhances and concentrates runoff in the ponds, causing an increase in infiltration and therefore recharging the aquifer.

2.1.6 Study Objectives and Goals

We use published GRACE groundwater storage change tools [7] to evaluate the historical use and sustainability of aquifers in Southern Niger. Our goals are: 1) to perform a defensible, quantitative analysis of the aquifers to determine historic use patterns and determine if an aquifer is being used in a sustainable manner, being depleted, or if it could be used more fully without depletion, 2) provide recharge estimates that allow managers to understand the magnitude of groundwater extraction that could be maintained in a sustainable manner, 3) determine if observed water level trends are correlated to rainfall in the region, and 4) to provide a published case study that can be used by groundwater managers globally that demonstrates how to use GRACE Earth observation data to better understand groundwater use patterns, evaluate aquifer sustainability, and used estimated recharge and aquifer history to develop more quantifiable and defensible groundwater management plans.

2.2 Study Area and Background

We analyzed aquifers located in Southern Niger within the Iullemeden and Lake Chad basins. The Iullemeden basin (Figure 2.1) is situated across five countries including Niger, Benin, Nigeria, Algeria and Mali in the Sahara and Sahel zones (arid and semi-arid regions) [94]. It has an area of about 620,000 km2 and is the main source of drinking water for the five countries [95]. It is bordered by the Tuareg shield in the north, by the Togo-Benin-Nigeria shields in the south, by the Liptako-Gourma discontinuous aquifer in the west, and by the dorsal of the Damagaram-Mounio crystalline basement in the east [96]. Precipitation varies between 550 and 650 mm per year with a wet season from May to October and a dry season between October and May. There is a north-south precipitation gradient with less than 50 mm of precipitation in the north and more than 800 mm in the south. Regional agriculture is dominated by rainfed crops; millet and sorghum. There is limited irrigation near villages with shallow water tables, with water table depths less than 10m [94].

The Lake Chad basin (Figure 2.1) covers around 2.5 million km^2. This basin spans Algeria, Sudan, and small areas of Libya, Cameroon, Chad, Niger, and Nigeria [97]. The climate of this region is semi-arid to arid. The average rainfall varies from 200 to 400 mm per year with a wet period from May to September and a dry season from October to April.

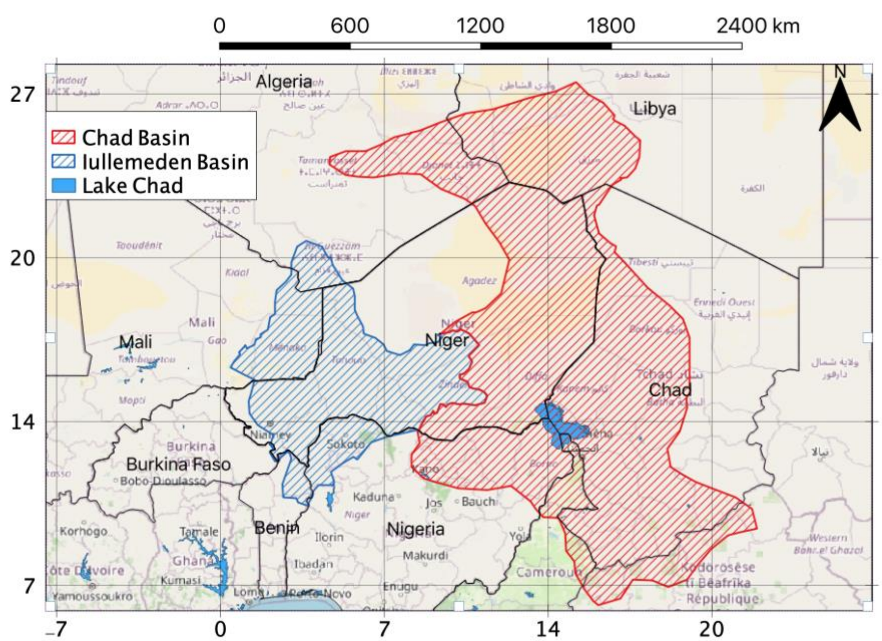


Figure 2.1: The Iullemeden and Lake Chad basins

2.3 Aquifers and Geology

The Iullemeden Basin is composed of sedimentary formations that vary from Quaternary, Tertiary, to the Cambrian-Ordovician. This basin is represented by 2,000 m thick sequences of sedimentary aquifer formations [94]. The principal shared aquifers in the Iullemeden basin are the Continental Intercalaire (CI), Continental Terminal (CT) (Tertiary), and Quaternary (Figure 2.2).

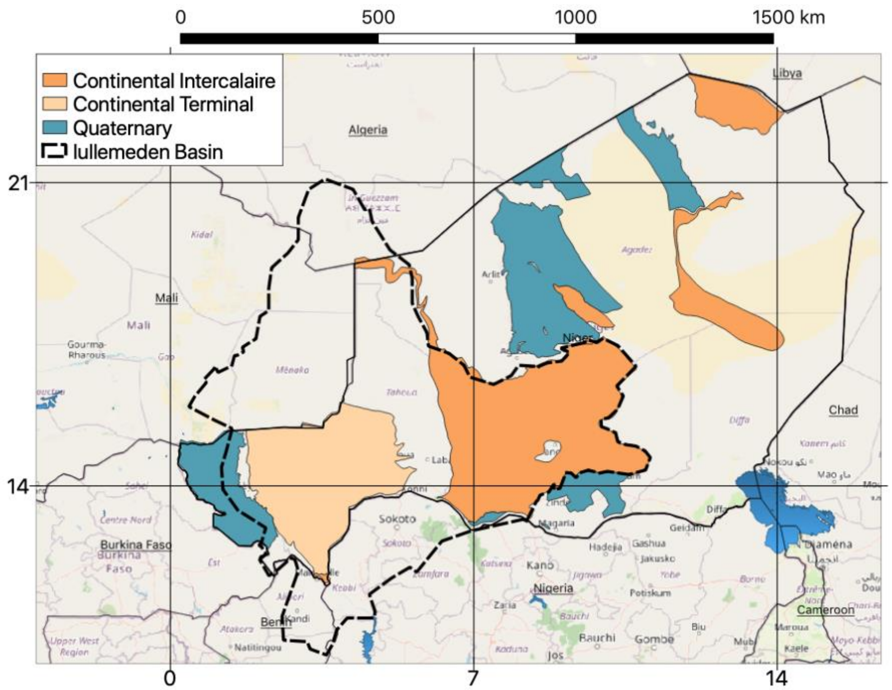


Figure 2.2: Principal shared aquifers in the Iullemeden Basin.

In general, the CI aquifer is composed of the Tegama sandstone, Farak clays, and the Continental Hamadien, from top to bottom [95]. The CT aquifer is a multi-layer aquifer in Niger including three separate aquifers: Continental Terminal 1 (CT1), Continental Terminal 2 (CT2), and Continental Terminal 3 (CT3) [95]. CT1 is a confined aquifer consisting of red and speckled clays with intercalations of sandstones. CT2 is a semi-confined aquifer containing sandy clays with lignite. The CT3 is an unconfined unit composed of a clayey sandstone with medium to fine sand on top and conglomeratic sand at the base.

The Lake Chad basin belongs to the West African rift system, which is considered the biggest intra-cratonic basin [98] with numerous aquifers recognized in the basin [99]. We analyzed two aquifers located in the Lake Chad Basin in southeast Niger. The Manga aquifer (Figure 2.3) has an area of approximately 150000 km^2 and is mainly composed of layers of sand and clay [100] with a series of sand dunes in the center that have depressions between 15 and 20 meters that affect recharge [101]. The aquifer has a small hydraulic gradient trending towards Lake Chad. The water table is shallow, with the maximum depth to groundwater of about 15 m [100]. The Korama Aquifer extends to the southern part of Niger with an area of around 6,000 km². The Korama aquifer is bordered in the west by the Damagaram Mounio Precambrian basement, in the east and north by crystalline rocks and in the south by Nigerian border for our analysis [102]. This aquifer consists of sandy-clay and alluvial sands layers with an apparent limited hydraulic connection to the sedimentary materials of the Chad Formation [100]. For both aquifers, groundwater recharge generally occurs in unconfined areas from rainfall, irrigation return flow, and by losing lakes and rivers [100]. This recharge (e.g., rainfall) is sensitive to periodic droughts, wet periods, and climatic changes. [103].

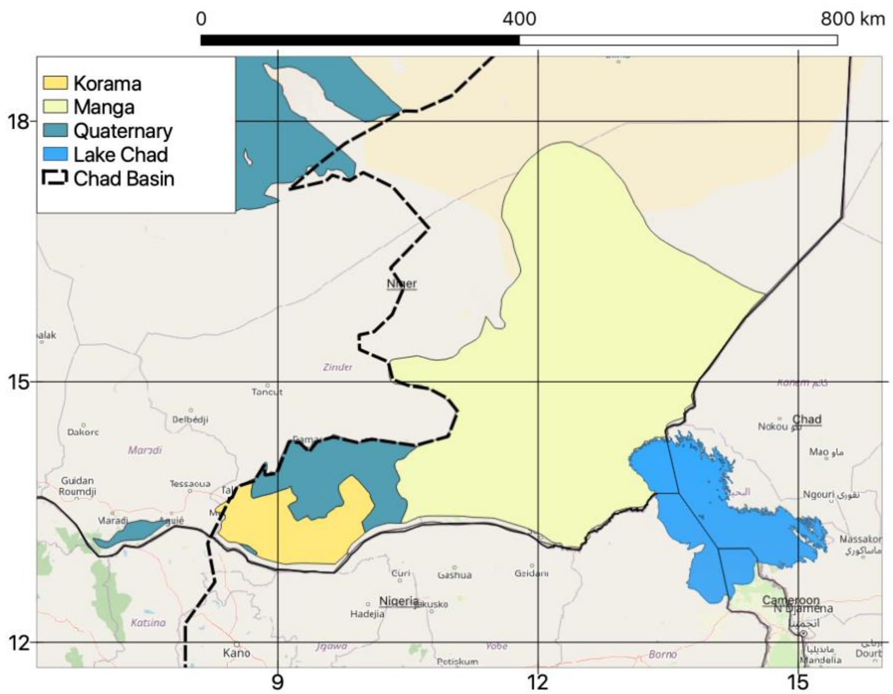


Figure 2.3: Principal shared aquifers in the Chad Basin

2.4 Aquifers Selected for Analysis

For our GRACE-derived groundwater storage analysis, we selected two sets of aquifers in Southern Niger based on their importance to the region determined by their potential for groundwater development and their location relative to the Iullemeden and Chad basins (Figure 2.4). In the Iullemeden basin we analyzed the CI and CT aquifers, the area of each aquifer are approximately 161,000 and 102,600 km2 respectively. For the Chad basin, we analyzed the Manga aquifer which has a study area of 13,000 km2 and the Korama aquifer with an approximate area of 124,600 km2.

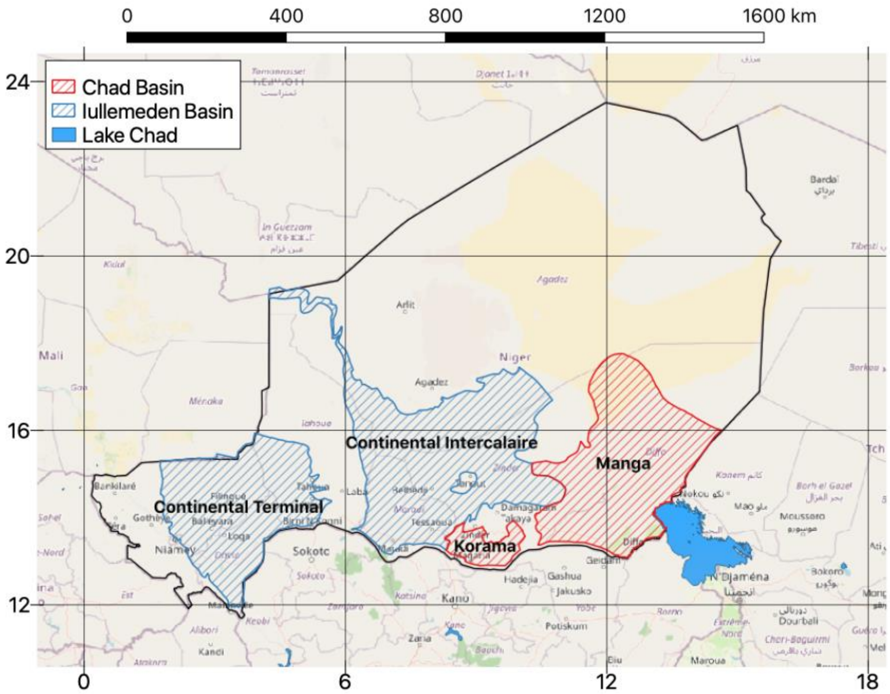


Figure 2.4: Principal shared aquifers in the Chad Basin

2.5 Previous West African Studies

There have been several GRACE studies in West Africa related to water storage changes. Forootan [104] estimated total monthly water storage changes using precipitation and sea surface temperature data and obtained results that matched the observed GRACE total water storage anomaly (TWSa) better than the changes estimated using a global hydrological model. Grippa [105] estimated GRACE surface water storage and soil moisture storage using land surface models in the Sahelian area which provided useful estimates of water storage changes over the Sahel and West Africa. They showed that the water storage interannual variability can be reproduced using GRACE data.

Hinderer [106] estimated and compared water storage changes using various ground and space geodesy methods in the Lake Chad basin and Niger. They found a good agreement between the CMAP (CPC Merged Analysis of Precipitation) cumulative precipitations, GRACE solutions, and GLDAS model predictions.

A similar comparison was carried out by Nahmani [107], who compared the hydrological loading deformation associated with Monsoon precipitation as computed by GPS, GRACE, and loading models along the Niger River in three stations (Timbuktu, Gao, and Niamey). They found a consistent match between the vertical ground deformations in the annual signal between GPS, a combination of hydrological, non-tidal oceanic and atmospheric models, and GRACE-derived deformation estimates. They found that the land deformation roughly parallels the seasonal groundwater depth fluctuations and speculated that the correlation was a result of shrinking/swelling of clays.

Werth [108] analyzed a decade of terrestrial water storage changes based on GRACE data and confirmed a water table rise in the Sahelian Niger River Basin resulting from an increase in groundwater storage. They concluded that zones with rising groundwater storage could be used to mitigate future droughts and distribute water to distant areas.

2.6 West Africa Groundwater Development and Regional Water Management

Agroforestry parklands are the established land-use system in the greater Sahel region. This traditional system has been maintained for many generations and is characterized by preserving trees on cultivated land [109] These trees are essential part of the agriculture system providing food, wood for buildings, fuel, and medicines, and contribute to water conservation, soil fertility, and environmental protection [110]. Due to the scarcity of surface water in the region, agriculture, industry, and domestic use rely on groundwater [57].During the last decade, local aquifers have been subjected to more use due to the increased need for water for agriculture and industrialization. This region has experienced several droughts [110] making groundwater an essential buffer, especially for agriculture [111]. This situation has resulted in local managers being motivated to use groundwater resources in a sustainable manner [57].

In general, the aquifers of the Iullemeden basin have been used mainly in southern Niger, with pumping rates between 20 and 100 m3/hr from wells 40 to 100 m in depth [112]. In this basin, there is an irregular distribution of wells, with wells located near population concentrations. The Niger River and groundwater from the CI and CT aquifers are the main water sources for industrial activities, with groundwater being Niger's most valuable water resource [112].

In the Chad basin there has been approximately a 200% increase in irrigation over the last 30 years causing an over-exploitation of surface water resources. This increase in water resource demand is mainly due to the lack of efficient irrigation systems and irregular rainfall [103]. In urban areas, groundwater is the primary source for drinking water, however, this groundwater source is inadequate, mostly due to the cost of development [103]. Despite the importance of this valuable groundwater resource in both basins, the groundwater infrastructure is not fully developed. Money from both local and foreign investments may be available to develop infrastructure, but first it must be demonstrated that groundwater can be developed sustainably in those regions.

2.7 Methods

2.7.1 GRACE Data

GRACE data are processed to provide a gridded gravitational anomaly map [15,19] by three institutions that use different algorithms: the NASA Jet Propulsion Laboratory (JPL), the University of Texas at Austin Center for Space Research (CSR), and the German Research Center for Geosciences (GFZ). Each of these methods generate a total water storage anomaly (TWSa) datasets that are distributed by NASA [113]. We used the JPL dataset in this analysis [114–116]. NASA provides a monthly-averaged TWSa dataset on a 0.5-degree grid resolution. They also provide an uncertainty estimate for each grid cell to quantify the uncertainty of the data processing methods [1,44,69].

We also used Global Land Data Assimilation System (GLDAS) data to separate groundwater data from the TWSa [67]. GLDAS includes three separate land surface models: Noah, VIC, and CLSM, each of which produces data estimating water volume in the form of canopy storage (CAN), snow-water equivalent (SWE), and soil moisture (SM). We converted the GLDAS data to an anomaly format based on the deviation from the 2004-2009 mean and labeled these anomaly datasets as CANa, SWEa, and SMa. The VIC and CLSM datasets are produced at 1.0-degree resolution and the Noah dataset is produced at 0.25-degree resolution.

2.7.2 Regional Groundwater Storage Analysis Using GRACE

We used the GRACE Groundwater Subsetting tool (GGST) to estimate groundwater storage changes [7]. GGST uses GRACE TWSa data and GLDAS data to estimate groundwater storage anomalies and allows us to globally monitor changes in groundwater for selected regions since 2002, with the exception of the high latitudes [7].

To study groundwater trends and sustainability over time in a regional aquifer, we first define a region or aquifer for study. We then use GGST to derive a groundwater storage anomaly (GWSa) dataset by subtracting the GLDAS surface water anomaly datasets from the GRACE TWSa dataset as follows:

$$GWSa = TWSa - SWEa - CANa - SMa \tag{2.1}$$

This mass balance approach has been used and validated by a number of researchers [69–73].

To compute the surface water components, we average the GLDAS data from the Noah, VIC, and CLSM land surface models which have different grid resolutions. To do this, we rescale the Noah dataset from 0.25-degree to 1.0-degree to match the resolution of the VIC and CLSM models. We also scale the TWSa dataset from 0.5-degree to 1.0-degree resolution. The resulting GWSa dataset is then at 1.0-degree resolution.

Once the GWSa dataset is computed, we then use the data from the three land surface models to estimate uncertainties in our predictions. We compute the standard deviation for each of the surface water components using the estimates from the VIC, CLSM, and Noah models and then estimate the uncertainty in the GWSa as:

$$\sigma \mathrm{GWSa} = \sqrt{(\sigma \mathrm{TWSa})^2 - (\sigma \mathrm{SWEa})^2 - (\sigma \mathrm{CANa})^2 - (\sigma \mathrm{SMa})^2} \quad (2.2)$$

where $\sigma SWEa$, $\sigma CANa, and\ \sigma SMa$ are the standard deviations of each component and $\sigma TWSa$ is the total water storage uncertainty provided by NASA [66]. The resulting uncertainty estimates vary both in space and time.

GGST clips each data set to the selected region, resulting in a set of clipped rasters for each dataset. It averages the raster values for each month to produce a time series indicating how each dataset varies over time since 2002. The GGST then multiplies the time-varying GWSa rasters by the region area resulting in a time series of cumulative water storage change for the region in units of millions of cubic meters or cubic kilometers [7]. This time-series product is useful as it presents managers and others with a simple and intuitive summary of water storage changes in a region of interest. It indicates if the aquifer is being sustainably used, if it is recharging, or if storage is being depleted in a non-sustainable manner.

We cannot compute the total amount of groundwater present, only the change in storage over time. We do compute annual recharge values, which can be compared to groundwater use data to determine how much additional water could be extracted, or how much extraction would need to decrease to result in sustainable year. This is discussed in Section 3.4.

2.7.3 Imputation of Missing Groundwater Storage Anomaly Data

The original GRACE mission has mostly complete data up to 2010 with a further seven years of additional collection that has periodic data gaps. There is an 11-month gap between the original mission and the GRACE-FO mission [117,118] Figure 2.5 presents derived GWSa data for the Iullemeden basin that shows these periods with missing data. Figure 2.5 shows that, for this location, the GWSa data have a seasonal pattern with an increasing trend. Data at other locations exhibit simliar patterns, seasonal variations with a trend; globably not all aqufers exhibit a seaonsal trend.

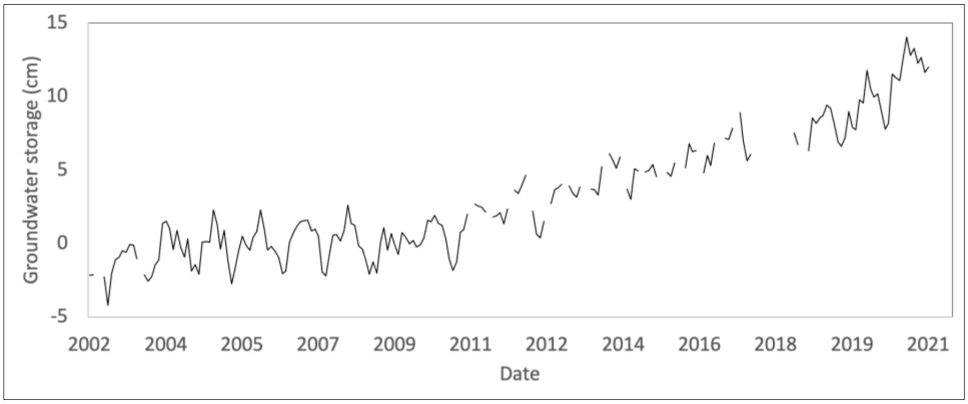


Figure 2.5: Original groundwater storage data from GRACE in the Iullemeden basin

For our analysis we need a data set without any gaps, so we need to impute the missing GRACE data to generate this complete data set. Since the data exhibit a trend with seasonal variation, we used a simple seasonal decomposition model (statsmodels.tsa.seasonal.seasonal_decompose) implemented in the statsmodels Python package [119] to impute the missing data. This model first removes the trend using a convolution filter (the trend component), then computes the average value for each period (the seasonal component), in our case months, with the residual component being the difference between the monthly average (seasonal component) and the actual monthly measurements. With this approach, we decompose the GWSa time series into three components: the trend, the seasonal, and the random components: [120].

$$Y[t] = T[t] + S[t] + e[t] \tag{2.3}$$

where, $Y[t]$ is the GWSa, $T[t]$ is the GWSa trend , $S[t]$ is the seasonal GWSa component , and $e[t]$ is the residual GWSa component .

Figure 2.6 shows the decomposition components for the GWSa from GRACE dataset for the Iullemeden basin. For visualization purposes, we added a linear least squares fit to the plot of the trend line, which is represented by the dashed line in the "trend" panel.

To impute the missing data, we use the trend from the data decomposition, then add the average of the monthly and residual values for that month to estimate the missing value. This model can be written as:

$$Y[t] = y(T[t]) + \overline{S[t] + e[t]} \tag{2.4}$$

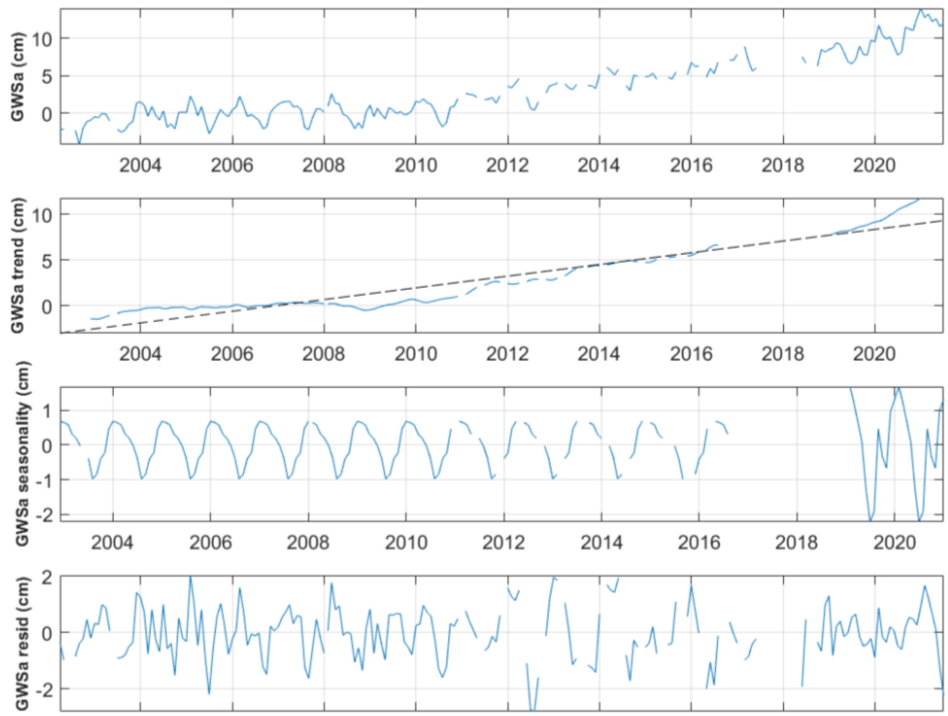


Figure 2.6: Decomposed GWSa data for the Iullemeden basin.

Figure 2.7 shows the original time series in black, with imputed values in red. Visually, the seasonality and trend are preserved and the imputation appears reasonable.

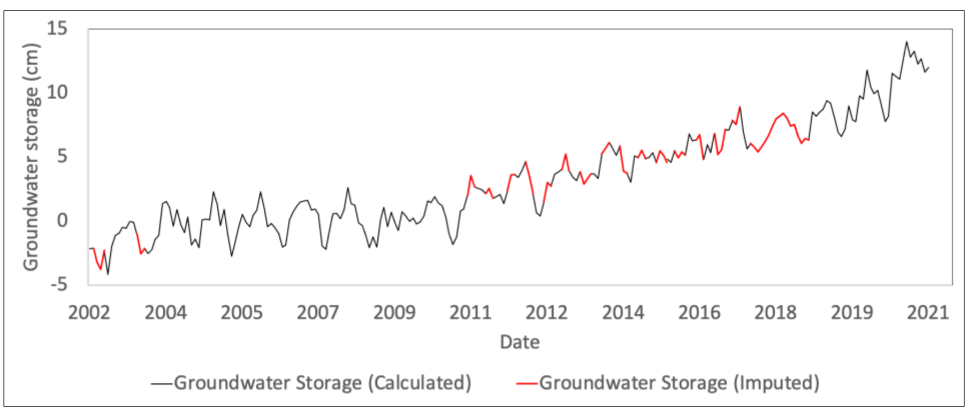


Figure 2.7: Measured (black) and imputed (red) GWSa data showing that visually, the imputed data honor the long-term trend and seasonal variation present in the data.

2.7.4 Estimating Annual Recharge Using GRACE-Derived Groundwater Datasets

To estimate groundwater recharge in the two aquifers, we use the WTF method [50]. The WTF method estimates groundwater recharge as:

$$R = S_y\left(\frac{\Delta h}{t}\right) \tag{2.5}$$

where R is the groundwater recharge in cm/yr, Δh is the change in height of the water table (cm), t is a specified interval over which the change was measured, and Sy is the specific yield [49]. The time period is usually selected based on seasonal fluctuations. Traditionally the water table fluctuation, Δh, is measured at selected wells . For this study, rather than well measurements, we used the computed GWSa for the aquifer and assumed that ΔGWSa = SyΔh [84].

To compute the recharge rate (cm/year) we examined seasonal fluctuations in ΔGWSa time series plots as shown in Figure 2.8. This allowed us to identify the seasonal fluctuations and select the appropriate time period. The WTF method assumes that during the dry period there is minimal recharge and the groundwater declines because of pumping (red line in Figure 2.8). The subsequent rise represents the recharge period.

Two methods are traditionally used to estimate the recharge rate from the curve. For the first method, we measure the distance from the trough of decline S_B to the peak of the rise S_p with the change being the net recharge (R_S). For method 2, we project the downward trend from the depletion curve fitted from S_A (peak of the previous year) down to the trough (S_L) to find the recharge that balances continuing discharge (R_D) and then add that to R_S to find a total recharge ($R_S + R_D$).

$$R_{method\ 1} = \frac{\Delta\text{GWSa}}{\Delta t} = \frac{S_p - S_B}{\Delta t} = R_S \tag{2.6}$$

$$R_{method\ 2} = \frac{\Delta\text{GWSa}}{\Delta t} = \frac{S_p - S_L}{\Delta t} = R_S + R_D \tag{2.7}$$

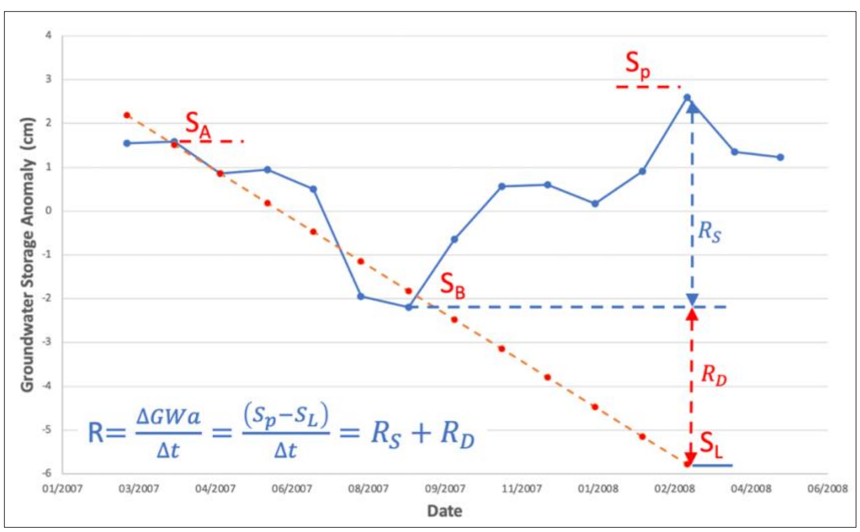


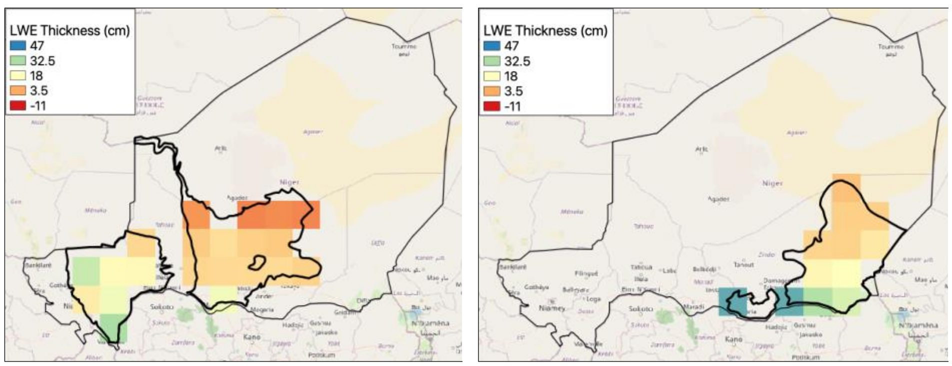
Figure 2.8: Conceptual diagram of the two approaches of the WTF method to show the groundwater storage anomaly (GWSa) from 2007/01 to 2008/06 in the Iullemeden basin (modified from Wu , et al. [84].

Taken together, these two methods provide both a low and a high estimate of recharge.

2.8 Results

2.8.1 GRACE-Derived Groundwater Storage Analysis

We processed both the selected regions in Southern Niger using GGST to analyze water storage change in the regions. We created clipped time-series grids for each water storage components: TWSa, surface water (SWEa and CANa), SMa, and GWSa. We produced a time series of the average value for each variable, averaged over each region with an uncertainty estimate. Figure 2.9 shows the 1-degree resolution regional maps of the Iullemeden and Chad basins for April, 2021. These maps represent the derived GWSa in cm of liquid water equivalent (LWE) thickness.



(**a**) (**b**)

Figure 2.9: Raster maps of groundwater storage anomaly for the Iullemeden basin aquifers (panel a) and the Lake Chad basin aquifers (panel b) for April, 2021.

To characterize and analyze the long-term groundwater storage trend in each basin, we generated time series curves over for the full time period of the GRACE missions (2002-2021). GGST provides these time series in two formats: average liquid water equivalent (cm) and cumulative storage change since 2002 in millions of cubic meters (MCM). This second format helps communicate how much water an aquifer is gaining or losing in a common volumetric unit [7].

2.8.2 Iullemeden Basin Aquifer Cumulative Storage Change

Figure 2.10 shows the GWSa anomaly in liquid water equivalent format for the selected aquifers in the Iullemeden basin for the period of April 2002 to September, 2021. The anomalies are relative to the mean storage value between 2004-2009. The trend shows a slight increase in groundwater storage during the first nine years (from 2002 to 2011) then a larger increase for the last ten years (2011 to 2021) reaching a total increase in storage of more than 10 cm of water equivalent. We fit a linear regression line to these two time periods to indicate the visual trend in the plots. This indicates a significant increase in groundwater storage in the region.

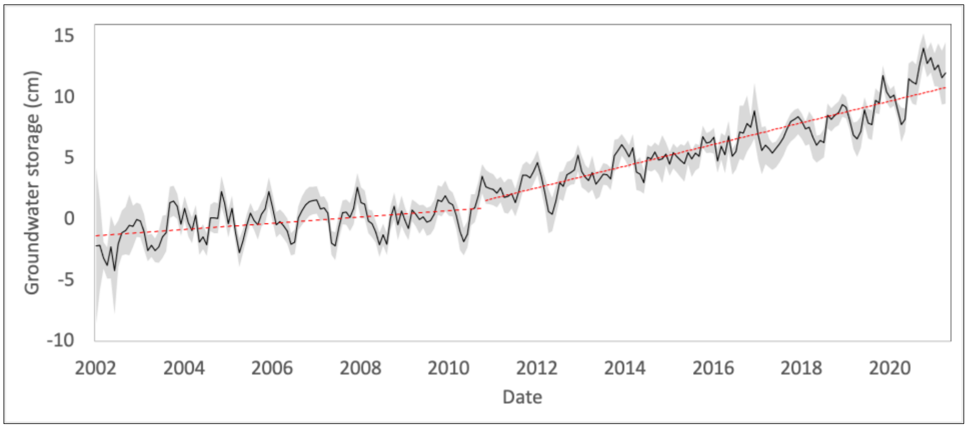


Figure 2.10: Groundwater storage anomalies in the Iullemeden basin region

Figure 2.11 presents the cumulative groundwater storage volume change in MCM over the same period. The plot shows seasonal cycles, with little net change through 2010, but then a steady upward trend for the next 11 year resulting in a net gain of approximately 3000 MCM or 3 KM^3.

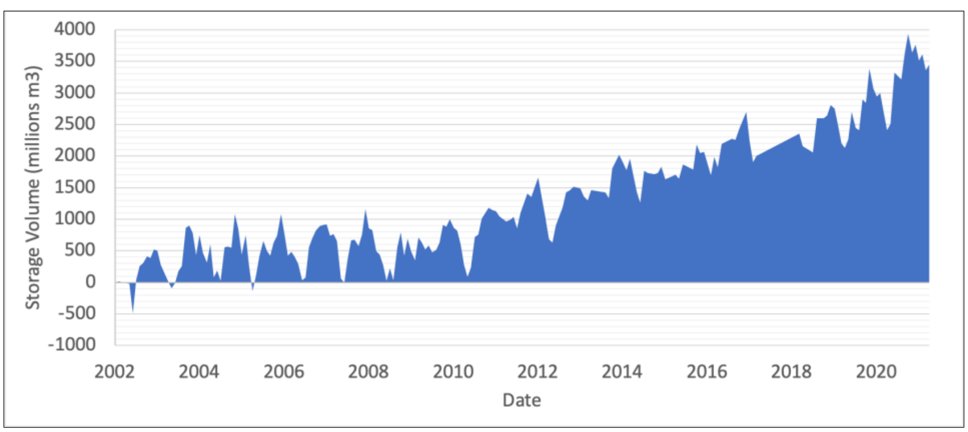


Figure 2.11: Groundwater storage anomalies in the Iullemeden basin region

2.8.3 Chad Basin Aquifers Cumulative Storage Change

For the aquifers in the Chad Basin, the results are similar but less pronounced (Figure 2.12). We observe in a slight decrease in the GWSa for 2002-2011 and an increase for 2011-2020. The average value of indicates a net gain in groundwater storage over the entire time range.

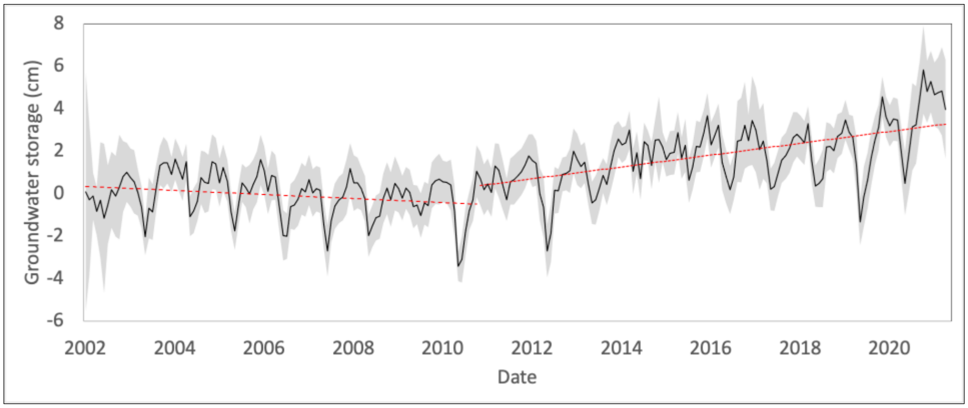


Figure 2.12: Groundwater storage anomalies in the Iullemeden basin region

Finally, Figure 2.13 shows the volumetric groundwater storage change curve for the Chad aquifers. The net volume storage values change seasonally with a slight downward trend until 2012 and then an upward trend with a net gain of approximately 600 MCM (0.6 KM^3) by late 2021.

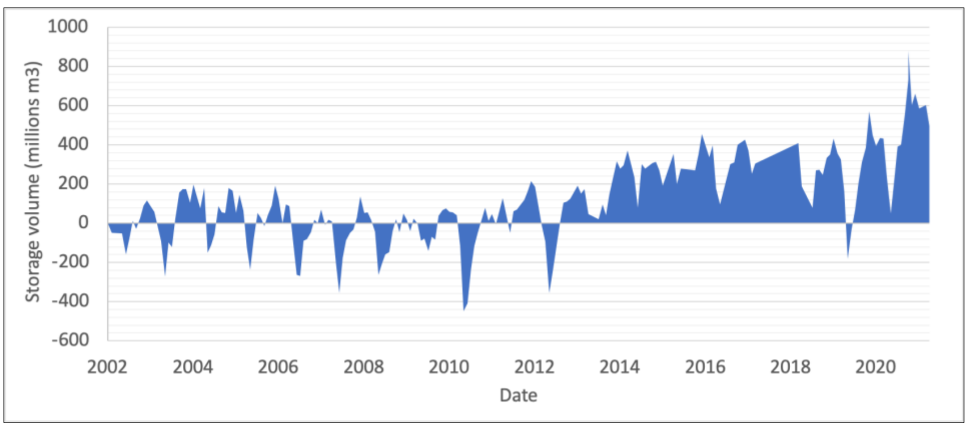


Figure 2.13: Cumulative groundwater storage change in the Chad basin region

2.8.4 Uncertainty of Storage Change Estimates

The groundwater storage change estimates illustrated in Figure 2.10 and Figure 2.12 and contain various types and levels of uncertainty. There is an uncertainty in the monthly TWSa data with an estimate of the magnitude of this uncertainty provided by NASA. We combined this with the standard deviation in the terrestrial water storage estimates provided by the three land surface models in GLDAS to estimate time-varying uncertainly shown by the shaded band in Figure 2.10 and Figure 2.12.

There is an additional source of uncertainty in these estimates due to a well-documented phenomenon called "leakage" [12,121,122]. While the TWSa datasets used in this study are provided by NASA at a 0.5-degree resolution, the original GRACE grid cells are at a 3.0-degree resolution. Mass conserving scaling factors are used to derive the finer resolution of the 0.5-degree values, but the data are still implicitly tied to the 3.0-degree resolution. One result of this is that when applying a GRACE analysis to a relatively small study area such as the two regions analyzed in this study, anomalies just outside the study area can impact the mass measured in the native 3.0-degree GRACE cells and impact the results (i.e., "leak" from adjacent areas to the target areas).

For our study regions , we anticipate that conditions to East, West, and South are likely similar to the study regions while conditions to the North may be different. The North is more arid resulting in less recharge, but there are also lower groundwater withdrawals as there are fewer wells in this region. As a result, we have not attempted to make a leakage adjustment, but recognize that the potential for leakage should be acknowledged as a source of uncertainty.

2.8.5 Correlation with Precipitation Data

We obtained monthly precipitation data from CHIRPS (Climate Hazards group Infrared Precipitation with Stations) which is computing using an algorithm presented by Funk et al [123]. While we used the monthly data, CHIRPS provides hourly, pentadal, and monthly data from 1981 to 2020 on a 0.05°×0.05° degree spatial resolution. We computed the correlation of annual precipitation (mm) in Niger with GWSa (cm) in the Iullemeden and Chad basins aquifers Figure 2.14 and Figure 2.15 for the period of 2002 to 2020.. During the first 9 years, the trend line shows that there has been a slight decrease in the average annual precipitation while from 2011 to 2020 rainfall average values increase.

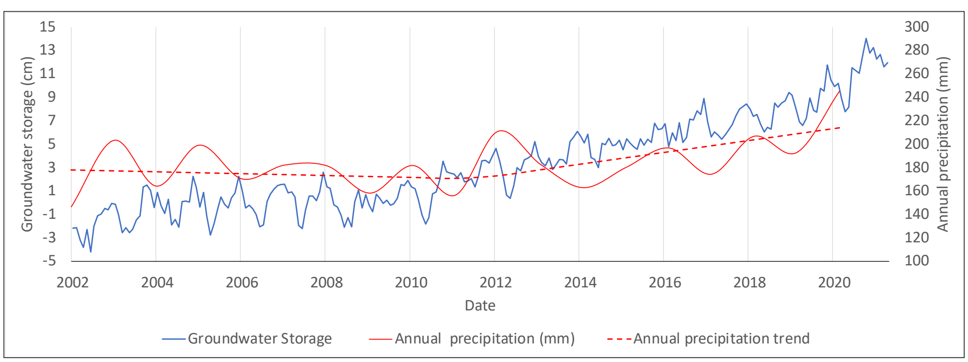


Figure 2.14: Groundwater storage (cm) and observed average annual precipitation (mm) of the Iullemeden basin

The behavior of the precipitation trend line parallels the behavior of the groundwater storage change curves. However, the calculated correlation coefficients with a time lag of seven month are 0.2 and 0.35 in the Iullemeden and Chad basins respectively indicating a low correlation between the two variables and highlighting the effect of the change in land use described in section 1.5 on increasing groundwater storage.

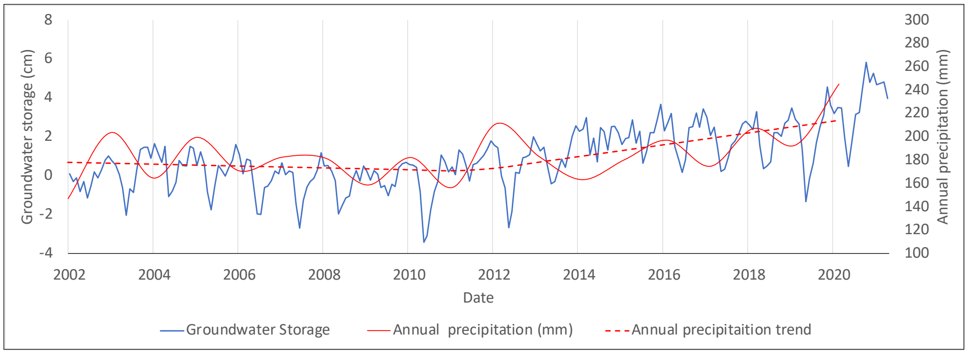


Figure 2.15: Groundwater storage (cm) and observed average annual precipitation (mm) of the Chad basin

2.8.6 Annual Recharge Analysis

We used both WTF approximation methods to estimate the recharge value for the Iullemeden and Chad basins aquifers over the 2002 to 2021 period. We examined the computed GWSa seasonal fluctuations and extracted the R_s and R_d recharge values from the peaks and troughs. However, Figure 2.10 ana Figure 2.14 show that there is a short period in both regions from 2014 to 2016 with little seasonal variation. Since this corresponds to a wet period, it could be the result of recharge being diffused over a larger time period during these years. Because of this, it is difficult to estimate groundwater recharge during these periods using the WTF method.

To address this issue, we examined the other years to determine the average downward slope during the dry period which the WTF method assumes is due to groundwater extraction. We then calculated the average timing of the seasonal trough and using the average slope and average time of the trough, we applied the WTF to estimate the groundwater recharge for the years 2014-2016 as illustrated in Figure 2.16.

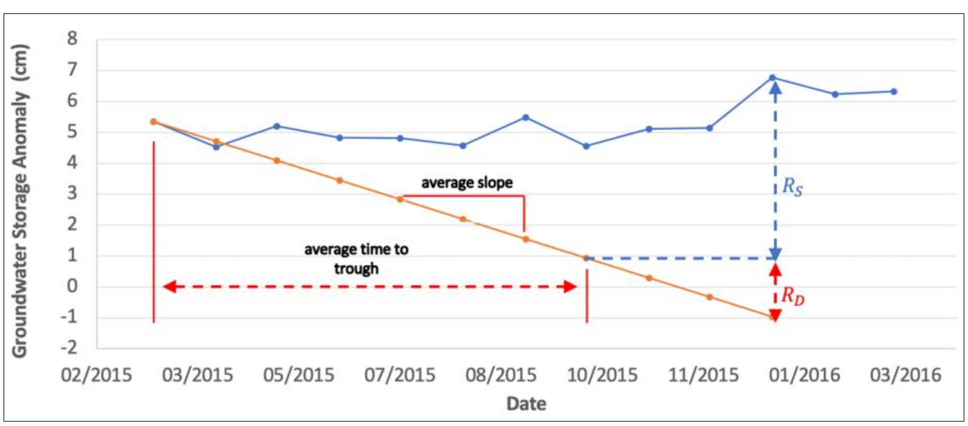


Figure 2.16: Conceptual diagram to show the change in the (GWSa) using the average slope from 2015/02 to 2016/03 in the Iullemeden basin

2.8.7 WTF estimated Recharge Rates

Figure 17 shows the groundwater recharge estimates using the two WTF methods for the Iullemeden aquifers. Both methods show relatively constant recharge between 20–02 - 2011 and an increase in recharge from 2011- 2020 matching the patterns observed for groundwater storage change. The average recharge values estimated for the 2002-2011 period are 4.02 cm/yr and 7.32 cm/yr for Methods 1 and 2, respectively. For the second period (2012-2021) the average groundwater recharge values are 4.53 and 9.15 for Methods 1 and 2, respectively.

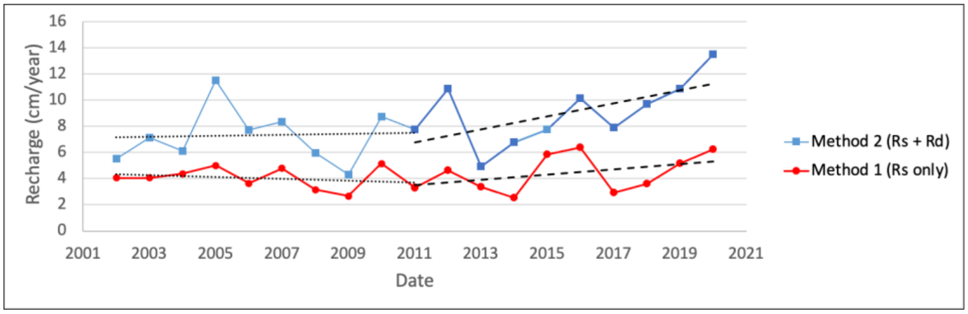


Figure 2.17: Estimated recharge values in the Iullemeden basins

For the Chad aquifers, the derived recharge rates exhibit a similar pattern (Figure 2.18). There is relatively constant recharge from 2002 to 2011 and overall increase in recharge in the last 10 years (2011-2021). The estimated average recharge rates are 2.90 cm/yr and 5.41 cm/yr for Method 1 and 2, respectively. For the second period (2012-2021) the estimated rates are 4.12 cm/yr and 7.60 cm/yr for Methods 1 and 2, respectively. The estimated recharge rates in the Iullemeden basin are higher than those the Chad basin, which correlates to the higher groundwater storage gains observed in the Iullemeden basin.

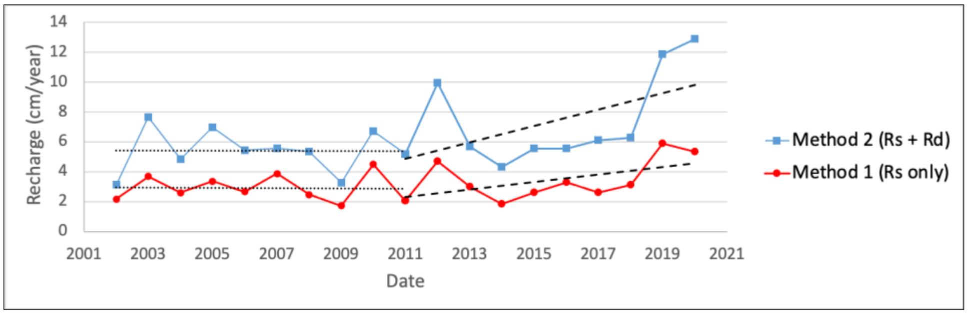


Figure 2.18: Estimated recharge values in the Chad basins

Figure 2.18 presents the recharge rates we estimated with reported values from the literature for the same region. Our estimated recharge rates using WTF Method 1 are listed as the low estimate for each range: 4.0 - 4.5 cm and 2.9 - 4.1 cm for the Iullemeden basin and Chad basins, respectively.

These values are in the range reported by Vouillamoz et al. [124] and Leduc et al.[125] who both used the WTF method (1 to 5 cm). The values we estimated using WTF Method 2 of 7.3 – 9.2 cm and 5.4 – 7.6 cm in the Iullemeden and Chad basins, respectively, are higher for both periods and basins than the published WTF values. The estimated recharge values found by Leduc et al. [125] and by Favreau et al. [126] using 14C and 3H , and by Bromley et al. [127] using the chloride mass balance (CMB) method, are all lower than the values we found. All of these values reported in the literature refer to Southwest Niger and the latest year of the reported groundwater recharge is 2000. With the period of high precipitation and groundwater accumulation from 2011-2021, we would expect the recharge rates we computed in the region to be higher than those from the literature.

Table 2.1: Average recharge value (from 2002 to 2020) compared with results from prior studies.

Reference	Country/Region	Method	Time	Recharge (cm/year)
Estimated values in this project	Iullemeden Basin	WTF	2002-2011	4.0 - 7.3
	Iullemeden Basin	WTF	2012-2021	4.5 - 9.2
Estimated values in this project	Chad Basin	WTF	2002-2011	2.9 - 5.4
	Chad Basin	WTF	2012-2021	4.1 - 7.6
Bromley et al., 1997	Southwest Niger	CMB (Chloride mass balance)	1992	1.3
Leduc et al. 1997	Southern Niger	WTF	1991	5 to 6
(Leduc et al., 2001) and (Favreau et al., 2002)	Southwest Niger	Radioisotopes (14C and 3H)	1950s–2000s	0.1 to 0.5
(Leduc et al., 2001)	Southwest Niger	WTF	1990s–2000s	2 to 5
(Vouillamoz et al., 2008)	Southwest Niger	WTF	1990s–2000s	2 to 5

2.9 Conclusions

We used published methods implemented in the GGST tool along with GRACE and GLDAS data to analyze historical groundwater storage change in selected aquifers in two basins in Southern Niger in West Africa. We applied a simple seasonal decomposition model impute missing data in the GRACE datasets and then derived groundwater storage change estimates by subtracting surface water storage datasets provided by the GLDAS model. Using this approach, we estimated the cumulative storage change of aquifers in Iullemeden and Chad over a 19-year period from 2002 to 2021. During the first 9 years we found a slight increase in the groundwater storage in the aquifers from the Iullemeden Basin and a slight decrease in aquifers associated with the Chad Basin. We found a considerable increase in the storage during the last 10 years in both basins. These changes can at least be partially ascribed to increased precipitation during the same period.

We estimated groundwater recharge rates for the basins using two WTF methods which assumed that the increment in the groundwater levels are due to the recharge. Our estimated annual average recharge rates are consistent with groundwater storage changes for the region, showing relatively constant values from 2002 – 2010 and an increase from 2011 – 2021. We compare the estimates we computed with those from other studies in the region and found that groundwater recharge calculated other methods such as CMD, 14C, and 3H resulted in lower estimated recharge rates. For reported values using the WTF method, our estimated values with WTF Method 1 are within the range of values reported by Leduc et al. and Vouillamoz et al. [124] while our estimates using WTF Method 2 are higher than the reported values. However, it is reasonable to expect higher recharge rates during a period of significant groundwater accumulation.

We found that groundwater storage in this region is not being depleted and rather has been increasing for the past 10 years. These results indicate that there is potential for additional groundwater infrastructure development in the region. Water managers should continue to monitor groundwater storage changes to ensure sustainable long-term use and this study shows that such an analysis can be performed using remote sensing products, which is especially helpful in this region where in situ data are scarce.

2.10 Abbreviations

Table 2.2: List of abbreviations used in the text, in alphabetical order.

Abbreviation	Full Form
CAN	canopy storage
CANa	canopy storage anomaly
CMB	chloride mass balance
CI	Continental Intercalaire
CSR	University of Texas at Austin Center for Space Research
CT	Continental Terminal
DLR	German Aerospace Center
GLDAS	Global Land Data Assimilation System
GRACE	NASA Gravity Recovery and Climate Experiment
GRACE-FO	GRACE Follow-On
GFZ	German Research Center for Geosciences
GGST	GRACE Groundwater Subsetting tool
GWS	groundwater storage
GWSa	groundwater storage anomaly
JPL	NASA Jet Propulsion Laboratory
LWE	liquid water equivalent
MCM	millions of cubic meters
SMa	soil moisture anomaly
SWEa	snow-water equivalent anomaly
Sy	Specific yield
TWSa	total water storage anomaly
WTF	water table fluctuation

3 *Analysis of Groundwater Storage and Recharge Trends using GRACE data in the Volta Basin in West Africa*

This chapter is composed from a paper entitled *"Analysis of Groundwater Storage and Recharge Trends using GRACE data in the Volta Basin in West Africa"* submitted for publication to the Journal of Hydrology - Regional Studies. I hereby confirm that the use of this article is compliant with all publishing agreements.

3.1 Introduction

3.1.1 Motivation

Freshwater is rapidly growing more important due to the world's population growth and increased global demand [4]. A study by UNICEF/WHO (2005) [128] estimated that around 56% of the population in sub-Saharan Africa had access to a safe water supply. The limited coverage was due to a shortage of investment in infrastructure and increasing population. Arid and semi-arid regions in sub-Saharan Africa obtain water primarily for domestic, agricultural, and industrial purposes from surface water sources such as rivers, lakes, ponds, dugouts, reservoirs, and harvested rainwater and groundwater sources such as springs, boreholes, and hand-dug wells. [4]. Sub-Saharan Africa's high rainfall variability causes surface water sources to be unreliable, prone to high evaporation, easily contaminated, and unable to keep up with increasing demand. Groundwater sources, on the other hand, are ideal for serving the spread-out demand of the expanding rural population, which constitutes the majority of the total population [4].

The Volta Basin in sub-Saharan Africa experiences significant variations in climate, soil, and vegetation due to its extensive size. Precipitation decreases from high values in the mid-section to extremely low levels in the north and south [6]. Most rivers in the Volta Basin are ephemeral, making it hard to access potable water during dry seasons. In addition, when streams and reservoirs are far away or during droughts, groundwater inevitably becomes the only source of water [5,6]. For this reason it is essential to study the changes in groundwater storage [5].

3.1.2 GRACE Data

The United States National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR) launched the Gravity Recovery and Climate Experiment (GRACE) in 2002, which uses two satellites that orbit 220 km apart and measure variations in the Earth's gravitational field by tracking changes in the distance between the two satellites [15]. These measurements are precise to 10 μm [14,15,65]. The original GRACE mission lasted for approximately 15 years and provided data from 2002 to 2017 [129]. In 2018, the GRACE Follow-On (GRACE-FO) mission was initiated [17], which continues to provide monthly gravitational anomaly data, similar to the original GRACE mission, up until the present day [16,17].

The GRACE satellites can be used to monitor changes in water storage globally because changes in mass that produces gravitational changes are driven primarily by changes in water storage in most locations, as few other changes affect Earth's mass on this scale [19]. Hence, GRACE data can be used to estimate variations or "anomalies" in water mass compared to a long-term mean but cannot estimate the total water mass [20]. NASA publishes a total water storage anomaly (TWSa) dataset to track changes in global water storage [31]. The TWSa dataset is widely utilized and its processing and applications in hydrological studies are well documented in the literature [31]. Additional studies have indicated that GRACE data can be employed to estimate changes in groundwater storage without relying on in situ measurements [7,36,44,130,131], including cases in arid and semi-arid regions [4,13,41,132].

3.1.3 Estimating Changes in Groundwater Storage with GRACE

GRACE data can be used to analyze groundwater, which is a portion of total water storage [1,7,36,43]. To separate the groundwater component from total water storage, most GRACE groundwater studies use results from global land surface models [7]. For instance, GRACE-derived Total Water Storage Anomaly (TWSA) minus the surface water storage components calculated by NASA's Global Land Data Assimilation System (GLDAS) model can serve as an estimate of the groundwater storage change anomaly [7,42,43].

The practice of using different land surface models to subtract non-groundwater components from GRACE data has been widely used [1,7,12,13,43,43,62,74–76,133–137]. Although it is possible to obtain groundwater data from GRACE TWSa, such data are seldom used for ongoing groundwater management outside of academia. Several tools have been developed for accessing and processing GRACE TWSa data, but many of these tools are limited in their datasets due to their size, and the majority do not provide derived groundwater datasets. Most of these tools are designed for scientific or technical experts and do not offer an easy way to support regional analysis, which is essential for local groundwater study and management [78–81,129,138].

We recently introduced tools that enable groundwater managers to readily estimate changes in groundwater storage over time for a selected aquifer or region using GRACE data [7,20]. These tools consist of a web application and a Python-based notebook interface that accesses GRACE and GLDAS model data, computes the gridded monthly groundwater anomaly, and subsets the data to the extent of the aquifer. By integrating the spatially gridded groundwater anomaly data over time, the tools generate an aquifer storage time history that is limited to the specific aquifer region being studied or managed. The resulting data and information can be used by local groundwater managers to assess groundwater use and gain a better understanding of the potential impacts of future development.

3.1.4 Assessing Groundwater Recharge

In addition to groundwater storage, assessing trends in groundwater recharge is essential for effective groundwater management. When choosing a suitable approach for estimating groundwater recharge, several factors must be taken into consideration such as the study's scope, the size of the study area, the time period of the study, and the reliability of the recharge estimation method. To estimate groundwater recharge, a range of methods have been employed, including physical, chemical, isotopic, and modeling techniques [45–48]. Groundwater level-based techniques are widely acknowledged as the primary methods for estimating recharge rates [49]. One of these methods is the Water Table Fluctuation (WTF) approach, which was developed in the early 1920s [49,50] to estimate episodic recharge by assessing groundwater table fluctuations. The increment of the annual fluctuation is classified as recharge, enabling the analysis of seasonal changes in the piezometric head at the aquifer. This approach is suitable for various temporal scales, ranging from daily to yearly, and is known for its ease of use, low data requirements, and relatively low cost [51].

While the WTF method is typically applied to in situ water level measurements, it can also be applied using water level anomalies derived from GRACE data. For example, Barbosa et al. [13] recently used GRACE and GLDAS (Global Land Data Assimilation System) data to evaluate groundwater storage changes and estimate groundwater recharge in two significant aquifers in Niger, Africa. Their findings suggest that recharge rates for the period between 2002 and 2021 are high, but still consistent overall with previous estimates. Similarly, Henry et al. [85] estimated groundwater storage anomalies and annual recharge rates in Mali from 2002 to 2008 using GRACE and GLDAS data. They compared their results with estimates obtained using the WTF method with data from available observation wells. The calculated recharge values using GRACE data and historical water level data were 16.4% and 14.8% of annual precipitation, respectively. In a study by Gonçalvès et. al. [86], recharge in the Northwestern Sahara Aquifer System was estimated using monthly records from GRACE, GLDAS, and groundwater pumping rates. The findings contradict the hypothesis that recharge rates in the region are low or even nonexistent, with the estimated recharge rate reaching 40% of precipitation. Ahmed, M., & Abdelmohsen, K. [87] conducted a study using GRACE data to quantify the rates of recharge and depletion in the Nubian aquifer located in Egypt. Their findings suggest that recharge in this aquifer is predominantly driven by a significant rise in the water level of Lake Nasser and/or unusually high levels of precipitation in the region. Finally, Obuobie et al. [4] used the WTF method to estimate recharge in the White Volta River Basin of Ghana (2006-2007) using water levels obtained from 19 monitoring wells. The study found significant seasonal and spatial variations in water levels, with a range of 1.2 - 5 m in 2006 and 1.6 - 6.8 m in 2007. Recharge values were estimated to range between 2.5% and 16.5% of the mean annual rainfall, with a mean recharge of 7-8%. They concluded that the primary source of recharge in the Volta Basin is seasonal rainfall.

3.1.5 Study Objectives and Goals

The objectives of our study are four-fold: (1) to assess changes in groundwater storage in the Volta Basin located in Ghana for the period between 2002 and 2022, using GRACE and GLDAS data; (2) to estimate annual groundwater recharge values in the Volta Basin using the Water Table Fluctuation method with GRACE-derived groundwater storage data, and compare the results with observed data from monitoring wells in the basin; (3) to examine the correlation between rainfall and changes in groundwater storage in the area of interest; and (4) to demonstrate the a broadly adaptable and effective method for using GRACE Earth observation data in understanding groundwater usage patterns, and thereby enhancing groundwater management strategies.

3.2 Study Area and Background

The Volta Basin spans approximately 400,000 km2 across six countries: Ghana, Burkina Faso, Benin, Ivory Coast, Togo, and Mali (Figure 3.1). However, over 90% of the basin's population resides in Ghana and Burkina

Faso [5,139]. The Volta Basin is a major basin in sub-Saharan Africa, with an extent of roughly 5° to 14° latitude and 3° to -2° longitude. It encompasses at least four different climates, ranging from lowland rainforest in the south to semi-arid Sahel-Sudan Desert in the north [140].

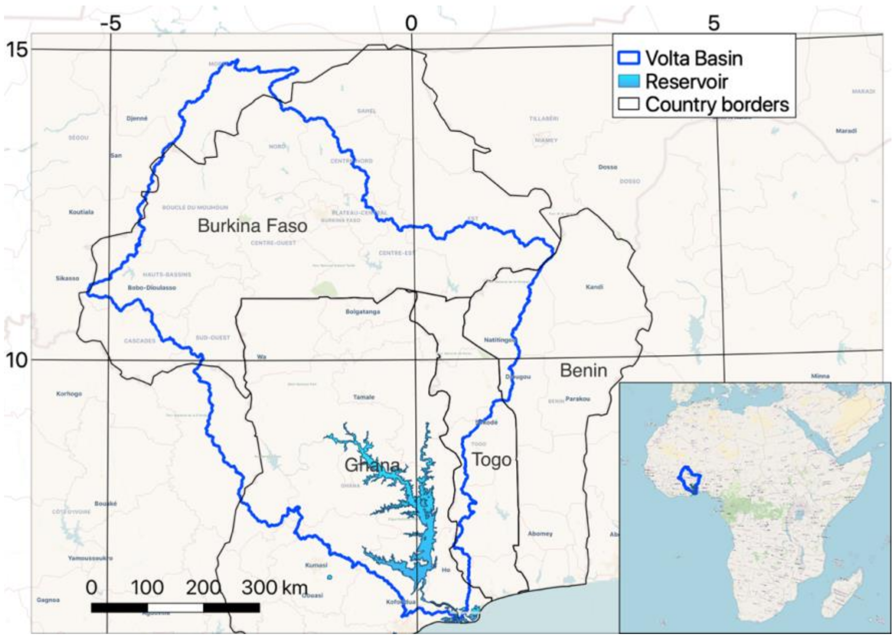


Figure 3.1: Estimated recharge values in the Chad basins

The aquifer zone and groundwater recharge distribution obtained from the World-wide Hydrogeological Mapping and Assessment Program [141] are shown in Figure 3.1. The climate of the basin is defined by two types of rainy seasons, bimodal and unimodal, which are largely driven by the movement of the Inter-Tropical Convergence Zone [140,142]. The Volta Basin is separated into three primary sub-catchments: the Nakambe Basin linked to the White Volta River, the Mouhoun Basin related to the Black Volta River, and the Oti River. The Volta River travels through Ghana and flows into the Gulf of Guinea. The flow of the rivers is managed by dams that generate power. The majority of aquifers in the Volta Basin are shallow, with a major groundwater aquifer located in the upper Volta Basin in the northwestern region [5].

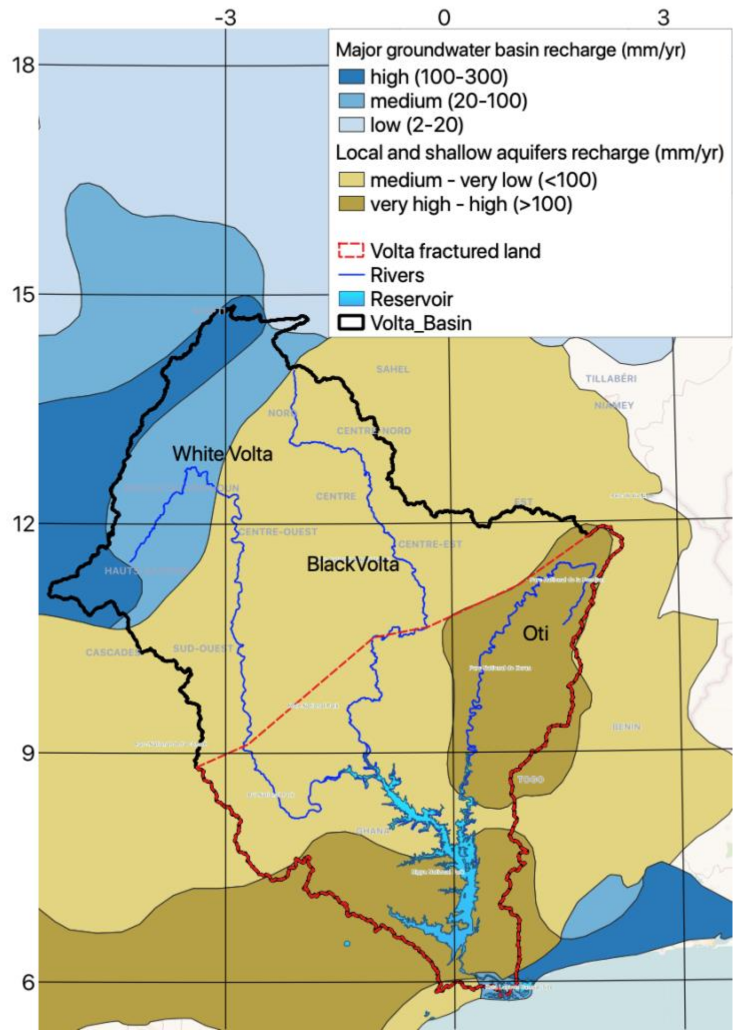


Figure 3.2: Groundwater Recharge Map from WHYMAP in the Volta Basin.

The Volta Basin is known for its sedimentary aquifers and is separated into a fractured zone and a blend of intergranular and fractured regions. The primary fractured area within the Volta Basin, referred to as the Volta Fractured Land (outlined by the red line in Figure 3.2), provides ideal conditions for groundwater storage during intense wet periods [92,143].

The hydrogeological conditions and groundwater occurrence in the basin are controlled by the regolith and fractured bedrock aquifer systems. These systems display significant spatial variabilities in terms of their hydrogeological properties. The regolith is an important unit with regards to rural water economies of the basin. There are three distinct units within the regolith [144]. These are the alluvium, the saprolite, and the saprock [145]. The saprolite is the most extensive of these three units and is regarded as a product of the physical decomposition and chemical weathering of the underlying bedrock. Its hydraulic properties are therefore dependent on the clay content. Where the clay content is high, its lateral hydraulic properties are much reduced, and this significantly reduces its groundwater transmissive properties. The thickness of the saprolite can exceed 50 m in places [144,146]. Many rural water supply wells in the basin are completed within the regolith. In the sedimentary part of the basin (dominated by the Voltaian Supergroup), groundwater occurrence and borehole success rates have been generally low. This is attributed to high clay content and generally lower thickness of the regolith in the Voltaian Supergroup compared to that of the basement complex (Birimian Supergroup) and its associated granitoids [146]. The saprock is more conductive but generally thinner compared to the saprolite [144,145]. Indeed, shallow groundwater resources, abstracted from the regolith are being used for small scale irrigation in some parts of the basin [147,148]. The fractured bedrock aquifer system is highly prolific in the basement and among the granitoids associated with the basement rocks. Generally, borehole drilling success rates have exceeded 80% in some parts of the Birimian basement and associated granitoids [146].

3.3 Data and Methods

3.3.1 GRACE Data

To obtain a gridded gravitational anomaly map, raw GRACE data is processed by three institutions using different algorithms, namely the NASA Jet Propulsion Laboratory (JPL), the University of Texas at the Austin Center for Space Research (CSR), and the German Research Center for Geosciences (GFZ) [14–17,19,65,129]. The output of each method is a total water storage anomaly (TWSa) dataset, which is distributed by NASA [149]. For our analysis, we used the JPL TWSa dataset [114,150], which is available on a downscaled 0.5-degree grid resolution with monthly averages. NASA also provides an uncertainty estimate for each grid cell to assess the data processing method's uncertainty [1,44,134].

3.3.2 Precipitation Data

We obtained daily and monthly precipitation data in millimeters (mm) from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) which is computed using an algorithm presented by Funk et al. [123]. This data is available on a 0.05°×0.05° degree spatial resolution and in hourly, pentadal (five-day), and monthly periods from 1985 until the present. CHIRPS data represent the total precipitation over the day or month, respectively.

3.3.3 Regional Groundwater Storage Analysis with GRACE Data

To derive groundwater storage anomaly (GWSa) data, we used a mass balance approach which has been validated by numerous researchers [13,42,43,133–137]. This method involves subtracting surface water storage changes from the total water storage changes using datasets generated by GLDAS [42]. GLDAS includes three models (Noah, VIC, and CLSM), each of which estimates terrestrial water volume as canopy storage (CAN), snow-water equivalent (SWE), and soil moisture (SM). We converted GLDAS data to an anomaly format (CANa, SWEa, and SMa) based on the deviation from the 2004-2009 mean. We then calculate the groundwater storage anomaly (GWSa) by subtracting the GLDAS surface water anomaly datasets from the GRACE TWSa dataset using the following formula:

$$GWSa = TWSa - (SMa + SWEa + CANa) \tag{3.1}$$

To calculate the surface water components, we averaged the data from the Noah, VIC, and CLSM land surface models. The VIC and CLSM datasets have a grid resolution of 1.0-degree, while the NOAH datasets have a resolution of 0.25-degree. The TWSa data from NASA JPL is in 0.5-degree format. To ensure that all components are in the same resolution, we upscaled the GLDAS Noah model components and the TWSa to 1-degree resolution. These processes were carried out using the GRACE Groundwater Subsetting Tool (GGST) application [7,151], which allows for global monitoring of groundwater changes in selected regions since 2002 using both either a web interface or a Python API.

To calculate the uncertainty in the derived GWSa estimate, we utilized the Total Water Storage anomaly uncertainty estimate (σTWSa) provided by NASA and calculated the standard deviation of the surface water components (σSMa, σSWEa, and σCANa) based on the three estimates for each provided by the Noah, CLSM, and VIC models within GLDAS. This resulted in uncertainty estimates that vary both spatially and temporally, as expressed by the following equation:

$$\sigma GWSa = \sqrt{\sigma TWSa^2 - (\sigma SMa^2 + \sigma SWEa^2 + \sigma CANa^2)} \tag{3.2}$$

The GGST performs clipping on each dataset to the selected region, producing a set of clipped raster data for each dataset. The monthly raster values are averaged to generate a time series, representing the temporal variations of each dataset since 2002. The GGST subsequently calculates the cumulative water storage change for the region in units of millions of cubic meters or cubic kilometers [7] by multiplying the time-varying GWSa rasters with the area of the region. The time-series product provides a straightforward and user-friendly summary of water storage changes in a given region, making it a valuable tool for water resource managers and other stakeholders. It enables them to assess whether the aquifer is being used sustainably, recharging, or experiencing non-sustainable depletion of storage.

3.3.4 Groundwater Storage Anomaly Data Imputation

The first GRACE mission provided nearly complete data up to 2010, with periodic data gaps in the following seven years from 2011-2017, including an 11-month gap between the original and GRACE-FO missions [117,118]. Since we require a complete time series of data for our analysis it was necessary to impute the gaps in the GRACE data to generate a complete dataset. Figure 3.3 depicts the derived GWSa data for the Volta Basin, illustrating the periods with missing data.

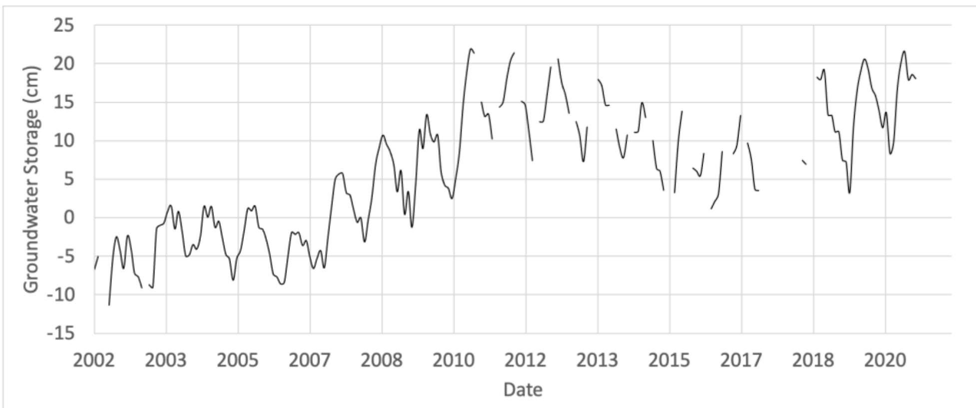


Figure 3.3: Original Groundwater Storage Data from GRACE for the Volta Basin

The GWSa data displays a seasonal pattern with various multi-year increasing and decreasing trends. To impute the gaps in the GRACE signal, we used a modified version of the seasonal decomposition method described by Barbosa et al. [13]. The original method uses the **statsmodel** Python library [152] to decompose the time series of groundwater storage anomalies (GWSa) into three distinct components: the trend, seasonal, and random components. To obtain these components, we apply a convolution filter to eliminate the trend component, followed by the computation of the average value for each time period, which in our case corresponds to months. The residual component is then derived as the difference between the monthly average (seasonal component) and the actual monthly measurements [120].

In our study, we improved the method by dividing the trends into multiple sections exhibiting linear trends over multiple seasons using the **piecewise-regression** Python library [153]. In this case, four breakpoints defining five sections were found as shown by the dashed lines in the "trend" panel of the groundwater time series in Figure 3.4. Our full data imputation method has been implemented in Python in a Google Colab notebook, which can be publicly accessed [151].

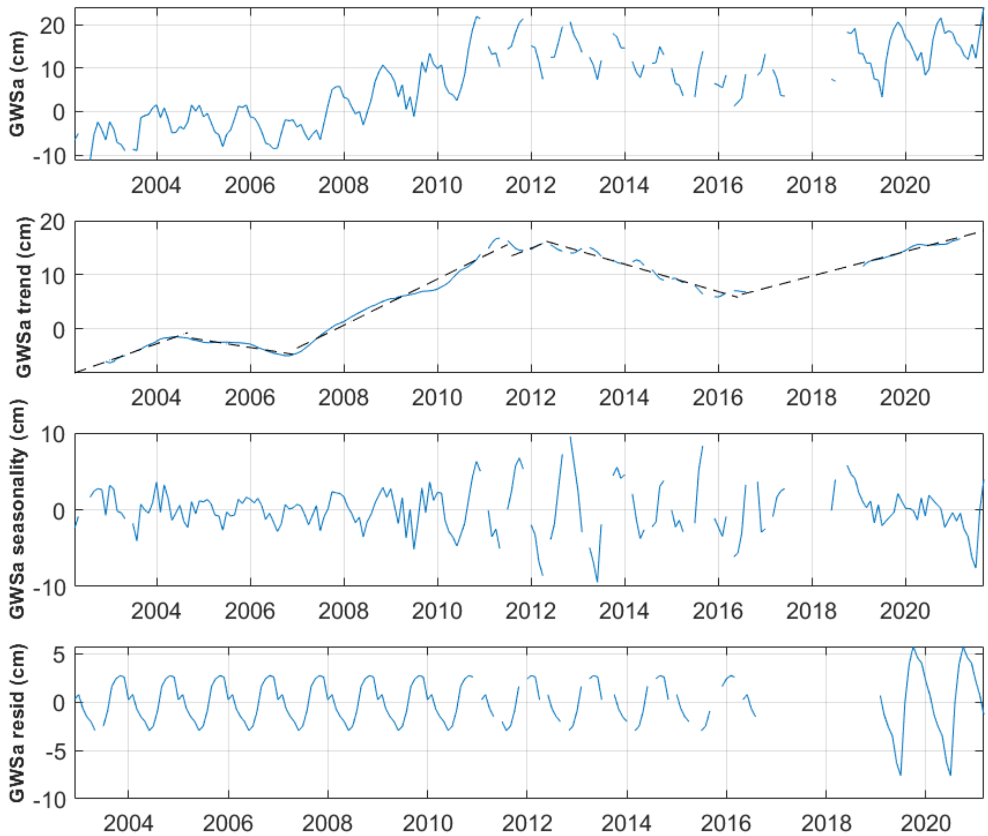


Figure 3.4: Decomposed GWSa Data for the Volta Basin.

Figure 3.5 displays the original time series represented in black, while the imputed values are shown in red. The imputation process maintains the seasonality and trend observed in the original data and appears to be a reasonable approximation.

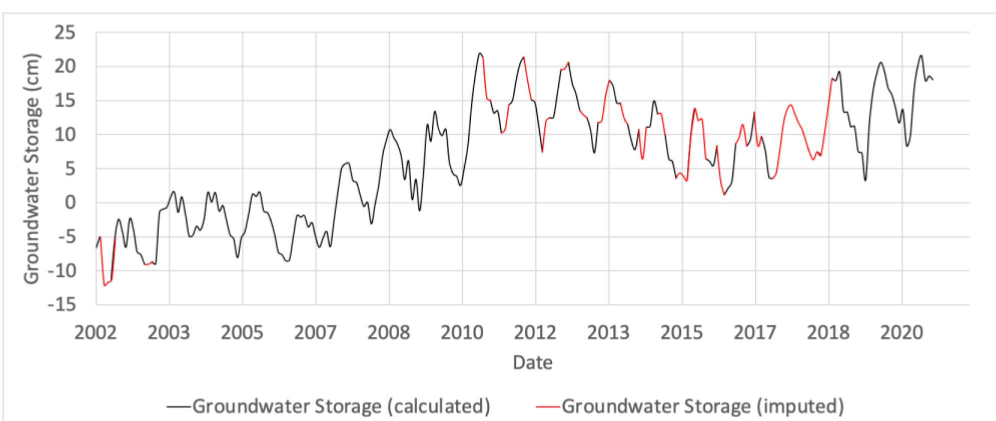


Figure 3.5: Imputed GWSa Data for the Volta Basin

3.3.5 Estimating Recharge

We employed the WTF method [85] to estimate groundwater recharge in the Volta Basin. The original intention behind the development of the WTF method was to assess recharge by analyzing seasonal variations in groundwater levels measured directly via monitoring wells. It is postulated that the declining phase during the dry season primarily stems from pumping and groundwater discharge, while the subsequent rise during the wet season is predominantly attributed to recharge, as illustrated conceptually in Figure 3.6.

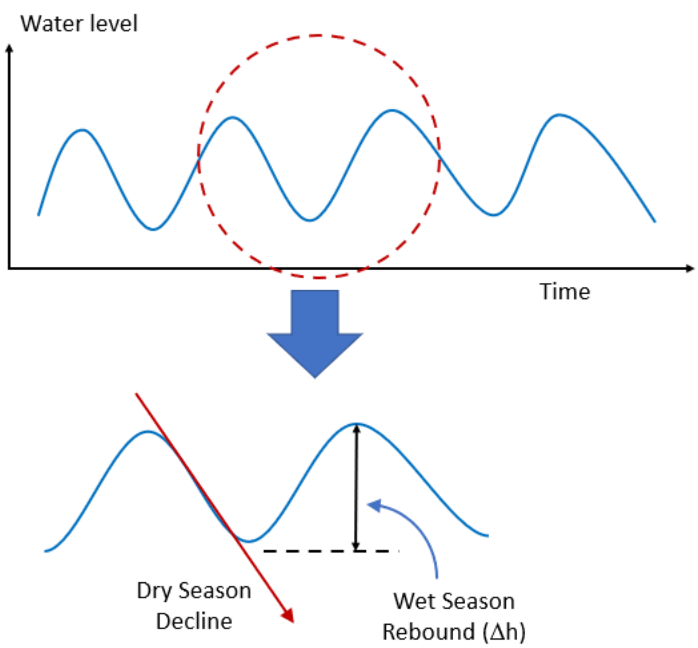


Figure 3.6: Premise of the Water Table Fluctuation Method

Using water levels derived from a monitoring well, we can therefore estimate the recharge as follows:

$$R = S_y \left(\frac{\Delta h}{t}\right) \tag{3.3}$$

where R represents the groundwater recharge in centimeters per year, Δh is the change in height of the water table in centimeters, t is the time interval (one year), and Sy is the specific yield [50].

Two approaches were used to estimate the recharge rate, one based on the distance between the trough of decline and the peak of the rise, and the other by projecting the previous year's peak to the trough (Figure 3.7). Method 1 provides a more conservative estimate than method 2.

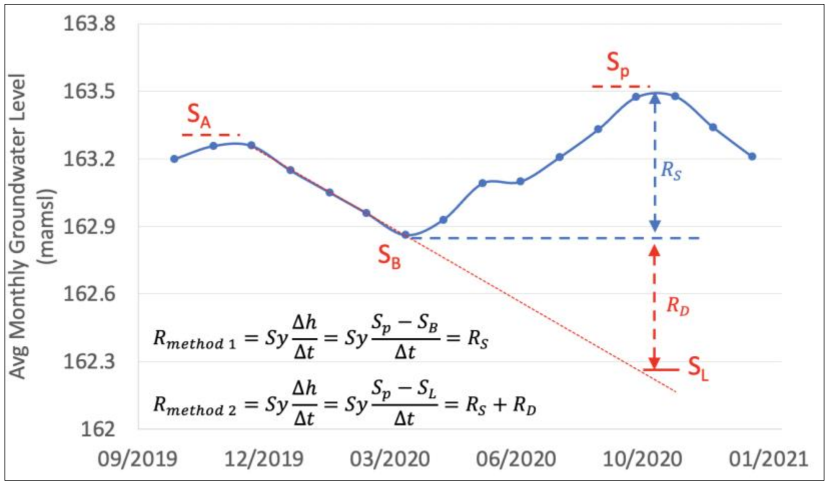


Figure 3.7: Conceptual Diagram of the Two Approaches for Estimating Recharge Using the WTF Method (modified from Wu et al.[84]).

The WTF method is traditionally applied to seasonal change in water levels observed in in situ monitoring wells. The inclusion of the storage coefficient is essential because the increase in water level within the adjacent aquifer takes place within the fractional void space. By employing the storage coefficient, this rise is converted into the corresponding component of liquid water equivalent necessary for recharge assessment. However, if we conduct this analysis using the groundwater storage anomaly curve derived from GRACE, the storage coefficient is not needed because the anomaly is already expressed in liquid water equivalent form. Thus, we can directly estimate the recharge as follows:

$$R = \frac{\Delta GWSa}{\Delta t} \tag{3.4}$$

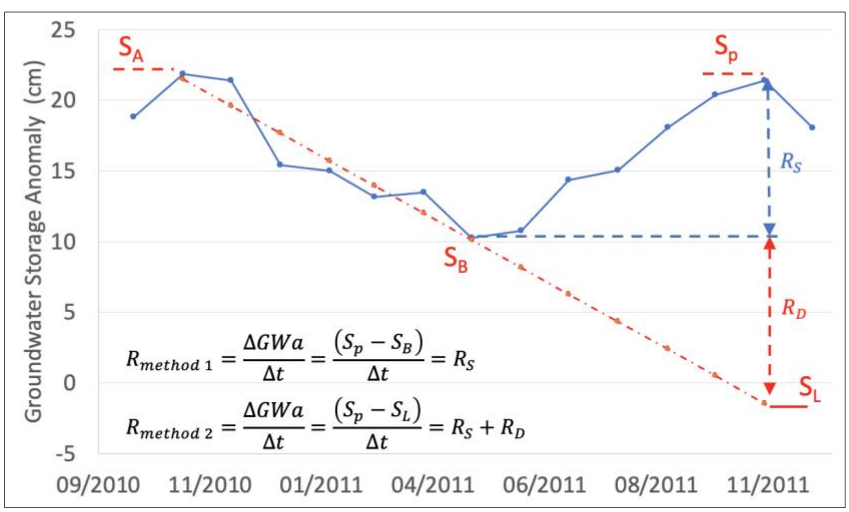


Figure 3.8: Recharge Estimation Using the GRACE-Derived Groundwater Storage Anomaly (GWSa).

Once again, there are two methods for determining the portion of the water table rise assigned to recharge as shown in Figure 3.8.

3.4 Results

3.4.1 Groundwater Storage Analysis

To examine the changes in groundwater storage in the Volta Basin, we used the GGST and generated clipped netCDF grids, as well as time-series with uncertainty estimates for each water storage component, including TWSa, SWEa, CANa, SMa, and GWSa. Regional maps of the netCDF grids with a 1-degree resolution were created using the derived GWSa values in cm of the liquid water equivalent (LWE) thickness for each month from 2002 through 2022 Figure 3.9.

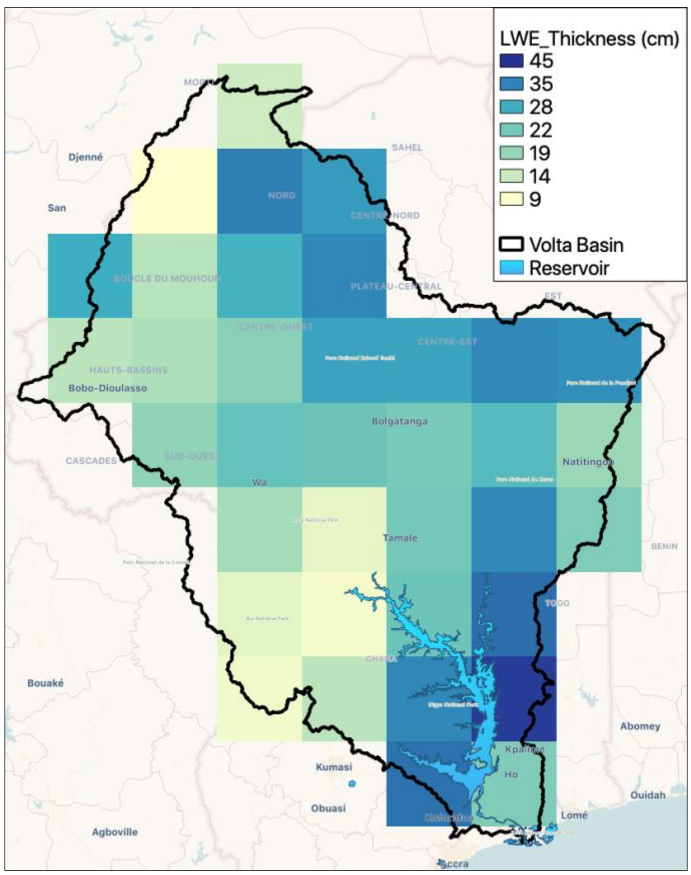


Figure 3.9: Sample Raster Map of Groundwater Storage Anomaly (GWSa) in the Volta Basin for October 2020

We generated time series plots spanning the period from 2002 to 2022 to investigate and characterize the extended groundwater storage trend in the Volta Basin. These time series are accessible in two formats, namely the mean liquid water equivalent (cm) and the cumulative storage change since 2002 in millions of cubic meters (MCM), as provided by GGST. The second format is useful in conveying the volumetric changes in water gain or loss within an aquifer in a standardized unit [7]. Figure 3.10 depicts the changes in groundwater storage anomaly (LWE) in the Volta Basin between April 2002 and July 2022 with the gray band reflecting the time-varying uncertainty calculated using Equation 2. Three main trends can be observed in the data. Between 2002 and 2010, an upward trend was identified. Additionally, between June and December 2010, there was a remarkable positive deviation of more than 20 cm from the 2005 to 2009 mean. However, during the subsequent five years, a declining trend in groundwater storage was observed. Finally, over the last seven years (2015-2022), there has been a resurgence in the GWSa, with LWE values exceeding 23 cm.

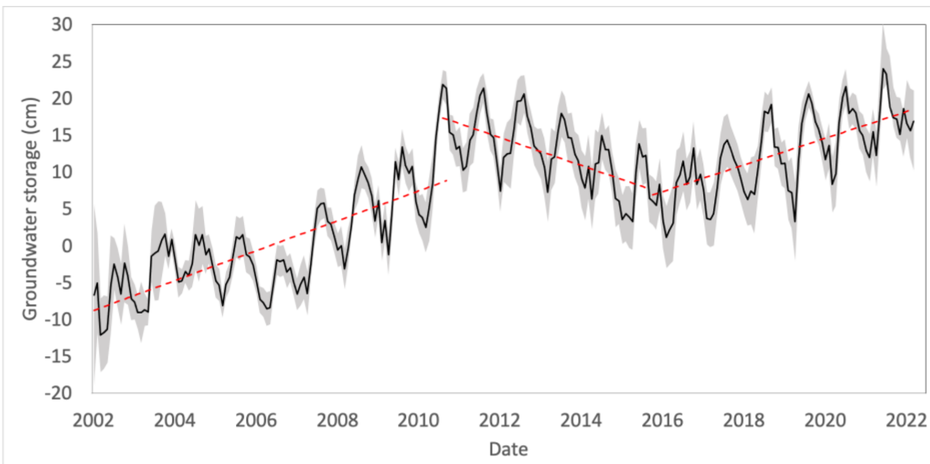


Figure 3.10: Groundwater Storage Anomalies Changes in the Volta Basin

To determine the total change in groundwater storage volume (in millions of cubic meters) between 2002 and 2022 in the Volta Basin, we multiplied the GWSa LWE values by the basin's area. The results are presented in Figure 3.11, which illustrates seasonal cycles that demonstrate an average negative volume of around -15,000 MCM during the initial five-year period. However, from 2008 until the end of the period, the figure reveals a net gain of roughly 41,000 MCM.

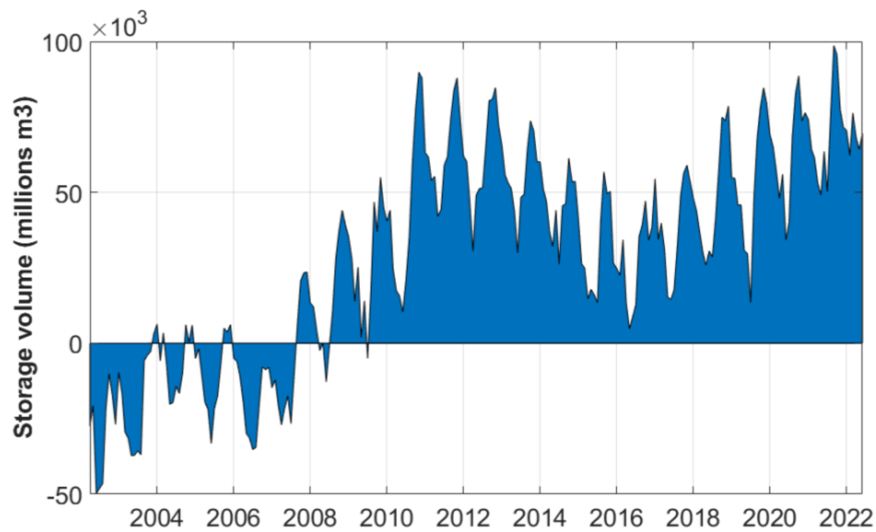


Figure 3.11: Volumetric Storage Change in the Volta Basin.

3.4.2 Groundwater Recharge Analysis

A.1.1.1 Assessment of Groundwater Recharge using GRACE Satellite Data

Using the two methods described above for the WTF method, we estimated the annual recharge for the Volta Basin using the GRACE-derived GWSa data set (Figure 3.12). The findings suggest a notable increase in the groundwater recharge rate from 2002 to 2010, followed by a substantial decline in recharge from 2011 to 2015, and a subsequent increase for the remaining period, in line with the observed changes in groundwater storage described above.

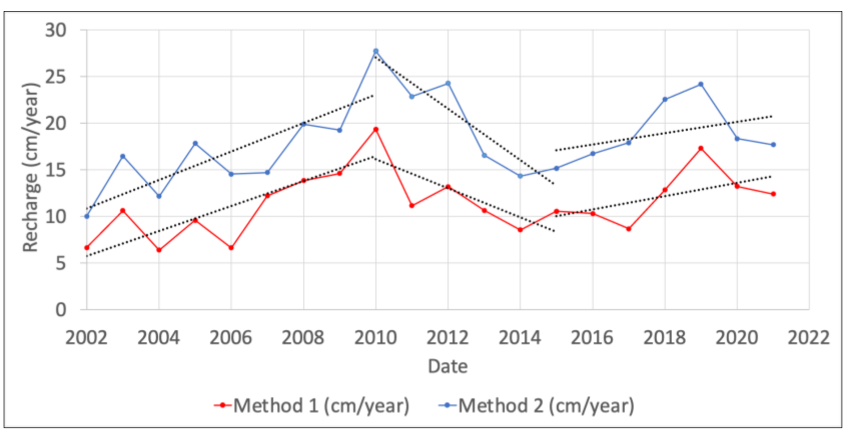


Figure 3.12: Recharge Estimates in the Volta Basin

The average recharge rates estimated by Method 1 for the 2002-2010 and 2011-2015 periods were 11.1 cm/yr and 10.8 cm/yr, respectively. In contrast, Method 2 estimated higher average recharge rates of 16.9 cm/yr and 18.6 cm/yr for the same time periods, respectively. Finally, the estimated recharge rates for the most recent time period (2015-2021) were 12.5 cm/yr and 19.6 cm/yr for Method 1 and Method 2, respectively.

A.1.1.2 Assessment of Groundwater Recharge using Observed Data

In addition to the recharge analysis using GRACE-derived groundwater storage anomalies, we examined the water level changes from 10 wells situated mostly within the Nasia Basin Figure 3.13. The Nasia Basin is a sub-catchment of the White Volta Basin which is one of the sub-basins in the Volta Basin system.

The well data were collected over a period of four years, from 2017 to 2020. However, it should be noted that not all wells contained data for every year, as some wells had data for only one or two years. We estimated the annual recharge value applying equation 3 and assuming a specific yield of 0.05 – which is consistent with field estimates in the area [144].

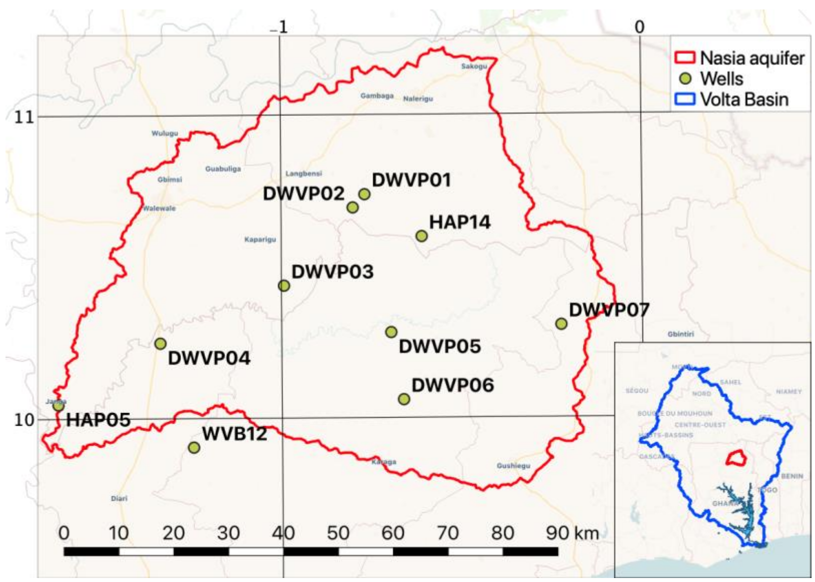


Figure 3.13: Nasia Aquifer and Well Locations.

We applied the WTF method using methods 1 and 2 for each well and the results are shown in Table 3.1. The average values for Method 1 and Method 2 for all wells are 10.7 and 19.2, respectively. Wells HAP014 and DWVP06 show significantly low recharge values, with values ranging between 2 and 6 cm lower than the averages. In contrast, some wells, such as DWP02, DWP05, and HAP05, exhibit high recharge values above 30 cm. This reflects the markedly high spatial variability in hydraulic properties of the vadose zone and the effect of such variations on rainfall infiltration rates and groundwater recharge. These variations have been underscored in previous studies of the characteristics of the regolith in the area [146,154].

Table 3.1: Estimated Recharge Values from Monitoring Wells Located in the Nasia Aquifer Using Method 1 (m1) and Method 2 (m2).

Well	2017		2018		2019		2020		2021	
	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2
DWVPO1	14.9	17.4	9.6	16.3	15.0	17.8				
DWVP02	23.1	30.6	24.8	31.2						
DWVP03			5.9	14.5						
DWVP04	7.0	12.2	22.3	28.6	5.9	23.0	11.3	20.8		
DWVP05							11.8	18.4	14.7	31.1
DWVP06			11.7	29.2	10.6	27.9	11.8	17.4		
DWVP07			1.2	3.4	2.0	6.7	3.1	5.8	2.4	5.0
HAP05			5.5	11.4	27.6	45.6	17.1	28.9	17.3	31.7
HAP014			2.9	4.8	4.2	8.4	3.1	5.6	3.3	6.6
WVB12			8.5	24.9	10.2	22.1	12.5	27.0		

A.1.1.3 Comparison of Estimated Groundwater Recharge Values

Next, we conducted a comparison of our estimated recharge values with the values found by Obuobie et al. [4] in a prior study. For this comparison, we used the values from our study found using Method 1 of the Water Table Fluctuation method as these values are more conservative and we have found that they generally compare more favorably with other methods [13]. A box plot of the estimated recharge values from our study from both the GRACE data and the in situ well data and the values from the Obuobie et al. [4] study are shown in Figure 3.14

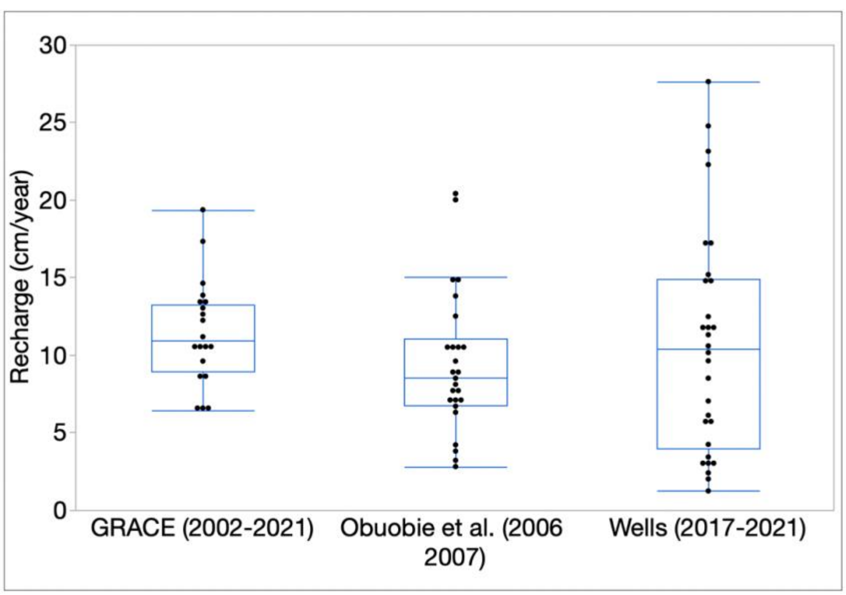


Figure 3.14: Boxplot of Recharge in the Volta Basin estimated with the WTF method 1

Figure 3.14 shows that the median recharge value found using GRACE data is around 11.8 cm/yr, with a lower quantile of 9.5 cm/yr and an upper quantile of 14.9 cm/yr. The boxplot for the monitoring wells shows that the median recharge value is around 10.6 cm/yr, with a lower quartile of 6.9 cm/yr and an upper quartile of 14.7 cm/yr. In the case of the estimated values from Obuobie et al., [4] the boxplot shows that the median recharge value is around 8.7 cm/yr, with a lower quartile of 6.25 cm/yr and an upper quartile of 12.5 cm/yr. Comparing the three boxplots, it can be observed that the recharge values obtaining from GRACE data are generally higher than those obtaining with the other two methods. The range of recharge values obtained from Obuobie et al. [4] appear to be the narrowest among the three methods with a high outlier. The datasets overlap but are from different time intervals. Nevertheless, the methods compare reasonably well.

Groundwater recharge estimates obtained from the GRACE data in this study are statistically similar to estimates made using other methods in the same basin. For instance, the Water Resources Commission [146] used the Soil Moisture Balance method to estimate groundwater recharge for parts of the Volta Basin and obtained values in the range of 0.5 - 38.9 cm/yr. Similarly, Addai et. al., [155] used the chloride mass balance technique for the Nasia Basin (in the Volta Basin) and obtained 7.3 - 11.0 cm/yr. Working within the Nabogo sub-basin, Yidana et. al., [156] used stable isotope data of porewater in the vadose zone to determine the nature, characteristics, and quantitative estimates of groundwater recharge. Their findings indicated groundwater recharge rates in the range of 1.1 - 18.5 cm/yr. The same research applied the WTF method to limited data in the basin to determine groundwater recharge to fall in the range of 6.5 - 15.2 cm/yr.

3.4.3 Correlation with Regional Precipitation

To analyze the correlation between rainfall and the groundwater storage changes in the Volta Basin for the period between 2002 to 2022, we compared the yearly precipitation (cm) from CHIRPS to the monthly GWSa in the basin and computed the correlation coefficient (Figure 3.15). We observed a consistent trend in both groundwater storage and precipitation. There is a distinct pattern of three phases: an initial increase from 2002 to 2010, followed by a significant decline from 2011 to 2015, and finally, a subsequent increase for the remaining period.

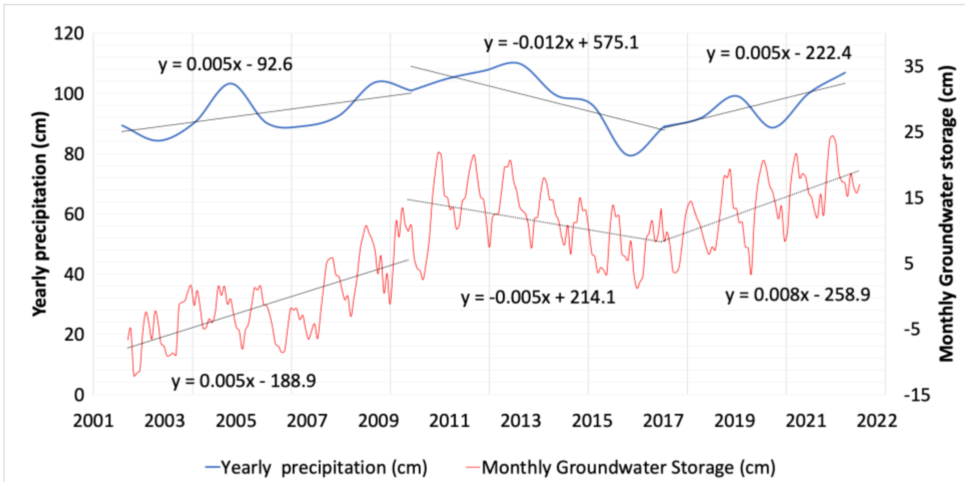


Figure 3.15: Groundwater Storage (cm) and Average Monthly Precipitation (cm) for the Volta Basin.

Long-term precipitation analysis suggests that there is a correlation between the groundwater storage levels and precipitation. Specifically, when precipitation is high, groundwater storage levels tend to increase, and when precipitation is low, groundwater storage levels tend to decrease. For example, in the period from 2016 through 2017, we see a significant increase in precipitation, which is followed by an increase in groundwater storage levels in the subsequent months. Similarly, we see a sharp decrease in precipitation levels in the time period from 2004 through 2005, which is followed by a decrease in groundwater storage levels in the subsequent months. Overall, this suggests that precipitation is a key factor influencing groundwater storage levels, and that changes in precipitation can have a significant impact on groundwater availability over time.

A cross-correlation coefficient of 0.37 at a lag of 4 months between groundwater change and precipitation time series suggests a weak positive correlation between the two variables. The positive sign of the correlation coefficient indicates that increases in precipitation tend to be associated with increases in groundwater storage. However, it is important to keep in mind that correlation does not necessarily imply causation. While this correlation suggests that there may be a relationship between precipitation and groundwater level change, it does not necessarily mean that changes in precipitation are causing changes in groundwater levels or vice versa. Other factors may also be influencing groundwater levels. In the context of the Volta Basin, the complex nature of the vadose zone is reflected in significant variations in the fraction of rainfall which eventually reaches the saturated zone, and the time lag between rainfall and groundwater level response. High potential evapotranspiration rates throughout the year significantly reduce the fraction of rainfall which eventually percolates into the saturated zone. Analysis of porewater chloride and stable isotope data of the vadose zone indicates that on account of high temperatures and high potential evapotranspiration rates, significant volumes of infiltrating rainwater are lost in transit and do not reach the saturated zone [155,156].

3.5 Long-Term Precipitation Analysis

While it is clear that groundwater storage is correlated with precipitation, it is not clear if this is the sole cause of increasing groundwater storage in the basin for the period analyzed. Previous research conducted by Djessou et al. 2022, [5] has suggested that the trends in terrestrial water storage anomalies and groundwater storage anomalies derived from GRACE in the Volta Basin are primarily influenced by hydro-meteorological conditions, such as floods and droughts. However, we raise an additional hypothesis that this increase in groundwater storage could be related to changes in precipitation patterns.

To evaluate our hypothesis, we present a comprehensive analysis of precipitation data. By examining long-term precipitation records and assessing any notable changes or trends, we aim to identify any potential correlations between precipitation patterns and the observed increase in groundwater storage. This analysis will provide valuable insights into the role of precipitation as a contributing factor to groundwater storage dynamics.

Figure 3.16 shows that the precipitation data are significantly right skewed. Most of the precipitation events are below 2 mm (red bracket on top).

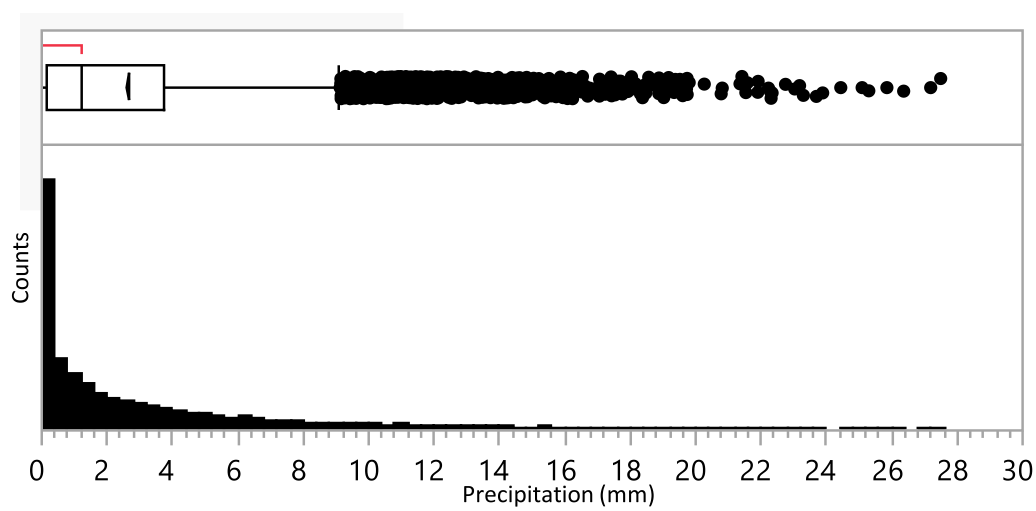


Figure 3.16: Daily Precipitation Histogram (mm).

The median and mean values are 1.24 mm and 2.64 mm, respectively (Table 3.2).

Table 3.2: A statistical summary of the daily precipitation events from 1985 through 2022.

Statistic	Value
N	13938
Mean	2.64
Std Dev	3.51
Std Err Mean	0.03
Upper 95% Mean	2.70
Lower 95% Mean	2.58
Skewness	2.10
Median	1.24

Table 3.3 shows that no precipitation occurred over 10% of the time, with a signification difference between the 99.5% and 100% percentiles with values of 17.71 mm and 27.49 mm, respectively. We observe 75% of the values below 3.75 mm with only 10% above 7.37 mm. This is graphically shown in the histogram in Figure 3.16.

Table 3.3: Percentile data for daily precipitation events from 1985 through 2022.

Percentile	Label	Value (mm)
100.0%	maximum	27.49
99.5%		17.71
97.5%		12.65
90.0%		7.37
75.0%	quartile	3.75
50.0%	median	1.24
25.0%	quartile	0.16
10.0%		0.00
2.5%		0.00
0.5%		0.00
0.0%	minimum	0.00

Daily rainfall varies considerably through the year with large differences in monthly totals and distributions as shown in Figure 3.17.

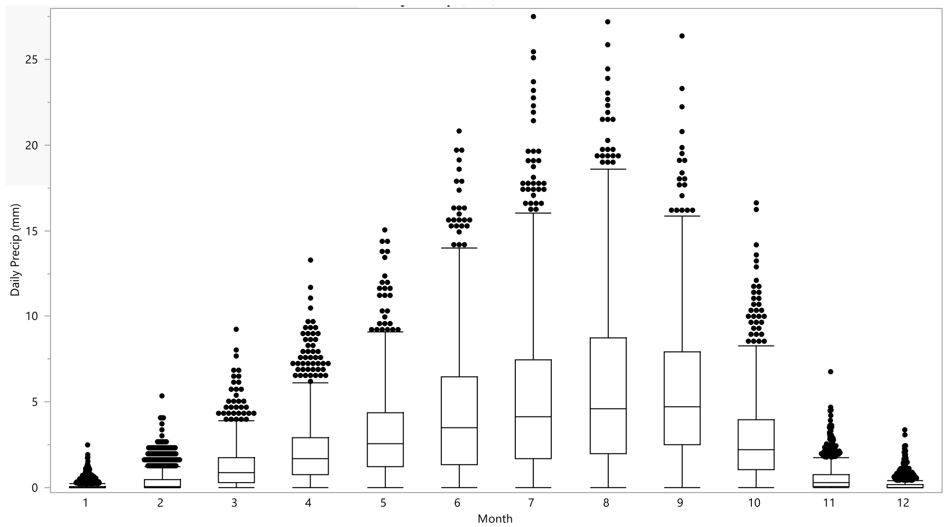


Figure 3.17: Whisker-Plots of Monthly Precipitation.

Rainfall mostly occurs from June through September, with the most intense events in July and August. The median rainfall in July, August, and September is significantly higher than most other months, though June is close. Most of the extreme events occur in these same months.

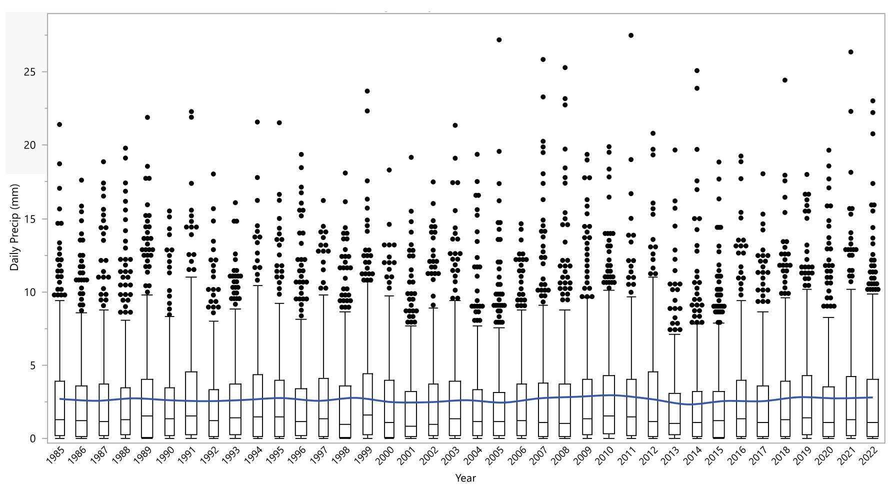


Figure 3.18: Whisker-Plots of Annual Precipitation.

Figure 3.18 shows the study period, but rainfall intensity may be increasing. To evaluate if intensity has increased, we performed an extreme value analysis, similar to that used to analyze flood probability. For this analysis, we generated two different data sets: 1) the maximum monthly daily-precipitation value which is the maximum daily precipitation event in a given month - this results in 12 values per year over the 38-year period excluding 2023, and 2) the maximum annual daily-precipitation which is the maximum daily precipitation event that occurs in a year, which results in 38 values, one for each year excluding 2023. For each of these data sets, we computed a maximum precipitation anomaly by centering or averaging each data set over the entire period, then subtracting this average from each value. We do not present the monthly maximum data because we found that seasonal variations make it difficult to see the trends.

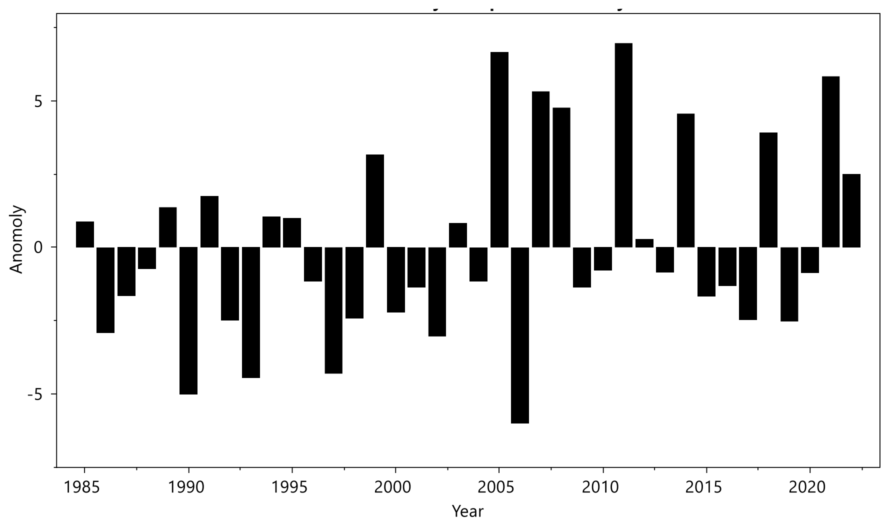


Figure 3.19: Maximum Annual Daily-Precipitation Anomaly from 1985 through 2022.

Figure 3.19 shows the maximum annual daily-precipitation anomaly from 1985 through 2022. Visually there are larger positive anomalies in the period from 2005 through 2022 than in the earlier part of the record from 1985 to 2004. There is one large negative anomaly in 2006. Figure 19 is instructive and explains the observed trend in groundwater recharge and groundwater storage variations in the basin. The period of negative variations in groundwater storage as computed from the GRACE data (2002 -2005) coincides with the period of negative anomalies in the rainfall data in Figure 3.19. Conversely, the periods of high positive anomalies coincide with the periods of increasing groundwater storage in the basin. Due to the high potential evapotranspiration rates, high volumes of rainfall in short periods have a higher likelihood to lead to more groundwater recharge and therefore cause positive excursions in groundwater storage variations. Perhaps more data over a longer period, will be required to confirm this hypothesis.

To quantify this trend, we used the Mann-Kendall (M-K) test [157]. The M-K test is commonly used to identify monotonic trends in environmental, climate, and hydrologic data and is recommended by the US EPA National Nonpoint Source Monitoring Program [158]. The M-K test is a non-parametric statistical test, which is ideal for this analysis because it is not affected by the data distribution – that is the data does not need to be normally distributed. We estimated the trend or rate of change using two different methods: a linear least squares fit and the Sen slope estimator. The Sen's slope estimate is computed as [159]:

$$\beta_1 = median\left(\frac{y_j - y_i}{x_j - x_i}\right) \tag{3.5}$$

for all i < j and i = 1, 2, …, n-1 and j = 2, 3,…, n. The Sen slope estimator is the median slope for all data pairs used to compute S in the M-K analysis.

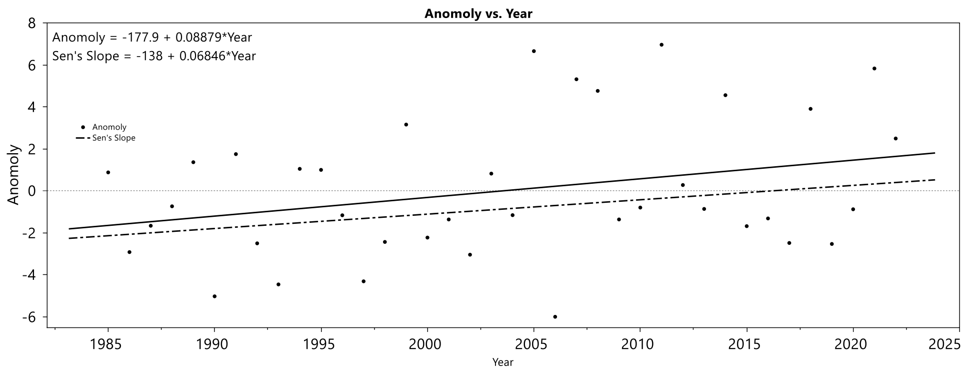


Figure 3.20: Annual Maximum Daily-Precipitation Anomoly vs Year With a Linear Least Square Fit (solid line) and Sen's Slope (dashed line).

As shown in Figure 3.20, we computed positive (increasing) annual slopes of 0.068 and 0.089 for Sen's slope and a linear least square fit, respectively. While both methods show a positive, increasing anomaly slope, the M-K test indicates that the trend is not statistically significant. There is a ~16% probability that this slope is the result of data variability (i.e., P=0.159).

This analysis shows that while both visual and statistical tests indicate that precipitation intensity may be increasing in the region, the data set size and variability mean that this increase is not statistically significant. Notwithstanding this analysis, the obvious increase in the number of rainfall events with volumes exceeding the mean, explains the pattern of groundwater recharge in the basin over the period of this analysis.

3.6 Conclusions

We have presented an approach to analyzing historical groundwater storage change using GRACE and GLDAS data that can be applied in semiarid regions globally, and applied it to the important Volta Basin study area. To derive estimates of groundwater storage change, we used an approach that involved subtracting the surface water storage data sourced from the GLDAS model, from the total water storage from GRACE. Our study covered a period of over 20 years, from 2002 to 2022, and revealed three main trends. From 2002 to 2010, there was an upward trend, whereas from 2011 to 2015, a decreasing trend was observed. For the remaining period (2016-2022), an increasing trend was noted. Moreover, the study found a negative storage until 2008, followed by a considerable net gain in storage of approximately 41,000 MCM for the rest of the period.

We also analyzed the correlation between rainfall and groundwater storage changes in the Volta Basin from 2002 to 2022. We found a consistent trend in both groundwater storage and precipitation, with three distinct phases: an initial increase from 2002 to 2010, a decline from 2011 to 2015, and a subsequent increase. The data indicated a correlation between precipitation and groundwater storage levels, showing that high precipitation led to increased groundwater storage and low precipitation resulted in decreased groundwater storage. We also found a weak positive correlation between groundwater change and monthly precipitation, indicating that increases in precipitation were generally associated with increases in groundwater change. However, it should be emphasized that the existence of a correlation does not imply a causal relationship, and it is essential to consider that groundwater levels can be influenced by various other factors.

We also estimated groundwater recharge in the Volta Basin using the two approaches of the WTF method, employing both satellite data (GRACE and GLDAS) and observed data from 10 monitoring wells in the Nasia aquifer. Our estimates using remote sensing data showed consistent findings with three trends observed in the groundwater storage change anomaly. In comparison with another study conducted in a smaller region, we found that our estimates of groundwater recharge, calculated using the WTF method, were slightly higher but fall within the range of groundwater recharge estimated in other parts of the basin using other methods. These findings suggest that the WTF method can provide reliable estimates of groundwater recharge in the Volta Basin, and that satellite data can be effectively used in combination with traditional methods to improve accuracy. The results of this study will prove significant in assessing the impacts of climate change on groundwater resources sustainability and will stimulate further investigations especially at the sub-basin levels.

3.7 Abbreviations

Table 3.4: List of abbreviations

Abbreviation	Full Form
CAN	canopy storage
CANa	canopy storage anomaly
CSR	University of Texas at Austin Center for Space Research
DLR	German Aerospace Center
GLDAS	Global Land Data Assimilation System
GRACE	NASA Gravity Recovery and Climate Experiment
GRACE-FO	GRACE Follow-On
GFZ	German Research Center for Geosciences
GGST	GRACE Groundwater Subsetting tool
GWS	groundwater storage
GWSa	groundwater storage anomaly
JPL	NASA Jet Propulsion Laboratory
LWE	liquid water equivalent
MCM	millions of cubic meters
SMa	soil moisture anomaly
SWEa	snow-water equivalent anomaly
Sy	Specific yield
TWSa	total water storage anomaly
WTF	water table fluctuation

4 *Exploiting Earth Observations to Enable Groundwater Modeling in the Data Sparse Region of Goulbi Maradi, Niger*

This chapter is composed from a paper entitled "*Exploiting Earth Observations to Enable Groundwater Modeling in the Data-Sparse Region of Goulbi Maradi, Niger*" to be submitted for publication in the MDPI Remote Sensing journal. I hereby confirm that the use of this article is compliant with all publishing agreements.

4.1 Introduction

4.1.1 Location and Socio-cultural Context

The Goulbi Maradi alluvial aquifer is located in the semiarid Southern region of Niger, on the southeastern boundary of the Iullemeden Basin (Figure 4.1). This region is important due to its relatively high population density, ranging from 81 to 105 individuals per square kilometer [52]. The inhabitants rely heavily on rain-fed crops, including sorghum, millet, and cowpeas, as well as animal husbandry for their livelihoods [53,54]. However, these activities have experienced reduced productivity as a result of climate change [53,55], leading to food shortages during dry years [53]. In case of heavy rains, generally between July to August, Maradi faces flooding, particularly in the Goulbi-Maradi area, with loss of property, crops and livestock and occasional deaths [160].

The region's main source of freshwater is derived from shallow groundwater located less than 100 meters below the surface. These shallow aquifers play a crucial role in supporting the local population during droughts, particularly for agricultural purposes and providing access to water in areas distant from water bodies [56–58]. However, the development of groundwater infrastructure in the region has been limited. Although numerous small-scale wells exist for human and animal use, large-scale groundwater-based irrigation practices are not prevalent. The lack of comprehensive field data on groundwater in the region has posed challenges for effective studies that drive better management practices of these resources [59–61]. This shallow alluvial aquifer is called the "Goulbi Maradi" aquifer.

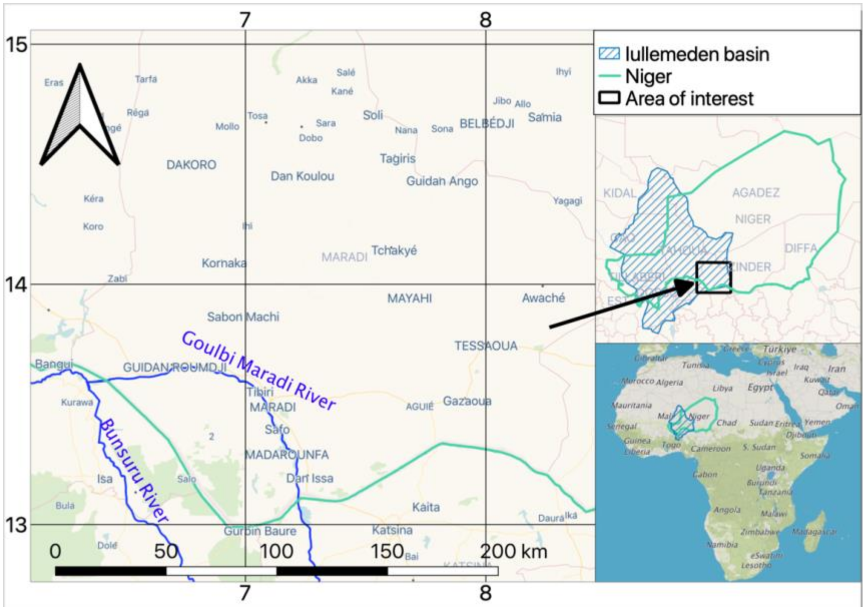


Figure 4.1: Map of the Area of Interest.

4.1.2 Geology and Hydrogeologic Setting

The Goulbi Maradi aquifer is composed of three distinct geologic units: Quaternary formations, the Continental Hamadien of the Upper Cretaceous, and the crystalline to crystallophile Precambrian basement [53].

The Precambrian basement unit is located in the southwest of the aquifer along the Nigerian border and is comprised of granites, gneisses, and schists. The aquifers within this basement area exhibit low well yields, ranging from 0.5 to 3 m^3/h, primarily due to limited weathering in the source rock which results in low permeability. As a result, local communities rely on manual digging of shallow wells in the sediments of ephemeral rivers for their water supply [53].

The Continental Hamadien unit forms an unconfined aquifer located in the central part of the Goulbi Maradi area and extends, as a transboundary aquifer, between Niger and Nigeria [161]. This geological unit consists of two distinct groups: a base composed of Farak-type sandstone and an upper part consisting of pebbly sand. Well yields exhibit spatial variation, ranging from 8 to 70 m^3/h [53].

Quaternary formations, including aeolian sands, are prevalent on the plateau, while alluvium is present along the Goulbi Maradi river and its tributaries. These alluvial sediments, with a thickness ranging from 10 to 30 m, are the result of erosion from the Continental Hamadien and Precambrian basement [162]. Currently, the alluvial aquifer is primarily used for irrigation purposes, surpassing the usage of the Continental Hamadien aquifer. Pumping rates in the alluvial aquifer are estimated to range from 20 to 70 m^3/h, while static water levels vary from 4 to 18 m below the surface [53].

4.1.3 Previous Research

Several researchers have developed numerical groundwater models in the Southern Niger region with promising results for understanding these critical groundwater resources. Qian et al. [57] developed a groundwater model in Zinder, Niger, where groundwater serves as a vital water source for agriculture, industry, and domestic use due to limited surface water and rainfall availability. The model was developed to accurately quantify and assess groundwater resources in the Zinder well field, aiming to generate data to support sustainable local development and provide a reliable evaluation of the groundwater resources. They found that the simulated heads of their model were in good agreement with field-observed heads and suggested an optimal withdrawal scheme.

The Sahara and Sahel Observatory [163] developed a hydrogeological model for the Iullemeden Aquifer System (IAS) in Niger, Mali, and Nigeria. The developed this model with the goal of improving the assessment of water resources within the aquifer system and identifying hydrogeological risks. Their purpose was to enhance the understanding of the aquifer system's behavior and the potential risks related to intensive water resource extraction. They found that withdrawals from the aquifer system have been increasing since the mid-1990s at rates surpassing the available resources. Their simulations suggest that this trend is likely to continue and may have implications beyond the borders of the countries sharing the aquifer, particularly between Niger and Nigeria.

There have been a few additional efforts to characterize the groundwater resources in the region using satellite data due to a scarcity of in situ information. Barbosa et al. [13] analyzed the changes in groundwater storage in two main aquifers in Niger and estimated the groundwater recharge values using the Water Table Fluctuation (WTF) method applied to satellite data. They concluded that the groundwater storage volume in the two aquifers has increased significantly in the past decade and groundwater infrastructure could potentially be developed further. Scalon et al. [90] used Gravity Recovery and Climate Experiment (GRACE) and the Gravity Recovery and Climate Experiment -Follow-On mission (GRACE-FO), altimetry, and MODIS satellite data to track different water storage components, including total water storage, reservoir storage, and vegetation indices. The study's conclusion emphasized the importance of implementing effective management strategies to address the challenges associated with localized groundwater flooding resulting from the rising groundwater levels in western Africa. Bonsor et al. [92] analyzed the relationships between terrestrial water storage and precipitation in 12 African aquifers using GRACE data combined with estimated changes in groundwater storage using land surface models (CLM2.0, VIC, MOSAIC, and NOAH models) and reported an increase in groundwater from 2012 to 2016, particularly in the Iullemeden Sahelian aquifer.

4.1.4 Objective

The objective of this study is to develop a well-calibrated numerical groundwater model of the Goulbi Maradi aquifer that can be used to analyze the sustainability of various groundwater infrastructure development strategies. Developing a groundwater model is especially challenging in this region due to severely limited data on monitoring wells, pumping rates, recharge rates, flow budgets, and other useful data. To mitigate these problems, we developed a model using a novel integration of in situ data and earth observation data. We use data from the NASA GRACE mission to derive recharge estimates and to bracket the volumetric flow budget in a manner that allows us to estimate pumping rates for the calibrated numerical model. We use the calibrated model as a predictive tool to analyze several groundwater development scenarios to determine the impact on the long-term water budget and sustainability.

4.2 Data

4.2.1 Well Data

We used data from a well database maintained by the Hydraulic Departmental Direction of Madarounfa in Maradi Niger (Figure 4.2). The database includes a variety of attributes, including well locations, well names, well depths, and, in some cases, construction dates. Additionally, information on the distance from surface elevation to the water table and estimated withdrawal rates are included for a subset of the wells. The database includes a pumping rate for some of the wells, however it does not contain data on time-varying pumping rates for any wells. Since well data were not available for the portions of the aquifer that extend into Nigeria, we created synthetic wells in these regions at approximately the same density as the wells in Niger. We adjusted the density and/or pumping rate of the wells during calibration.

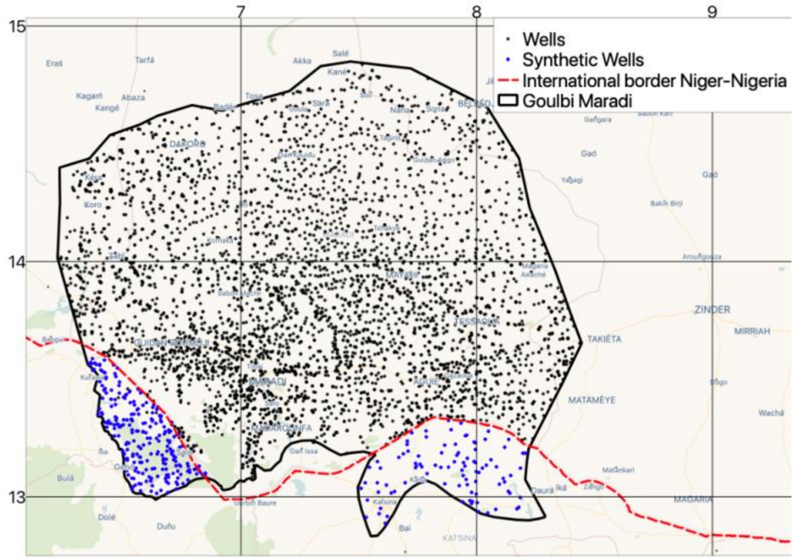


Figure 4.2: Well Locations in the Goulbi Maradi Aquifer.

4.2.2 Boreholes

In addition to the well data, we obtained information on 550 boreholes in the larger Maradi and Korama regions, within the longitudes 6° and 10° (Figure 4.3). The depths of these boreholes in this region range from 6 to 304 meters. Each borehole record includes the borehole ID, latitude-longitude coordinates, and borehole logs with the depths and thicknesses of more than 30 geological materials.

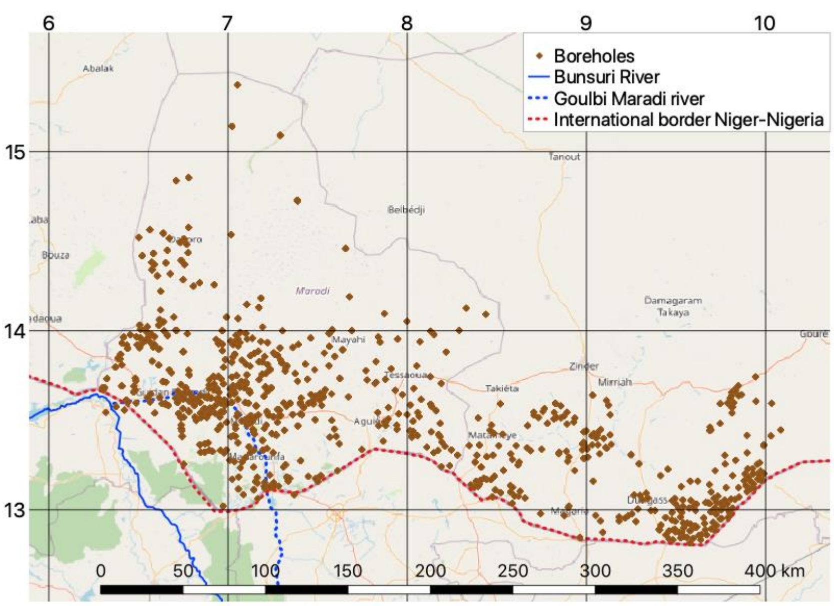


Figure 4.3: Boreholes Located in Goulbi Maradi and Korama Region.

4.2.3 GRACE Data

The GRACE mission was launched in 2002 through a collaboration between NASA and the German Aerospace Center and consists of two satellites positioned 220 km apart that travel along the same orbital path. The initial GRACE mission spanned 15 years, from 2002 to 2017 [18], while the subsequent GRACE Follow On (GRACE FO) mission, initiated in May 2018, continues to provide monthly gravitational anomaly data to the present [16,17].

The distance between these satellites varies in response to fluctuations in the Earth's gravitational field [14,15,65]. Precise measurements of these distance changes, are used to quantify gravitational anomalies, indicating variations in mass [14]. These variations are mainly driven by fluctuations in water storage for most locations, as there are limited other factors that significantly affect the Earth's mass on such a large scale. GRACE data have proven valuable in monitoring global water storage changes [19].

GRACE data are processed by NASA to generate the Total Water Storage Anomaly (TWSa) dataset which captures the change in water storage globally in an anomaly format [31]. GRACE data have been used for various applications, such as flood studies [21,23,25,30,33], drought studies [22,27,29,32,34,35] and general hydrologic investigations focusing on regional water storage and trends [24,26,28]. Recent research has demonstrated the use of GRACE data for monitoring variations in groundwater storage [7,36–38,164] including variations in groundwater depletion in arid and semi-arid regions [13,165,166].

4.3 Methods

4.3.1 Conceptual Model

We developed a conceptual model of the Goulbi Maradi aquifer system, including boundary conditions, hydrostratigraphy, and a flow budget before constructing the numerical model. This included boundary conditions, hydrostratigraphy, and a flow budget, each of which are discussed in turn.

A.1.1.4 Boundary Conditions

We delineated the boundary conditions based on a combination of geological and hydraulic features (Figure 4.4).The boundaries were based on: 1) the Damagaram Mounio Precambrian basement to the north and east, representing a no-flow boundary, 2) the Bunsuru river and the sedimentary formations of the Iullemeden Basin to the west, establishing both a river and a no-flow boundary, and 3) the basement complex to the south, establishing a no-flow boundary.

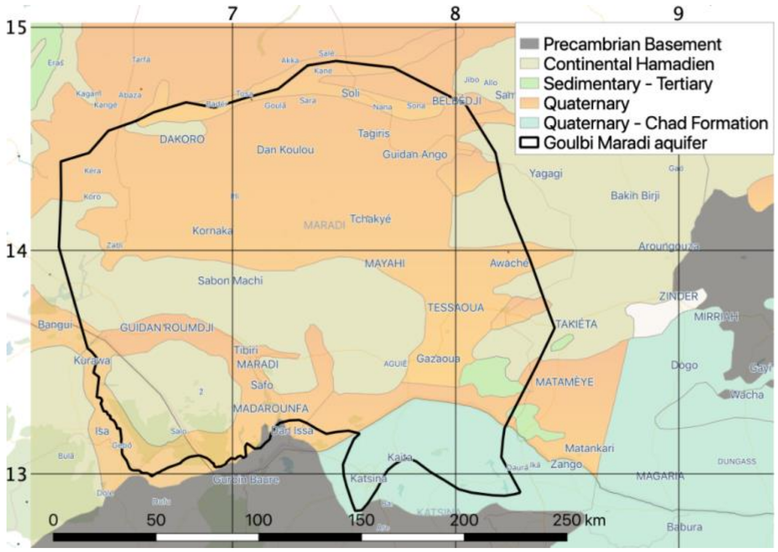
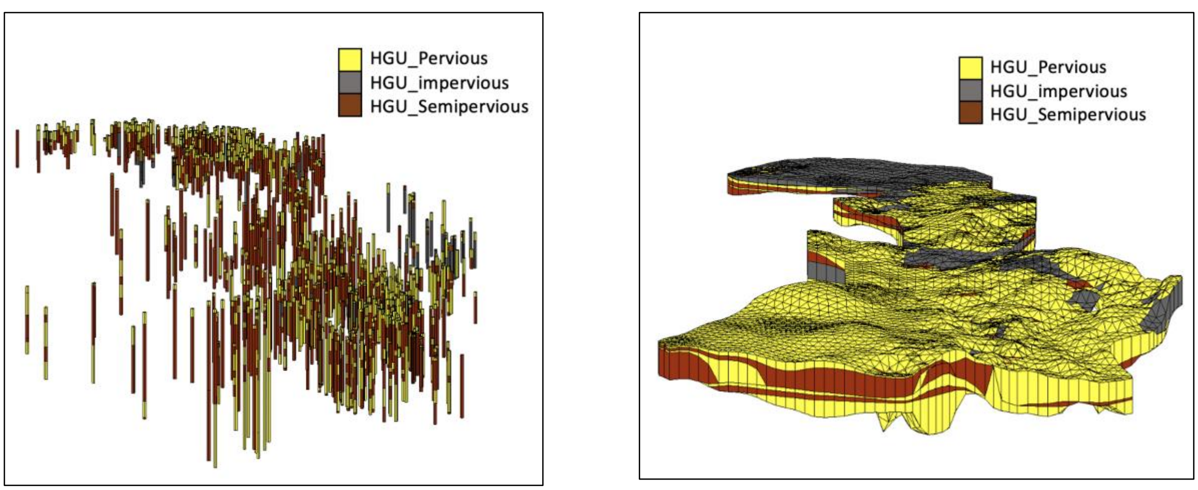


Figure 4.4: Boundary Conditions in the Goulbi Maradi Aquifer.

A.1.1.5 Hydrostratigraphy

We used the borehole data and applied a "horizons to solids" geometric algorithm described by Lemon & Jones [167] to build three-dimensional solid models of the hydrostratigaphy in the region. This algorithm assigns horizon IDs to each borehole contact, with the IDs representing the sequence of sedimentary layers. The algorithm generates solids by interpolating the surfaces defined by the horizons and extruding them into 3D volumetric structures (Figure 4.5). We classified the 30 materials into three main hydrogeologic units (HGU's) corresponding to pervious, impervious, and semipervious units.



(**b**)

(**a**)

Figure 4.5: (a) 3D Representation of Borehole Logs (b) Solids Generated by the Horizons-to-Solids Algorithm.

A.1.1.6 Flow Budget

Developing a water budget involves quantifying the major sources and sinks in the aquifer. We classified them into gains and losses from rivers, losses to evapotranspiration, recharge to the aquifer from precipitation and infiltration, extraction by pumping wells, and fluctuations in aquifer storage. Due to data scarcity in the region, quantifying the water budget proved to be one of the most challenging aspects of this project and required the development of an integrated method that leverages Earth observations.

In general, the water budget can be defined as follows:

$$\Delta storage = (inflows - outflows) \quad (4.1)$$

i.e., the change in volume of water stored in the aquifer is the difference between aquifer inflows and outflows.

More specifically:

$$\Delta_{storage} = (Recharge + River_{in}) - (River_{out} + ET + Q_{wells}) \quad (4.2)$$

where:

$\Delta_{storage}$	=	Change in aquifer storage
Recharge	=	Infiltration from rainfall
$River_{in}$	=	Gains from rivers
$River_{out}$	=	Losses to rivers
ET	=	Evapotranspiration
Q_{wells}	=	Extraction from wells

Changes in aquifer storage (Δstorage). Change in aquifer storage is often the most difficult part of the water budget to quantify. Storage change estimates can be made by analyzing water table fluctuations over time and estimating the aquifer storage coefficient. However, there are very few water level measurements in the Goulbi Maradi region and certainly not enough to characterize storage change over time. Therefore, to quantify the storage, we used GRACE mission data. GRACE data can be used to estimate variations in groundwater storage [7,36,43,66]. To separate the groundwater component from the overall water storage, which includes surface water changes, we subtracted surface water components generated by a land surface model from the GRACE TWS_a [7,12,13,38,43,66,68–76]. For this study, we used data from the NASA's Global Land Data Assimilation System (GLDAS) model for snow water equivalent (SWE) though zero in this region, plant canopy (CAN), and soil moisture (SM). We used the GRACE Groundwater Subsetting Tool (GGST) to compute groundwater storage changes [7]. GGST converts the GLDAS data to an anomaly format to obtain SWEa, CANa, and SMa, then computes the groundwater storage anomaly using Equation (4.3 [13]

$$\mathrm{GWSa} = \mathrm{TWSa} - (\mathrm{SWEa} + \mathrm{CANa} + \mathrm{SMa}) \tag{4.3}$$

This resulted in a monthly GWSa dataset in units of centimeters of liquid water equivalent (LWE) in gridded format with a resolution of 1x1 degree over the period from 2002 - 2022. We computed the storage volume by multiplying the change in GWSa LWE by the area of the aquifer.

Infiltration (Recharge). The primary source of recharge to the aquifer is from rainfall. Recharge is notoriously difficult to estimate, though it can be estimated with field tests [84], but the tests are expensive, time-consuming, and do not yield results with a high degree of accuracy. Over a long period of time, aquifer recharge estimates can be iteratively refined. However, these long-term data are scarce in Niger.

Remote sensing techniques can be used to assess the recharge spatial and temporal distribution [168]. Barbosa et al. [13] and Wu et al. [84] have used remote sensing data to estimate groundwater recharge values in two important aquifers in Niger and the Ordos Basin in China, respectively, using the WTF method [49] [50].

We estimated groundwater recharge values using the WTF method, which analyzes the seasonal changes in piezometric head at monitoring wells or within the aquifer [49,50]. Using WTF, the rising portion of the annual fluctuation is categorized as recharge. The WTF method calculated recharge (R) in cm/yr using Equation (4.4):

$$R = S_y \left(\frac{\Delta h}{\Delta t} \right) \tag{4.4}$$

where Δh represents the change in height of the water table (cm), Δt is the specified interval over which the change was measured, and S_y denotes the specific yield [49]. For this study, instead of relying on well measurements, we used the GRACE-derived GWSa in place of $S_y\Delta h$. We applied this approach to each one-year period as shown in Figure 4.6.

Using WTF, there are two approximations commonly used to estimate the groundwater recharge from the seasonal fluctuations. The first method involves determining the net recharge (R_S) as the distance between the trough of decline (S_B) and the peak of the rise (S_p) [13]. In the second method, the downward trend from the peak of the previous year (S_A) to the trough (S_L) is projected using a depletion curve. This projection allows us to find the recharge (R_D) that balances the continuing discharge. The total recharge is then calculated as the sum of (R_s) and (R_D) [13].

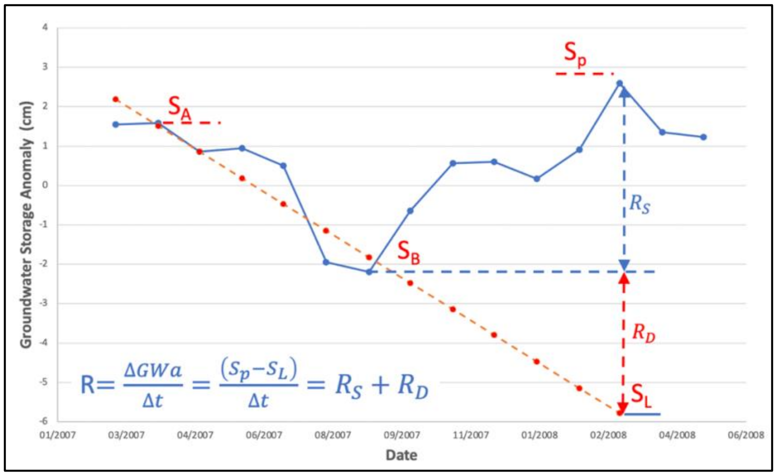


Figure 4.6: Conceptual Diagram of the Two Approaches of the WTF Method.

Gains and losses from rivers (River$_{in}$, River$_{out}$). In the Goulbi Maradi aquifer, there are two primary rivers: the Bunsuru river, part of the upper Rima basin, and the Goulbi Maradi river, which spans both Niger and Nigeria (). The Tarka river, located on the north boundary, is an intermittent stream. The Goulbi Maradi river serves as the primary source of surface water in the transboundary river basin. Its flow is seasonal, occurring irregularly between July and October, influenced by local rainfall and water release from the Jibya dam in northern Nigeria. The river travels 120 km into Niger, where it joins Sokoto Rima, a tributary of the Niger River [169,170]. These rivers can act as sources or sinks depending on the elevation of the groundwater relative to river stage with the flowrate between the river and surface water mediated by the thickness and permeability of the river bottom sediments.

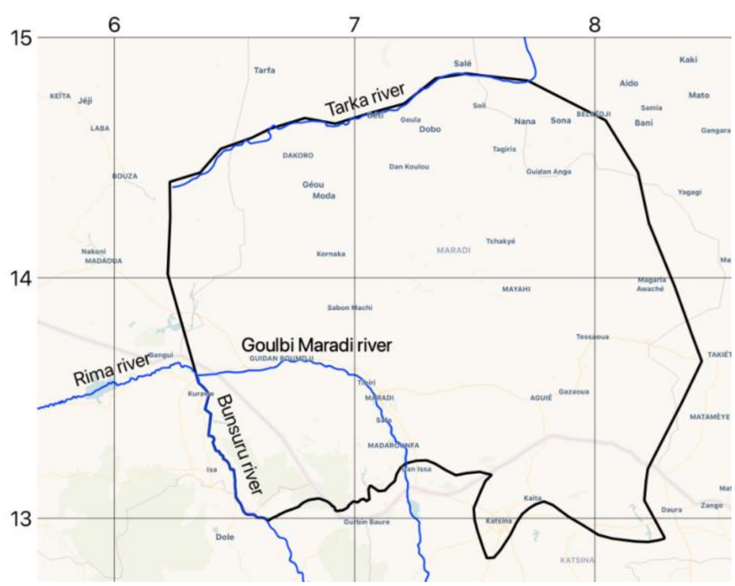


Figure 4.7: Rivers Located in the Study Area.

Evapotranspiration (ET). For areas in the region where the groundwater is near the surface, groundwater is lost via evaporation and transpiration. We assumed values, similar to those reported by Lutz et. al.,[171] where ET occurs when the water table is in the upper 3.5m of the soil profile and the rate varies from zero at the extinction depth to a maximum of 540 mm per year (0.0015 m/day) at the surface.

Well extraction (Q_{wells}). The well database provided information on the rate at which new wells were added over the period 2002 to 2009 but did not contain any reliable data about pumping rates.

Because we were able to estimate both recharge and the change in groundwater storage, the extracted water volume is the only major unknown in Equation 4. We estimated the overall pumping rate by adjusting the pumping rates until the model-simulated storage matched the GRACE-derived groundwater storage changes. This process is described in more detail below on the calibration section.

4.3.2 MODFLOW

From the conceptual model we developed a numerical groundwater model using the 2005 version of MODFLOW [172]. We used the Groundwater Modeling System (GMS) software to process the borehole, GIS, and other geospatial data to construct the MODFLOW input files, run the simulations, and calibrate the model [173].

4.4 Model Development

4.4.1 Groundwater Volume

We multiplied the GWSa liquid water equivalent by the area of the aquifer to obtain estimates of groundwater storage volume change from 2002 to 2022 (Figure 4.8) on a 1x1 degree resolution grid. Since the Goulbi Maradi aquifer only covers a range of 1.5 degrees latitude, the groundwater storage anomaly is more representative of the larger Iullemeden basin of which the Goulbi Maradi aquifer is just a portion. This adds an element of uncertainty to the storage values that must be factored in during the calibration process.

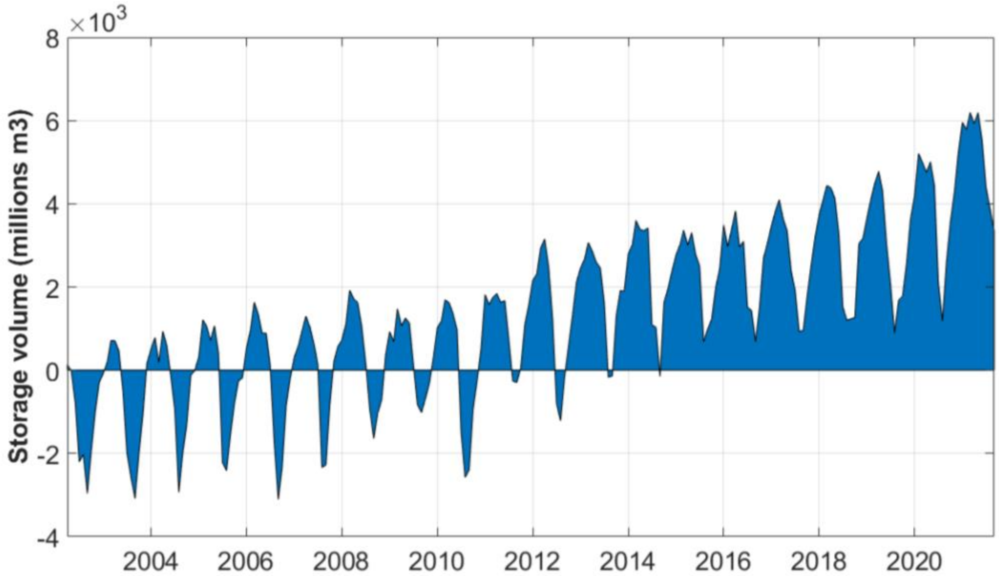


Figure 4.8: Storage Volume in Millions of Cubic Meters in the Goulbi Maradi Aquifer.

4.4.2 Recharge Rates

Using the WTF method, we used GWSa seasonal fluctuations to estimate both a high and low recharge estimate for each month shown in Figure 4.9. The two methods associated with WTF provide a range of recharge values, although in our experience, the lower value typically correlates better to recharge values estimated via field techniques [13].

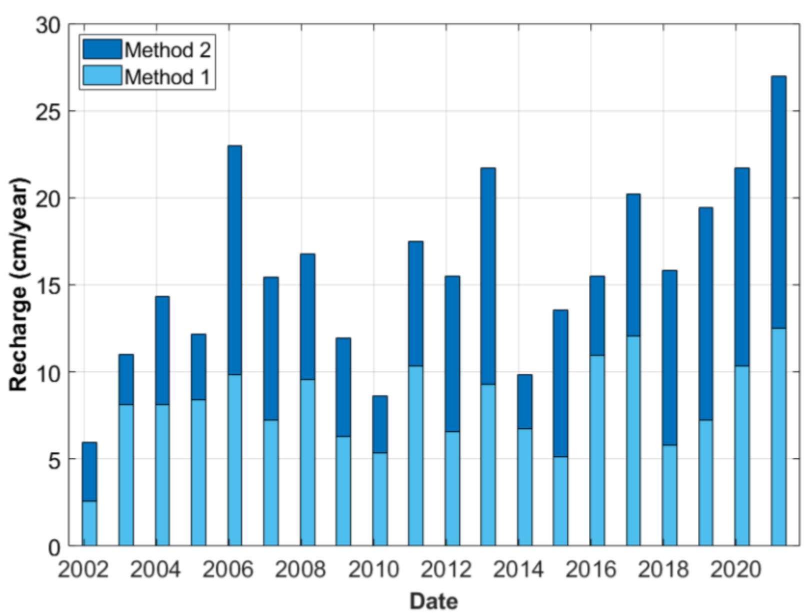


Figure 4.9: Annual Recharge Values Estimated by the WTF Method for the Iullemeden Basin.

4.4.3 Computational Grid

We identified two stratigraphically distinct layers by analyzing the borehole data (Figure 4.5). We used borehole logs and a DEM of the ground surface to generate a MODFLOW computational grid with 80 cells in the X and Y directions and two layers in the Z direction using the described boundary conditions (Figure 4.10).

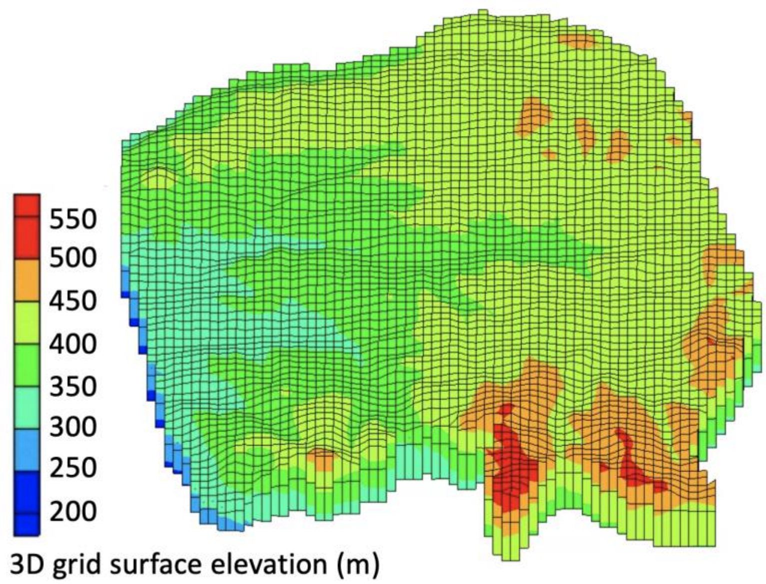


Figure 4.10: 3D Grid Representation of the Goulbi Maradi Aquifer.

4.4.4 Model Calibration

To calibrate the model, we used recharge, hydraulic conductivity, and pumping rates as the parameters and head observations and storage changes as the observations. We initially developed a steady-state groundwater model to gain insights into key aquifer characteristics, including conductivity values, evapotranspiration rates, approximate pumping rates, recharge values, and head distribution across different zones of the aquifer. We then converted the steady-state model into transient one. The transient model encompassed 40 stress periods, with each stress period comprised of six timesteps, which represent monthly time steps from 2002 to 2021. We performed both manual (trial and error) calibration and automated calibration using the PEST utility [174].

A.1.1.7 Parameters

We assumed recharge was zero during the dry half of the year and at the full rate, estimated rate during the wet period using a range of WTF-derived values (Figure 4.9). We identified a set of polygonal zones that allowed us to bias the estimated recharge toward either the high or low estimate based on the feedback from the calibration process. We varied hydraulic conductivity using polygonal zones defined both by the 3D hydostratigraphic regions and based on feedback from the calibration process. We assigned pumping rates to wells organized by zones based on feedback from the calibration process. In addition to the pumping oil locations, we had data indicating how many new wells were added each year between 2002 and 2009 thereby resulting in a gradual increase in overall groundwater extraction during this period. Given the limited number of new wells constructed between 2009 and 2019, we maintained constant pumping rates during this period.

A.1.1.8 Observations

One limitation of this study is the lack of time-varying groundwater levels at monitoring wells, which is typically the primary observation used for model calibration. We obtained 723 observed heads, each of which was from a separate well at a unique point in time between 2002 and 2009 (**Error! Reference source not found.**). These were depth to water table values collected during well construction. Since we did not have ground surface elevations for the wells, we sampled a global, 30-meter digital elevation model [175] to estimate ground surface elevations at the well locations and then calculated water table elevations by subtracting the depth-to-groundwater values from the estimated surface elevations

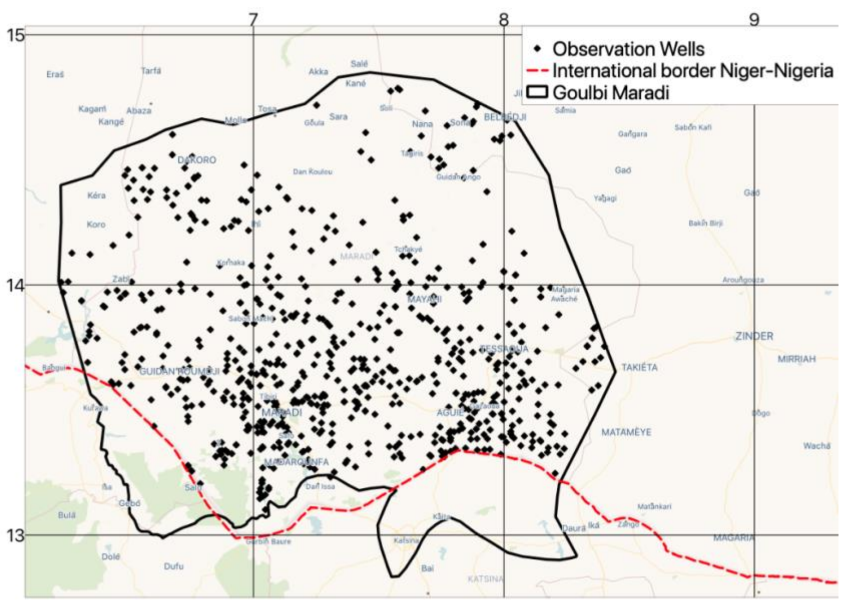


Figure 4.11: Observation Wells in the Goulbi Maradi Aquifer.

We used the GRACE-derived storage changes as an additional observation target. One of the outputs of the model was the change in aquifer storage. We compared these model-simulated storage changes with the GRACE data and adjusted our model inputs until the two estimates matched reasonably well. The storage change results were most sensitive to the groundwater pumping rates and to the recharge values. We found that these storage observations were particularly useful during the period of 2009 to 2021 where we did not have field observed heads.

4.4.5 Conversion to Predictive Model

We used the calibrated model as a predictive model forecasting aquifer conditions 40 years into the future to evaluate aquafer behavior. This included aquifer response to a variety of groundwater development strategies, and to determine what level of groundwater development could be implemented that would result in sustainable aquifer conditions.

4.5 Results

4.5.1 Calibration Results

Though model calibration, we determined a set of parameter values that minimized the difference between the simulated and observed head and storage values.

A.1.1.9 Optimized Parameter Values

The hydraulic conductivity values for our model of the Goulbi Maradi aquifer that resulted in the best calibration are presented in Figure 4.12. The majority of the zones have conductivity values below 40 m/day, indicating the presence of semi-pervious very fine sand materials [176]. The exception is the polygon located on the western side above the Goulbi Maradi river, which has a conductivity value of 145 m/day. This area is composed of pervious materials, primarily sand and gravel.

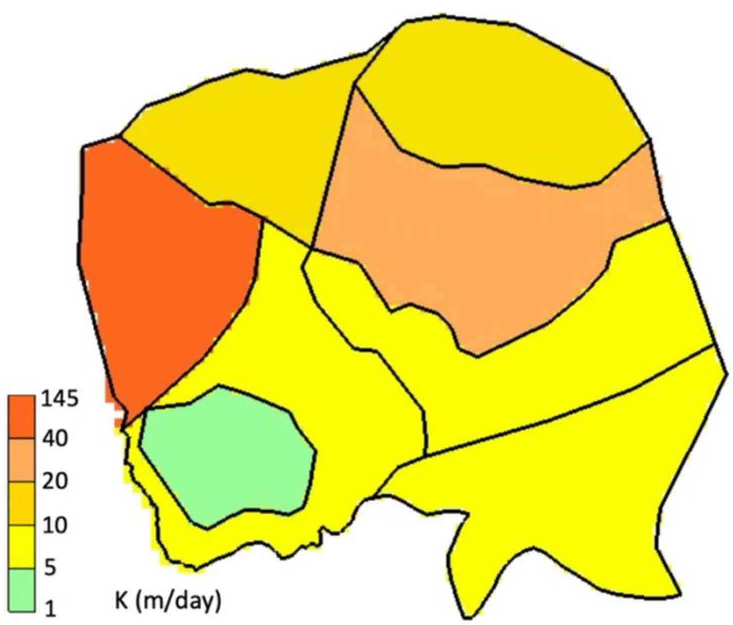


Figure 4.12: Estimated Hydraulic Conductivity (m/day).

The estimated recharge values based on the best fit to the data are shown in Figure 4.13. In the initial eight years of the study, the best-fit recharge values that were those obtained using Method 1. Specifically, the lowest values within the range between the recharge values estimated by Method 1 and Method 2 were found to provide the optimal fit. However, beginning from 2009, the calibrated recharge values fell within a range that exhibited a higher value in 2014 and then used the lowest values in the years 2015 and 2016.

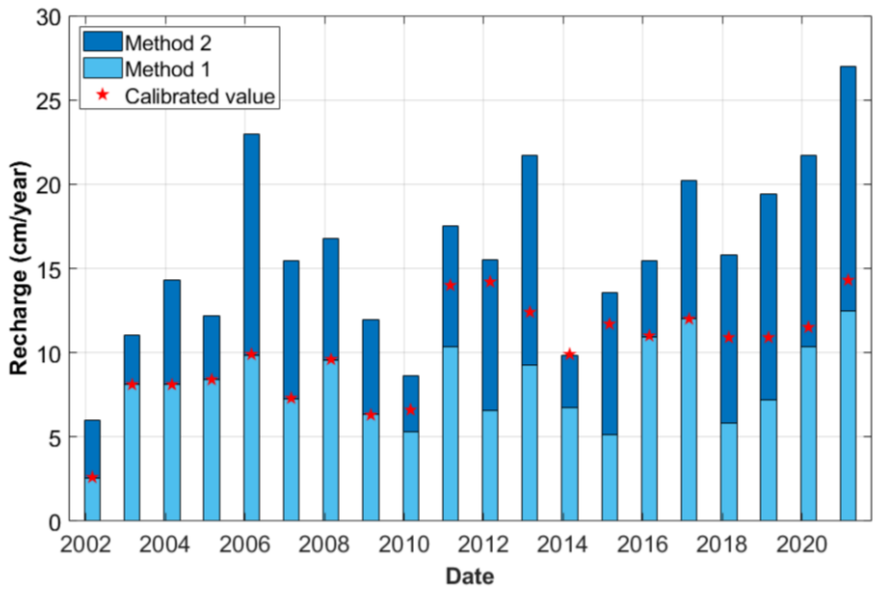


Figure 4.13: Optimized Recharge Values.

We adjusted the pumping rates in the model using nine distinct zones. The estimated pumping rates varied between 550 and 1520 m3/day.

A.1.1.10 Computed vs Observed Head Values

We applied three commonly-used statistical metrics to evaluate the fit of the computed to the observed 723 observed head values, these were: root mean square error (RMSE), mean error (ME), and mean absolute error (MAE) [177,178]. The resulting metrics were RMSE: 8.43 m, ME: 0.42 m, and MAE: 6.89 m. The ME values indicate that the positive and negative errors are mostly balanced with a small bias to a positive error. The RMSE and MAE values are relatively close indicating that there are few outliers in the dataset. Figure 4.14 illustrates a comparison between the observed and simulated heads with the solid line indicating an exact match. Together, computed vs observed plot and the error metrics indicate a reasonably good fit for a regional model.

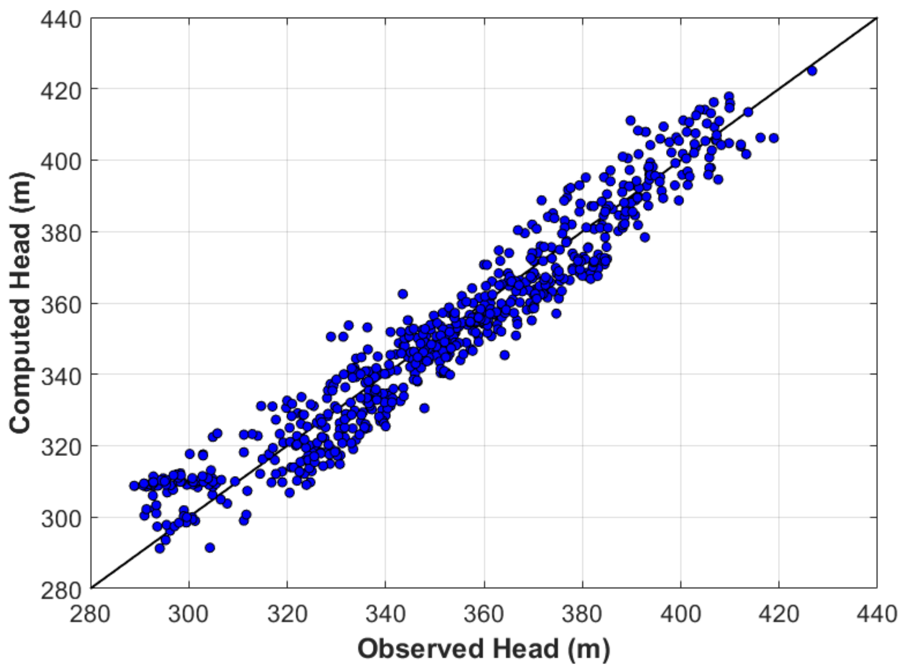


Figure 4.14: Simulated vs. Observed Head Values in the Goulbi Maradi Aquifer.

4.5.2 Storage Changes

Figure 4.15 presents a comparison of the cumulative groundwater storage volume estimated using GRACE data and that simulated by the model for the period 2002 to 2021. The simulated storage changes show the same seasonality as the GRACE-measured changes but are biased to the high side. During the calibration process, we found that we could not reduce the storage changes further while still matching the head observations and maintaining model stability. The GRACE results include data from the larger Iullumeden basin which contains the smaller Goulbi Maradi aquifer, because of the resolution of the GRACE grid cells. The Goulbi Maradi aquifer sits on the southern edge of the Iullemeden basin. The GRACE cells overlapping the Iullemeden basin include more arid zones north of the Goulbi Maradi aquifer therefore it is reasonable to expect that the storage changes would be higher in the Goulbi Maradi aquifer given that it is in a less arid portion of the Iullemeden basin.

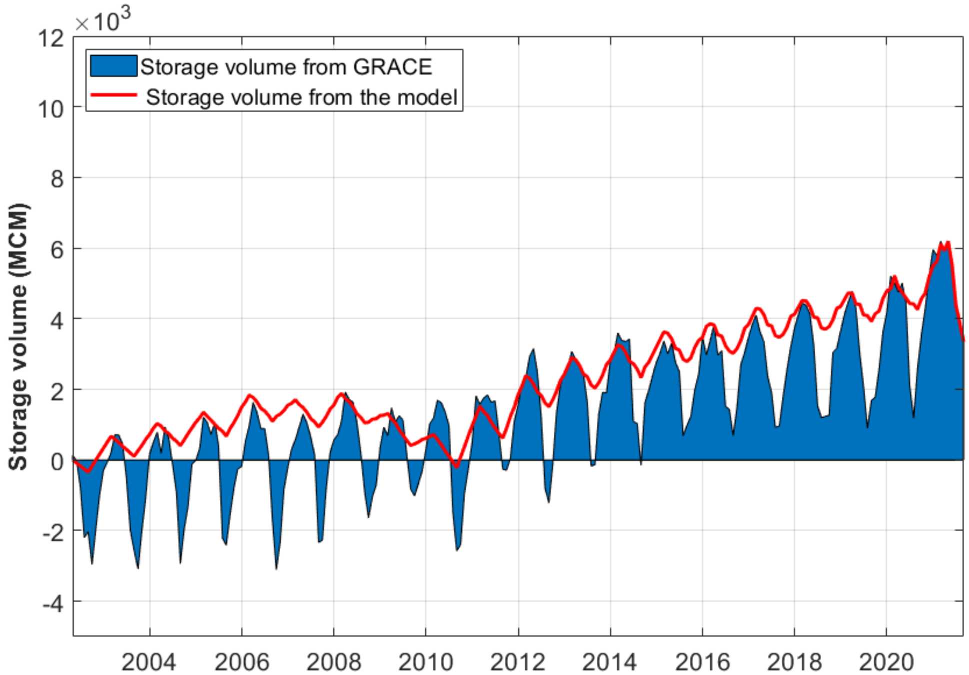


Figure 4.15: Simulated vs. Observed Groundwater Storage Changes in the Goulbi Maradi Aquifer.

4.5.3 Predictive Model

Following successful calibration, we used the model to predict changed over an additional 40 years, to February, 2061. We simulated a set of groundwater development scenarios involving an increase in pumping commensurate with the development of additional groundwater infrastructure in the region. For each of these scenarios we assumed the average recharge rate either stayed the same or increased by some percentage in the future and a evaluated a percentage increases in pumping over the current volume. The objective of this exercise was to determine what percentage increase in pumping would result in sustainable aquifer conditions for each of the recharge assumptions.

A.1.1.11 Scenario 1: 5-year Average Recharge

For the first set of scenarios, we assumed future recharge values were the same as the last five years of the calibration period (2016-2021). Given that this five-year period corresponds to an increase in storage and is therefore relatively wet, this is an optimistic, but not particularly conservative assumption. Using this recharge rate, we ran the model iteratively to determine a pumping rate that resulted in a stable water balance.

Figure 4.16 shows the results of this scenario. In panels A and B, we increased the pumping rate by 20% and 30%, respectively over the first 20 years, and then held constant for the final 20 years. The in the 20%-increase scenario (panel A), storage increases indefinitely, indicating that the aquifer can sustain a higher pumping rate. In the 30%-increase scenario (panel B), there is a slight decrease in storage after 2038. In Panel C, we adjusted pumping rates until aquifer storage was relatively constant over the later portion of the simulation. We found that a pumping increase of 22% represents the maximum pumping that results in sustainable conditions based on the assumed recharge value.

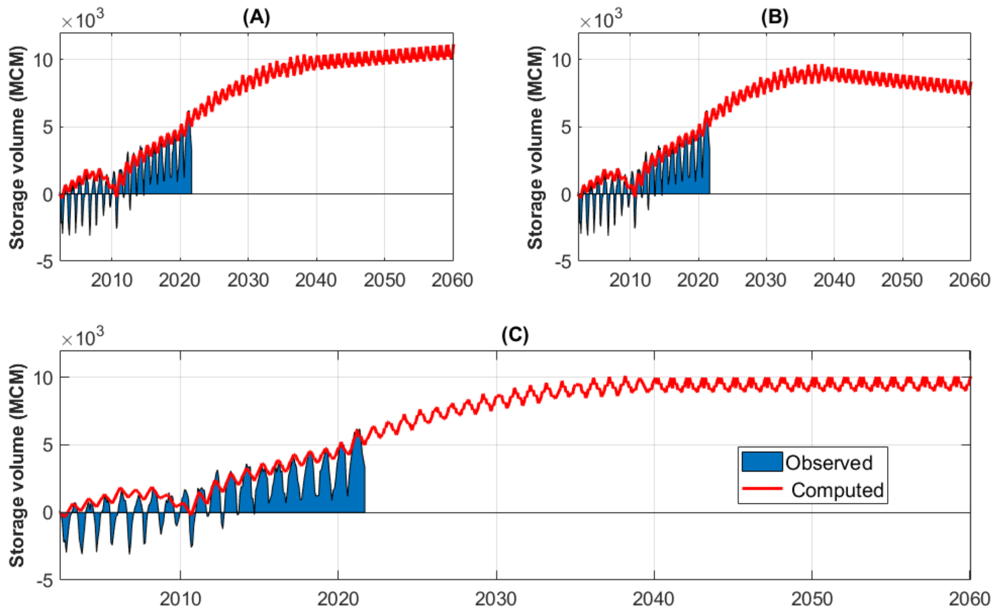


Figure 4.16: Simulated vs. Observed Groundwater Storage Changes in the Goulbi Maradi Aquifer Using the Last 5 Years Average Recharge Value, with a 20%, 30%, and 22% increases in pumping over the first 20 years for Panels A, B, and C, respectively which results in increasing, decreasing, and steady storage conditions in the latter portions of the scenarios, respectively.

A.1.1.12 Scenario 2: 10-year Average Recharge

For scenario 2, we projected the average recharge rate determined the the last 10 years of the calibration phase into the future. Figure 4.17 shows the results of this scenario. Panels D and E corresponds pumping increases of 20% and 25%, respectively over the first 20 years, with pumping held constant in the last 20 years. These results bracket a balanced solution, shown in Panel F which represent a 24% increase in pumping over the first 20 years.

A.1.1.13 Scenario 3: 20-year Average Recharge

For our third scenario (Figure 4.18) we used a recharge value corresponding to the average recharge over the entire 20-year calibration range. This is the most conservative of the three scenarios as it has the lowest recharge. Panels G and H represent increased pumping of 5% and

10% per year for the first 20 years, then constant, respectively. Like the previous two scenarios, these results indicate a slight increase in storage for the 5% increase, and a decrease in storage for the 10% increase. Panel I depicts a 7% increase in pumping over the first 20 years with pumping held constant the last 20 years. Under this scenario, storage is essentially constant in the latter portion of the scenario.

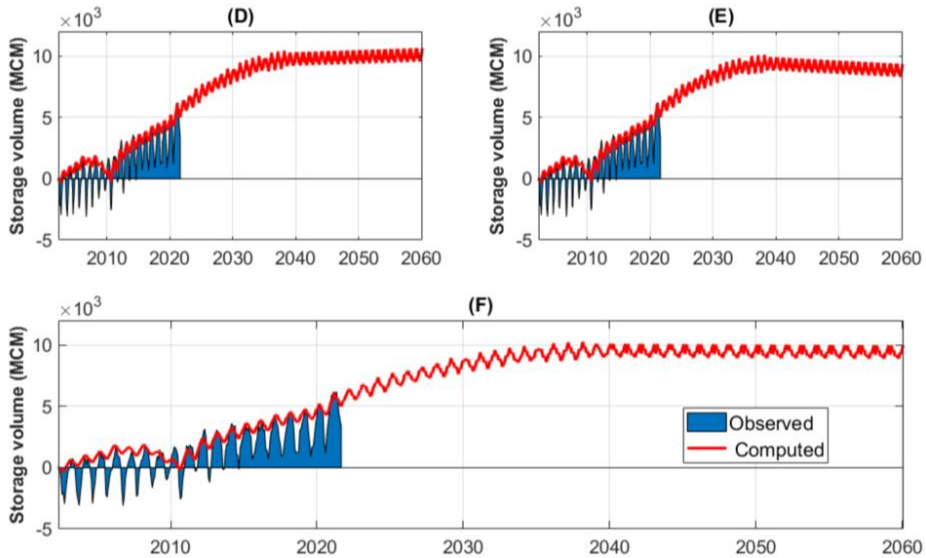


Figure 4.17: Simulated vs. Observed Groundwater Storage Changes in the Goulbi Maradi Aquifer Using the Last 10 Years Average Recharge Value.

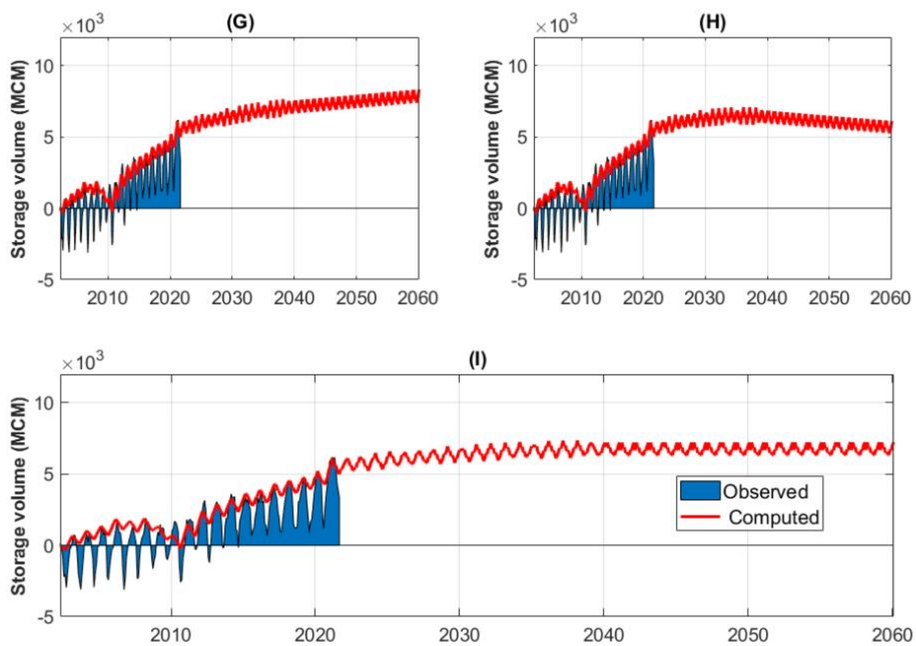


Figure 4.18: Simulated vs. Observed Groundwater Storage Changes in the Goulbi Maradi Aquifer Using the Last 20 Years Average Recharge Value.

4.6 Conclusions

We developed a transient groundwater model of the Goulbi Maradi aquifer in southern Niger. We have successfully used Earth observations to calibrate the model and compensate for a severe scarcity of groundwater data in the region, a unique feature of this study. Specifically, we used data from the GRACE mission to estimate groundwater storage changes over the period of 2002 to 2021 as calibration data. We also used GRACE data to estimate recharge rates using the WTF method. We used these estimated recharge rates and storage changes to compute well pumping rates in the region. This allowed us to calibrate to observe heads over the time period when data were available (2002-2009), but also have confidence in the calibration over the subsequent 10 years were no observed had data, only GRACE data, were available.

We used the calibrated model as a predictive model to evaluate the sustainability of various groundwater development strategies over the next 40 years. These simulations showed that groundwater withdrawals could be increased as much as 7%, 22% and 24% percent for 20 years, then held constant, depending on assumed recharge rates.

While we were able to develop and calibrate a groundwater model, there is still a significant amount of uncertainty with a model. Even though we were able to use GRACE data to calibrate the flow budget, the GRACE results come from a set of grid cells the cover a region much larger than the Goulbi Maradi aquifer. We believe this model could continue to be iteratively refined and improved as investments are made in the region in terms of monitoring well development, data collection, additional methods for estimating recharge, etc.

5 *Conclusions*

5.1 General Conclusion of this Dissertation

This research project has evaluated and analyzed groundwater resources in two important regions in West Africa using Earth observations and groundwater modeling. The research has provided significant insights into groundwater storage changes analysis within selected aquifers, specifically focusing on the Iullemeden Basin and Chad basin in Southern Niger, as well as the Volta basin in sub-Saharan Africa. Additionally, the study has encompassed the estimation of groundwater recharge in these areas, utilizing satellite data and the Water Table Fluctuation method.

The development of a groundwater model to assess and forecast future scenarios, as well as to evaluate the sustainability of the Goulbi Maradi aquifer located in Southern Niger, marks a notable contribution to the field. This model provides essential tools for decision-makers and stakeholders to make informed choices concerning groundwater management and usage in the region under different conditions.

In the broader sense, this research has demonstrated how Earth observations can be used in data-sparse regions to perform comprehensive analyses of groundwater storage change and sustainability. We have built, demonstrated, and documented a systematic process to analyze storage change, estimate recharge, and analyze the underlying drivers of those changes. We have also shown how Earth observations can be used to build a groundwater model with limited in situ data and how that model can be used to assess aquifer sustainability under various future groundwater development scenarios.

5.2 Chapter 2 Conclusions

In this study, we have successfully analyzed historical groundwater storage changes in four selected aquifers located in the Iullemeden and Chad Basins in Southern Niger (West Africa). The analysis was conducted using the GGST Web application in combination with GRACE and GLDAS data.

To address missing data in the GRACE datasets, we utilized a simple seasonal decomposition python model, which enabled us to fill in the data gaps effectively. With a complete data series, we derived the Groundwater Storage changes by subtracting the Surface Water Storages components from the Total Water Storage. This approach allowed us to estimate the cumulative storage change of the selected aquifers over a 19-year period from 2002 to 2021.

Our findings revealed a slightly increasing trend in groundwater storage in the Iullemeden basin aquifers and a slight decrease in the Chad basin aquifers from 2002 to 2011. However, during the last 10 years (2011 to 2021), we observed an increase in the storage in the aquifers of both basins. These changes can, at least in part, be attributed to increased precipitation during the same period.

Furthermore, we conducted groundwater recharge estimations using GRACE data through two different approaches of the Water Table Fluctuations method, which operates on the principle that the rise in the water level is indicative of recharge. The estimated annual average recharge rates align well with the observed groundwater storage changes in the region. Specifically, we found relatively constant recharge values from 2002 to 2010, followed by an increase from 2011 to 2021.

We compared our recharge rate estimates with values obtained from other studies in the region. The recharge values calculated using alternative methods such as CMD, 14C, and 3H yielded lower estimated recharge rates when compared to our results.

In conclusion, our analysis leads to the observation that groundwater storage in the selected aquifers within the two basins has not been undergoing depletion; instead, it has exhibited a consistent increase over the past decade. This encouraging trend suggests a favorable environment for further groundwater infrastructure development in the region.

5.3 Chapter 3 Conclusions

In a manner similar to Chapter 2, we applied the same methodology to analyze groundwater storage using satellite data, focusing on the significant Volta basin situated in sub-Saharan Africa. The study period spans 20 years, from 2002 to 2022.

Throughout this investigation, we identified three primary trends in groundwater storage changes. Firstly, from 2002 to 2010, there was an upward trend in groundwater storage. Secondly, between 2011 and 2015, we observed a decreasing trend. Finally, from 2016 to 2022, there was another increasing trend in groundwater storage.

Notably, during the initial period from 2002 to 2008, there was a negative storage trend. However, this was followed by a remarkable net gain in groundwater storage of approximately 41,000 million cubic meters (MCM) for the remainder of the study period.

In addition to the groundwater storage analysis in the Volta basin, we further explored the correlation between rainfall patterns and groundwater storage changes during the mentioned period. Notably, our findings revealed a consistent trend in both groundwater storage and precipitation, characterized by the three distinct patterns identified earlier.

The analysis of the data revealed a clear correlation between precipitation and groundwater storage levels. Specifically, it was observed that periods of high precipitation corresponded to increased groundwater storage, whereas periods of low precipitation led to decreased groundwater storage. However, it is important to emphasize that Groundwater levels can be influenced by a multitude of other factors, and the observed correlation with precipitation is just one aspect of the complex hydrological system.

We conducted an estimation of groundwater recharge in the Volta Basin using the same data source and methodology. To validate our estimates, we compared them with observed data from 10 monitoring wells in the Nasia aquifer.

Our values derived from GRACE data exhibited the same three trends observed in the groundwater storage change

We further compared our groundwater recharge estimates with data from another study conducted in a smaller region. Our findings indicated that our values were slightly higher, although they still fell within the range of recharge values computed in other areas of the basin using different methods.

These results strongly indicate that the recharge values estimated using the Water Table Fluctuation method are reliable in the Volta Basin. Moreover, the successful integration of GRACE data with traditional methods demonstrates its effectiveness in enhancing the accuracy of groundwater recharge estimates.

5.4 Chapter 4 Conclusions

In the study described in chapter 4, a transient groundwater model of the Goulbi Maradi aquifer in southern Niger was successfully developed. The study addressed the challenge of limited groundwater data in the region by utilizing Earth observations, specifically data from the GRACE mission. GRACE data was used to estimate groundwater storage changes and recharge rates, enabling the calibration of the model and computation of well pumping rates over the period 2002 to 2021.

The calibrated model was then employed as a predictive tool to assess the sustainability of various groundwater development strategies over the next 40 years. The simulations demonstrated that groundwater withdrawals could be increased by up to 7%, 22%, and 24% for 20 years, with subsequent stabilization, contingent on the assumed recharge rates.

Despite the successful development and calibration of the groundwater model, it is acknowledged that uncertainties still exist. The GRACE data used for calibration covers a larger region than the Goulbi Maradi aquifer, which introduces some limitations. The researchers suggest continuous refinement and improvement of the model as investments are made in the region, such as well monitoring, data collection, and alternative methods for estimating recharge rates. This iterative approach could enhance the model's accuracy and reliability for future studies and groundwater management efforts in the region.

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