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

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Abstract: Accurately assessing groundwater storage changes in Niger is critical for long-term water resource management but is difficult due to sparse field data. We present a study of groundwater storage changes and recharge in Southern Niger, computed using data from NASA Gravity Recovery and Climate Experiment (GRACE) mission. We compute a groundwater storage anomaly estimate by subtracting the surface water anomaly provided by the Global Land Data Assimilation System (GLDAS) model from the GRACE total water storage anomaly. We use a statistical model to fill gaps in the GRACE data. We analyze the time period from 2002 to 2021, which corresponds to the life span of the GRACE mission, and show that there is little change in groundwater storage from 2002–2010, but a steep rise in storage from 2010–2021, which can partially be explained by a period of increased precipitation. We use the Water Table Fluctuation method to estimate recharge rates over this period and compare these values with previous estimates. We show that for the time range analyzed, groundwater resources in Niger are not being overutilized and could be further developed for beneficial use. Our estimated recharge rates compare favorably to previous estimates and provide managers with the data required to understand how much additional water could be extracted in a sustainable manner.

Keywords: groundwater recharge; water table fluctuation method; long-term storage change; imputed GRACE data; web-application; sustainability; Niger; Africa

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1. Introduction

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 [4]. Groundwater is especially important in dry, arid regions of the world where other water resources are scarce [5]. Groundwater resources can be stressed due to several factors, with one of the primary concerns being groundwater depletion [6].

Limited groundwater data can make managing groundwater resources difficult [2,7,8], especially over the longer time periods required to evaluate aquifer sustainability [5]. 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 [5]. 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 [9–11]. This creates what Famiglietti [8] 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 [12].

Groundwater demand is increasing, with a 3% annual growth in groundwater use globally from 1990 to 2010 [6]. 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.

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) [13]. 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 [13–15]. 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 [16]. 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 [17,18].

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 [21]. 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 [21]. Example applications include drought studies [22–27], flood studies [28–32], and other general hydrologic studies involving regional water storage and trends [33–35]. Recent work has shown that GRACE data can be used to monitor groundwater storage changes remotely [5,36–39], including groundwater depletion in arid and semi-arid areas [40,41].

1.3. Groundwater Storage Change Estimation Using GRACE

While GRACE measures the total change in mass, and by inference, the total change in water storage, GRACE data can be used to study groundwater, a subset of the total water storage [2,5,37,42]. Most GRACE groundwater applications use global land surface model results to separate the groundwater component from total water storage [5]. 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 NASA's Global Land Data Assimilation System (GLDAS) model from the GRACE-derived TWSa [5,42,43]. This approach, subtracting the land surface model nongroundwater components from GRACE data, has been widely applied using various land surface models [2,4,5,9,39,42,44–51].

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 ongoing 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 [16,52–56].

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 [20]. 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 spatially gridded groundwater anomaly data over time to generate an aquifer storage time history limited to the aquifer region being studied or managed [20]. 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.

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 [57]. Considerations for selecting the appropriate method include the 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 [58]. The chemical techniques that have been used extensively in our study region are the chloride mass balance (CMB) method and the tritium (^{3}H) peak concentration method [58,59]. However, these methods have disadvantages. The tritium method is not usable when the unsaturated zone is shallow [60], 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 [60]. 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 [61,62]. WTF analyzes seasonal changes in the 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. [63] 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 of 16.4% and 14.8% of the annual precipitation using GRACE and historical water levels data, respectively. Gonçalvès et al. [64] 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 [65] 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. [60] 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 from the values calculated with an environmental tracer.

1.5. Causes of Groundwater Storage Change

Long-term water levels changes can be due to changes in groundwater pumping, irrigation practices, climatic variations, or fluctuations in precipitation [66]. For example, Leduc et al. [67] 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. Furthermore, 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. [68] recently reported an increase in total water storage trends in West Africa, particularly in the Iullemeden aquifer. Favreau et al. [69] also reported a continuous rise in the water table in southwestern Niger. Furthermore, Bonsor et al. [70] and Cuthbert et al. [71] 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.

1.6. Study Objectives and Goals

We use published GRACE groundwater storage change tools [5] 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. Study Area and Background

We analyzed aquifers located in Southern Niger within the Iullemeden and Lake Chad basins. The Iullemeden basin (Figure 1) is situated across five countries, including Niger, Benin, Nigeria, Algeria, and Mali, in the Sahara and Sahel zones (arid and semi-arid regions) [72]. It has an area of about 620,000 km^2 and is the main source of drinking water for the five countries [73]. 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 [74]. 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 10 m [72].

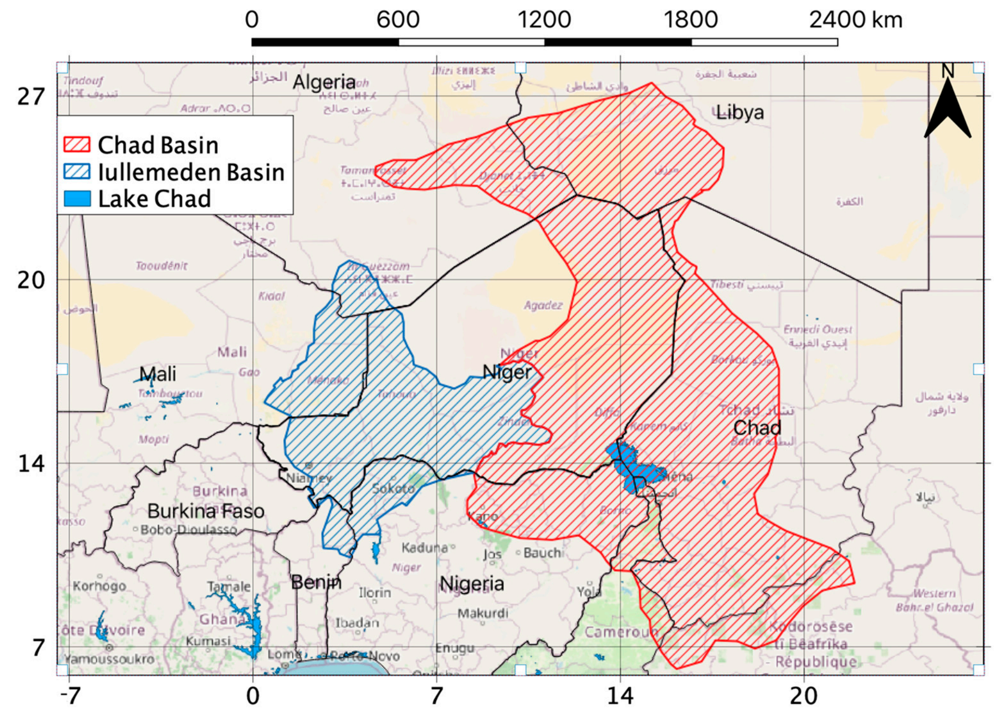


Figure 1. The Iullemeden and Lake Chad basins.

The Lake Chad basin (Figure 1) covers around 2.5 million km^2. This basin spans Algeria, Sudan, and small areas of Libya, Cameroon, Chad, Niger, and Nigeria [75]. 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.

2.1. 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 2000 m thick sequences of sedimentary aquifer formations [72]. The principal shared aquifers in the Iullemeden basin are the Continental Intercalaire (CI), Continental Terminal (CT) (Tertiary), and Quaternary (Figure 2).

In general, the CI aquifer is composed of Tegama sandstone, Farak clays, and the Continental Hamadien, from top to bottom [73]. 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) [73]. 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 [76], with numerous aquifers recognized in the basin [77]. We analyzed two aquifers located in the Lake Chad basin in southeast Niger. The Manga aquifer (Figure 3) has an area of approximately 150,000 km^2 and is mainly composed of layers of sand and clay [78] with a series of sand dunes in the center that have depressions between 15 and 20 m that affect recharge [79]. The aquifer has a small hydraulic gradient trending towards Lake Chad. The water table is shallow, with the maximum depth to groundwater being about 15 m [78]. The Korama aquifer extends to the southern part of Niger with an area of around 6000 km^2. 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 the Nigerian border for our analysis [80]. This aquifer consists of sandy-clay and alluvial sands layers with an apparent limited hydraulic connection to the sedimentary materials of the Chad formation [78]. For both aquifers, groundwater recharge generally occurs in unconfined areas from rainfall, irrigation return flow, and by losing lakes and rivers [78]. This recharge (e.g., rainfall) is sensitive to periodic droughts, wet periods, and climatic changes [81].

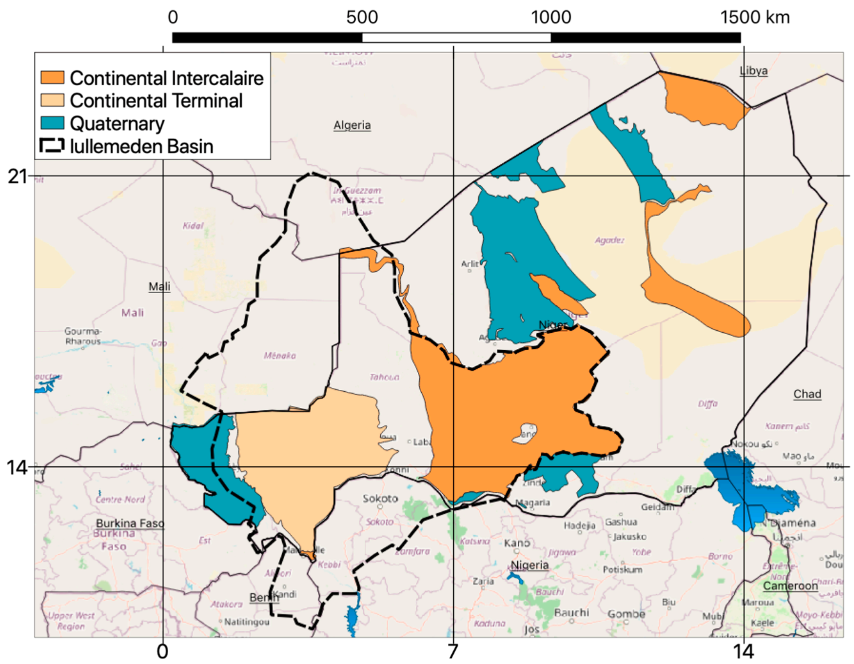


Figure 2. Principal shared aquifers in the Iullemeden Basin.

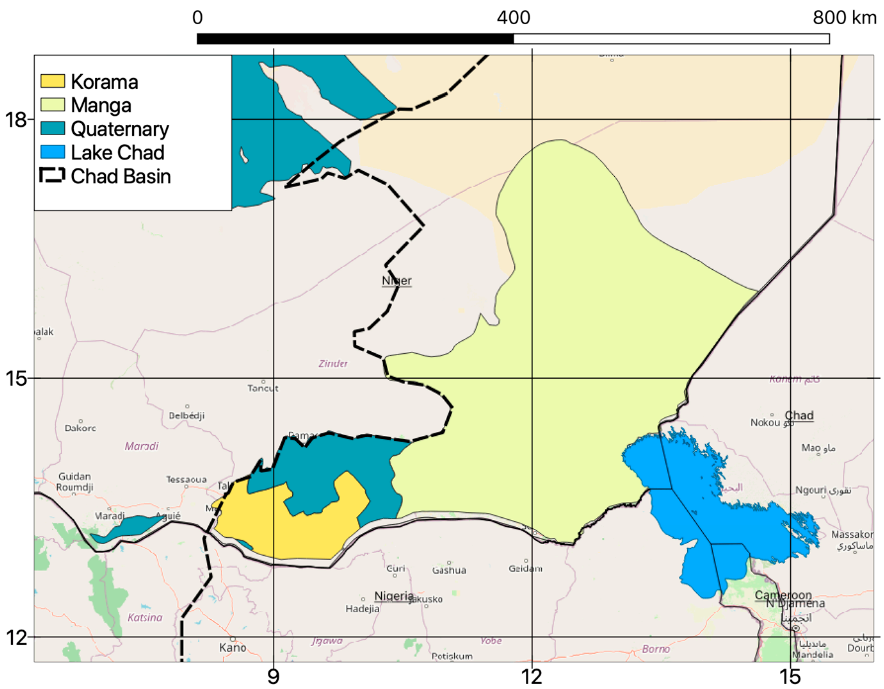


Figure 3. Principal shared aquifers in the Lake Chad basin.

2.2. 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 4). In the Iullemeden basin, we analyzed the CI and CT aquifers, the area of each aquifer is approximately 161,000 and 102,600 km^2, respectively. For the Chad basin, we analyzed the Manga aquifer, which has a study area of 13,000 km^2, and the Korama aquifer, with an approximate area of 124,600 km^2.

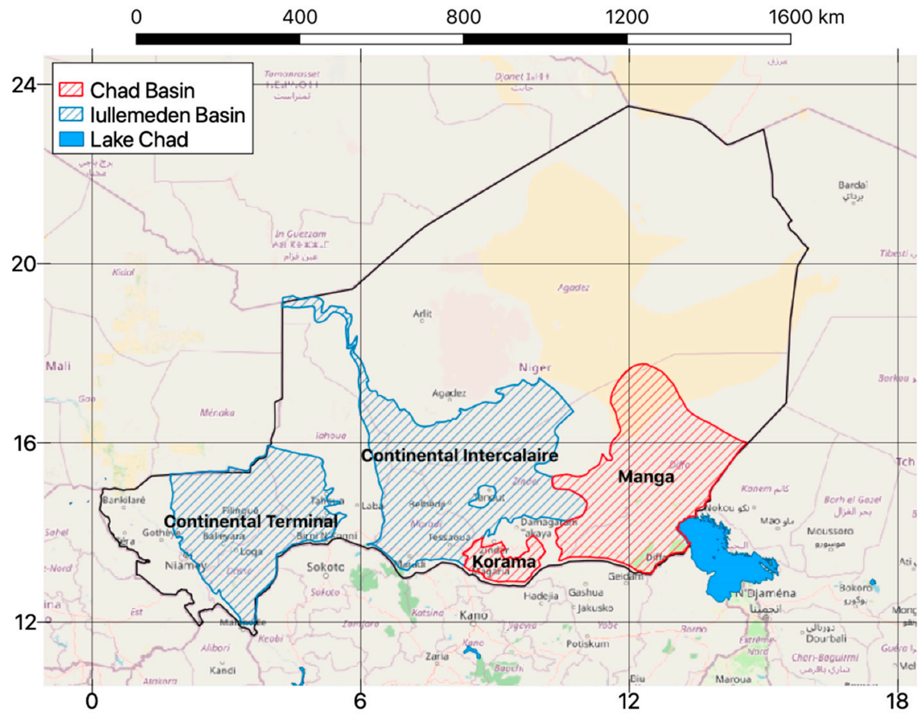


Figure 4. Selected aquifers of the Iullemeden and Chad basins (GGSA).

2.3. Previous West African Studies

There have been several GRACE studies in West Africa related to water storage changes. Forootan [82] 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 [83] 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 could be reproduced using GRACE data.

Hinderer [84] 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 [85], 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 paralleled the seasonal groundwater depth fluctuations and speculated that the correlation was a result of the shrinking/swelling of clays.

Werth [86] 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.

2.4. 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 [87]. These trees are an essential part of the agriculture system providing food, wood for buildings, fuel, and medicines, and contribute to water conservation, soil fertility, and environmental protection [88]. Due to the scarcity of surface water in the region, agriculture, industry, and domestic use rely on groundwater [89]. 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 [88], making groundwater an essential buffer, especially for agriculture [90]. This situation has resulted in local managers being motivated to use groundwater resources in a sustainable manner [89].

In general, the aquifers of the Iullemeden basin have been used mainly in southern Niger, with pumping rates between 20 and 100 m^3/h from wells 40 to 100 m in depth [91]. 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 [73].

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 [81]. In urban areas, groundwater is the primary source of drinking water; however, this groundwater source is inadequate, mostly due to the cost of development [81]. 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.

3. Methods

3.1. GRACE Data

GRACE data are processed to provide a gridded gravitational anomaly map [13,19] by three institutions that use different algorithms: 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). Each of these methods generates total water storage anomaly (TWSa) datasets that are distributed by NASA [91]. We used the JPL dataset in this analysis [92,93]. 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 [2,45,94].

We also used Global Land Data Assimilation System (GLDAS) data to separate groundwater data from the TWSa [43]. 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.

3.2. Regional Groundwater Storage Analysis Using GRACE

We used the GRACE Groundwater Subsetting tool (GGST) to estimate groundwater storage changes [5]. 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:

$$GWSa = TWSa - (SWEa + CANa) \quad (1)$$

This mass balance approach has been used and validated by a number of researchers [42–48].

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:

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

where σSWEa, σCANa, and σSMa are the standard deviations of each component and σTWSa is the total water storage uncertainty provided by NASA [2]. The resulting uncertainty estimates vary both in space and time.

The 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 has varied 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 [5]. 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 a sustainable year. This is discussed in Section 3.4.

3.3. 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 [95,96]. (Figure 5) presents derived GWSa data for the Iullemeden basin that shows these periods with missing data. Figure 5 shows that, for this location, the GWSa data have a seasonal pattern with an increasing trend. Data at other locations exhibit similar patterns, seasonal variations with a trend; globally, not all aquifers exhibit a seasonal trend.

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 [97] 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: [98].

$$Y[t] = T[t] + S[t] + e[t] \tag{3}$$

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.

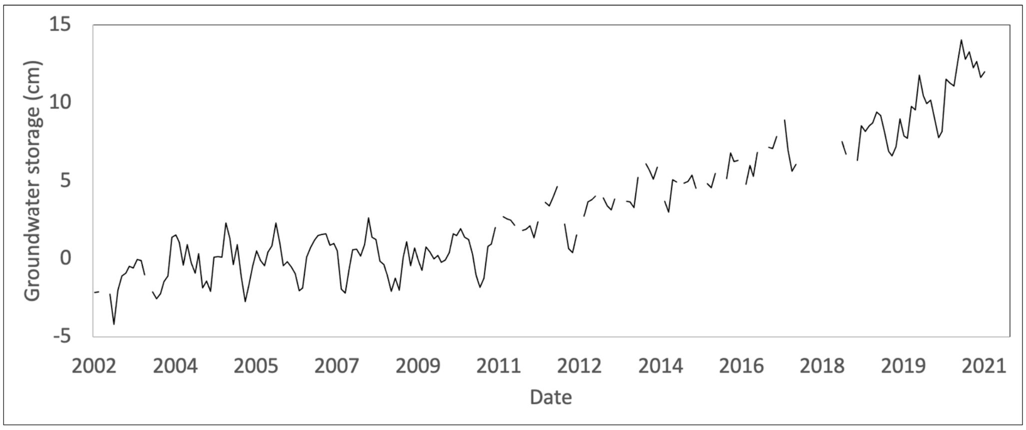


Figure 5. Original groundwater storage data from GRACE in the Iullemeden basin.

Figure 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.

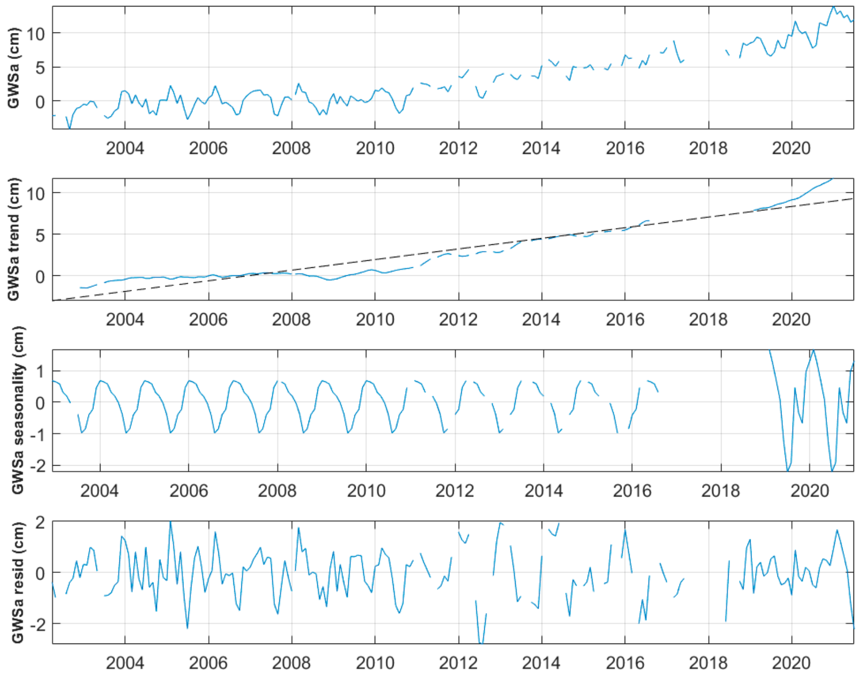


Figure 6. Decomposed GWSa data for the Iullemeden basin.

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:

$$Y[t] = y(T[t]) + \overline{S[t] + e[t]} \tag{4}$$

Figure 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.

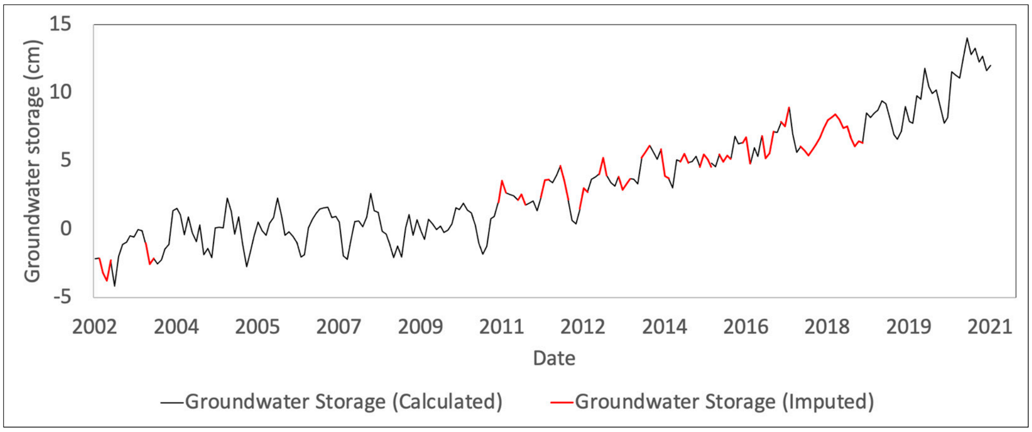


Figure 7. Measured (black) and imputed (red) GWSa data showing that visually, the imputed data honor the long-term trend and seasonal variation present in the data.

3.4. Estimating Annual Recharge Using GRACE-Derived Groundwater Datasets

To estimate groundwater recharge in the two aquifers, we use the WTF method [62]. The WTF method estimates groundwater recharge as:

$$R = S_y\left(\frac{\Delta h}{t}\right) \quad (5)$$

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 S_y is the specific yield [61]. 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 = $S_y \Delta h$ [60].

To compute the recharge rate (cm/year), we examined seasonal fluctuations in ΔGWSa time series plots, as shown in Figure 1. 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 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 $(R_S + R_D)$.

$$R_{method\ 1} = \frac{\Delta \text{GWSa}}{\Delta t} = \frac{S_p - S_B}{\Delta t} = R_S \quad (6)$$

$$R_{method\ 2} = \frac{\Delta \text{GWSa}}{\Delta t} = \frac{S_p - S_L}{\Delta t} = R_S + R_D \quad (7)$$

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

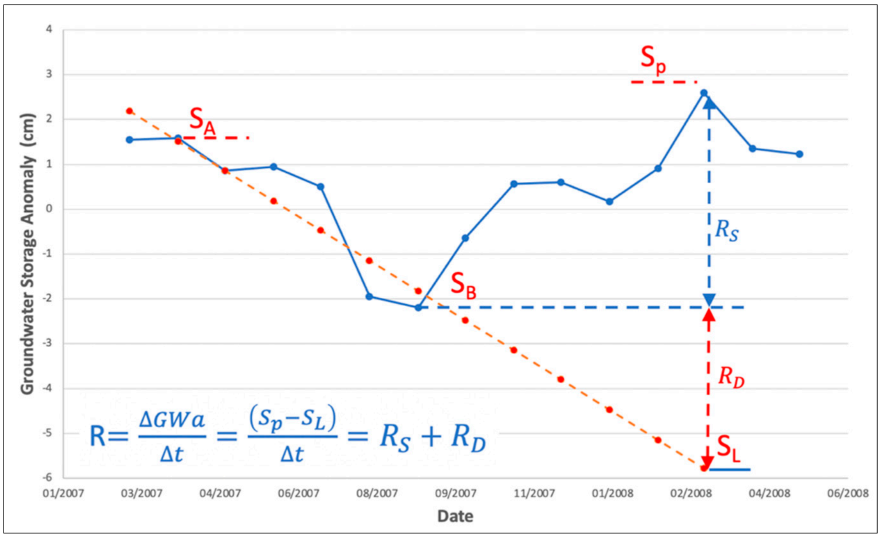
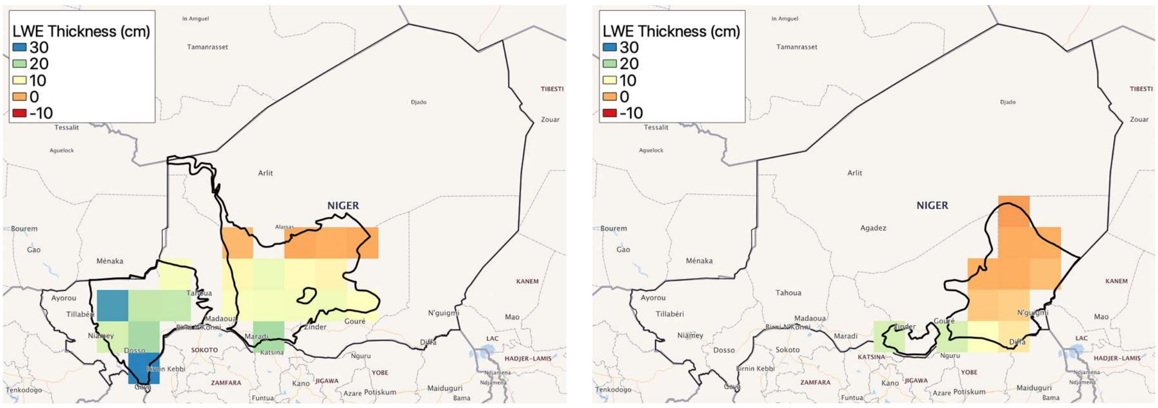


Figure 8. Conceptual diagram of the two approaches of the WTF method to show the groundwater storage anomaly (GWSa) from 01/2007 to 06/2008 in the Iullemeden basin (modified from Wu, et al. [60].

4. Results

4.1. 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 of the 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 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 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). The 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 [5].

4.1.1. Iullemeden Basin Aquifer Cumulative Storage Change

Figure 10 shows the GWS anomalies in liquid water in an 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.

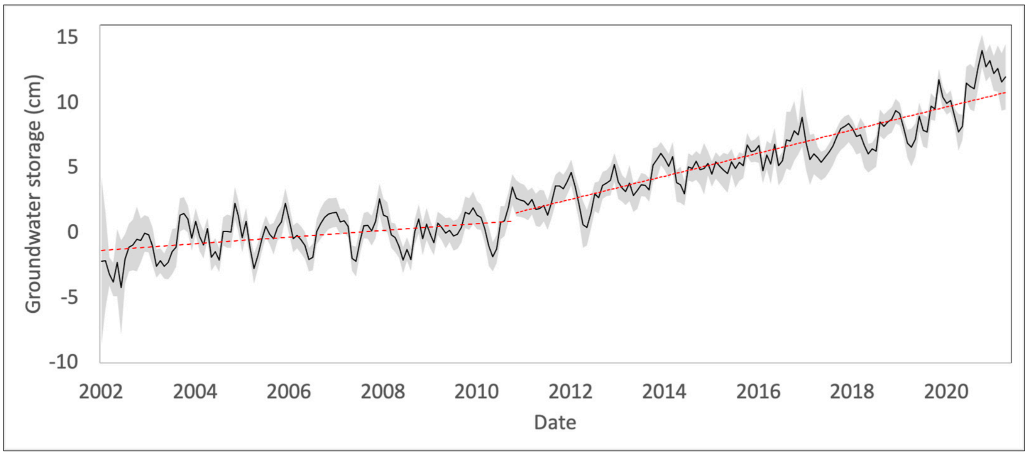


Figure 10. Groundwater storage anomalies in the Iullemeden basin region.

Figure 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 years, resulting in a net gain of approximately 3000 MCM or 3 KM^3.

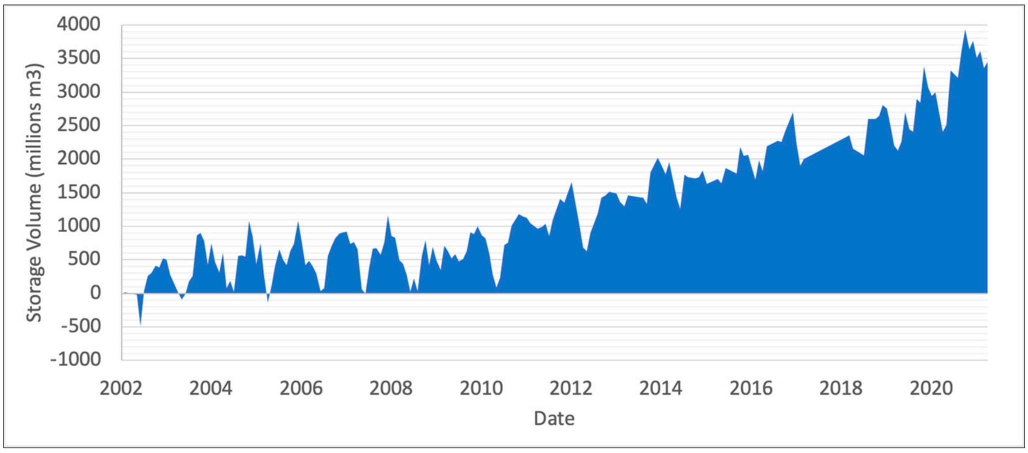


Figure 11. Volumetric storage change in the Iullemeden basin region.

4.1.2. Chad Basin Aquifers Cumulative Storage Change

For the aquifers in the Chad Basin, the results are similar but less pronounced (Figure 12). We observed a slight decrease in the GWSa for 2002–2011 and an increase for 2011–2020. The average value indicates a net gain in groundwater storage over the entire time range.

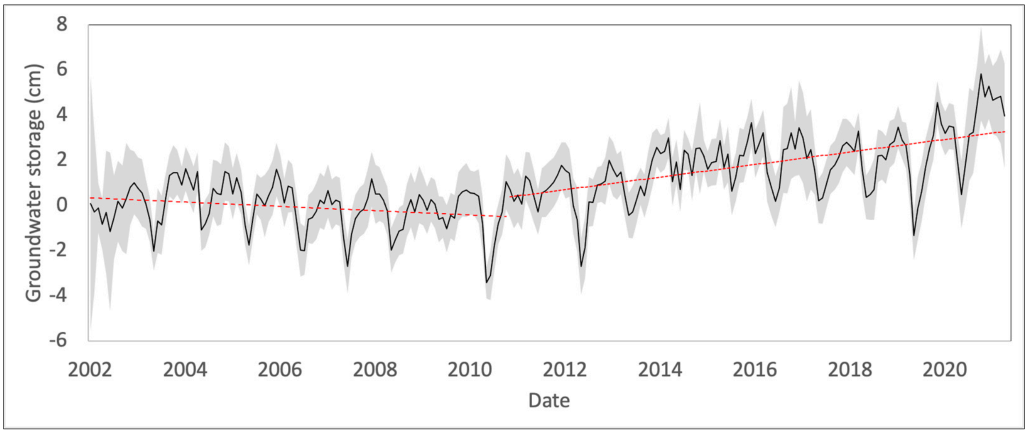


Figure 12. Groundwater storage anomaly change in the Chad basin region.

Finally, Figure 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.

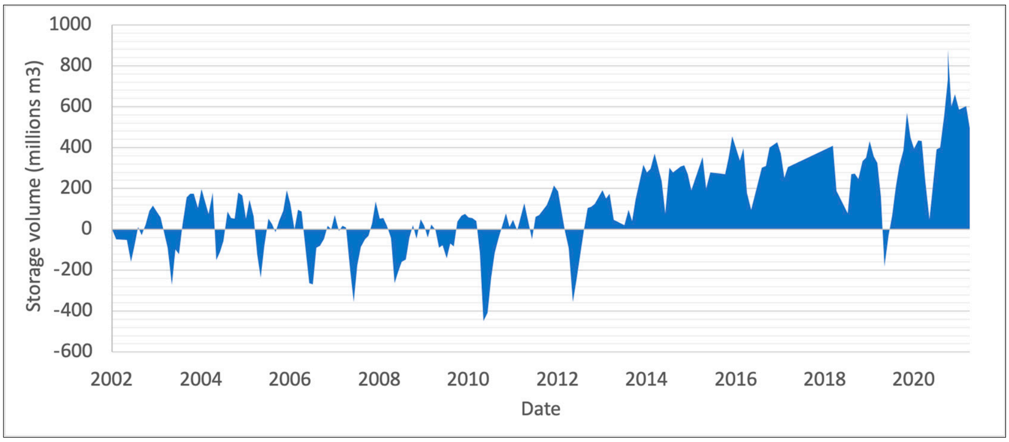


Figure 13. Cumulative groundwater storage change in the Chad basin region.

4.2. Uncertainty of Storage Change Estimates

The groundwater storage change estimates illustrated in Figures 10–13 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 Figures 10 and 12.

There is an additional source of uncertainty in these estimates due to a well-documented phenomenon called "leakage" [9,99,100]. 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.

4.3. 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. [101]. 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 Figures 14 and 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.

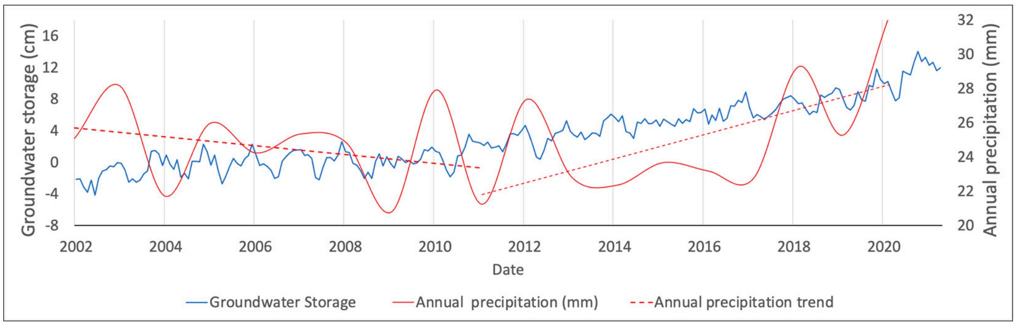


Figure 14. Groundwater storage (cm) and observed average annual precipitation (mm) of the Iullemeden basin.

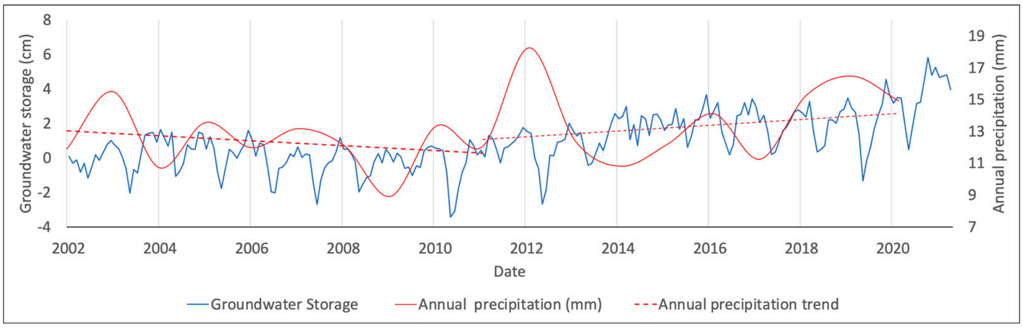


Figure 15. Groundwater storage (cm) and observed average annual precipitation (mm) of the Chad Basin.

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 months 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.

4.4. 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, Figures 10 and 12 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 16.

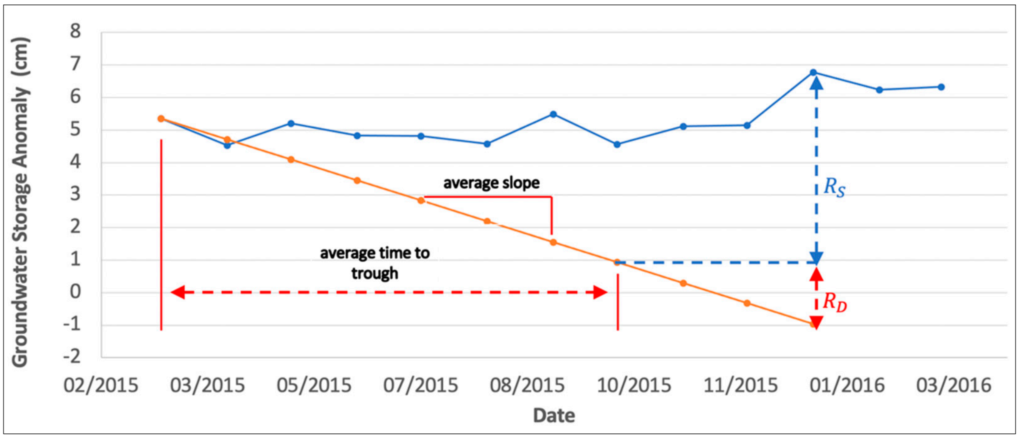


Figure 16. 2015/02 to 2016/03 in the Iullemeden basin.

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/year and 7.32 cm/year 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.

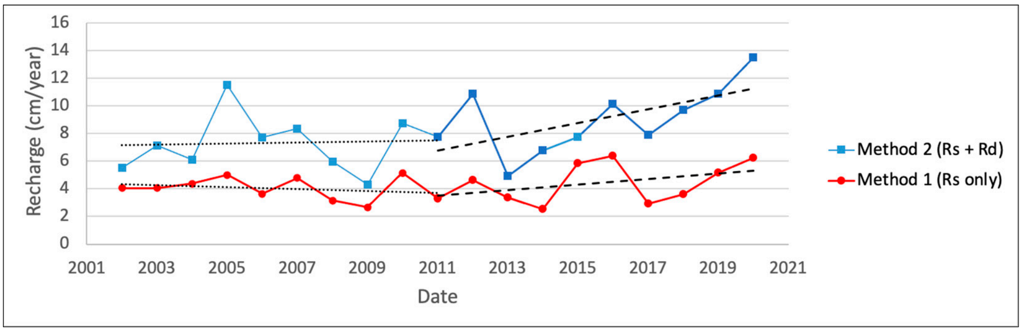


Figure 17. Estimated recharge values in the Iullemeden basins.

For the Chad aquifers, the derived recharge rates exhibit a similar pattern (Figure 18). There was a relatively constant recharge from 2002 to 2011 and an 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 in the Chad basin, which correlates to the higher groundwater storage gains observed in the Iullemeden basin.

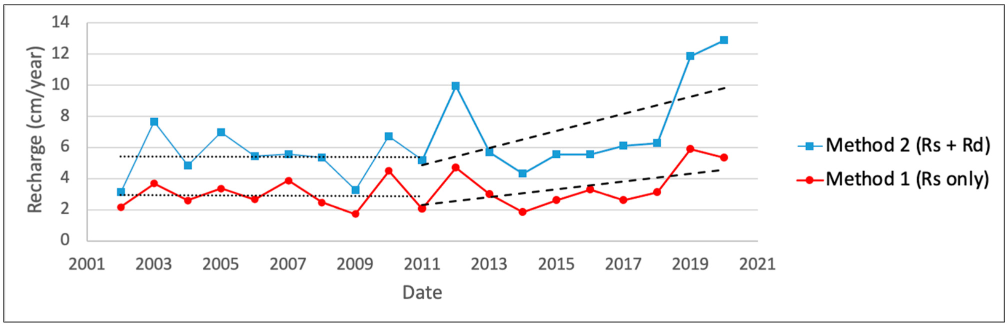


Figure 18. Estimated recharge values in the Chad basins.

Table 1 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. [102] and Leduc et al. [103] whom 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. [103] and by Favreau et al. [104] using ^{14}C and ^{3}H, and by Bromley et al. [105] 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 to 2021, we would expect the recharge rates we computed in the region to be higher than those from the literature.

Table 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. [105]	Southwest Niger	CMB (Chloride mass balance)	1992	1.3
Leduc et al. [67]	Southern Niger	WTF	1991	5 to 6
Leduc et al. [104] and Favreau et al. [104]	Southwest Niger	Radioisotopes (^{14}C and ^{3}H)	1950s–2000s	0.1 to 0.5
Leduc et al. [103]	Southwest Niger	WTF	1990s–2000s	2 to 5
Vouillamoz et al. [102]	Southwest Niger	WTF	1990s–2000s	2 to 5

5. 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 to 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 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 changes 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 compared the estimates we computed with those from other studies in the region and found that groundwater recharge calculated other methods such as CMD, ^{14}C, and ^{3}H 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. [102], 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.

Author Contributions: Conceptualization, G.P.W. and N.L.J.; methodology, G.P.W. and S.T.P.; software, G.P.W. and S.T.P.; investigation, S.A.B., J.L.S. and B.M.; N.L.J. and B.M.; data curation, S.A.B., J.L.S., S.T.P. and B.M.; writing—original draft preparation, G.P.W. and S.A.B.; writing—review and editing, G.P.W., N.L.J., S.A.B., S.T.P., B.M. and J.L.S.; supervision, B.M. and N.L.J.; project administration, B.M. and N.L.J.; funding acquisition, N.L.J. and G.P.W. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

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

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