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Article

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

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Abstract: Groundwater modeling is a useful tool for assessing sustainability in water resources planning. However, groundwater models are difficult to construct in regions with limited data availability. We illustrated how remote sensing data can be used leverage limited in situ data to build and calibrate a regional groundwater model in the Goulbi Maradi alluvial aquifer in Southern Niger in Western Africa. We used data from the NASA Gravity Recovery and Climate Experiment (GRACE) satellite mission to estimate recharge rates, the primary source of water to the aquifer. Additionally, we incorporated groundwater storage changes obtained from GRACE data from 2009 to 2021 to establish an overall water budget from which we could back-calculate groundwater withdrawals from pumping in the region. This approach allowed us to calibrate the model and then convert it to a predictive tool to analyze the impact of various assumptions about future recharge and groundwater extraction patterns associated with the development of groundwater infrastruction in the region. The results indicate that the Goulbi Maradi alluvial aquifer is sustainable, even an increase of groundwater extraction up to 28%.

Keywords: Groundwater Modeling; MODFLOW; West Africa; GRACE; sustainability

1. Introduction

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 (**Error! Reference source not found.**). This region is important due to its relatively high population density, ranging from 81 to 105 individuals per square kilometer [1]. The inhabitants rely heavily on rain-fed crops, including sorghum, millet, and cowpeas, as well as animal husbandry for their livelihoods [2,3]. However, these activities have experienced reduced productivity as a result of climate change [2,4], leading to food shortages during dry years [2]. Occasional heavy rains between July to August can result in loss of property, crops, and livestock and occasional deaths [5].

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 [6–8]. 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 [9–11].

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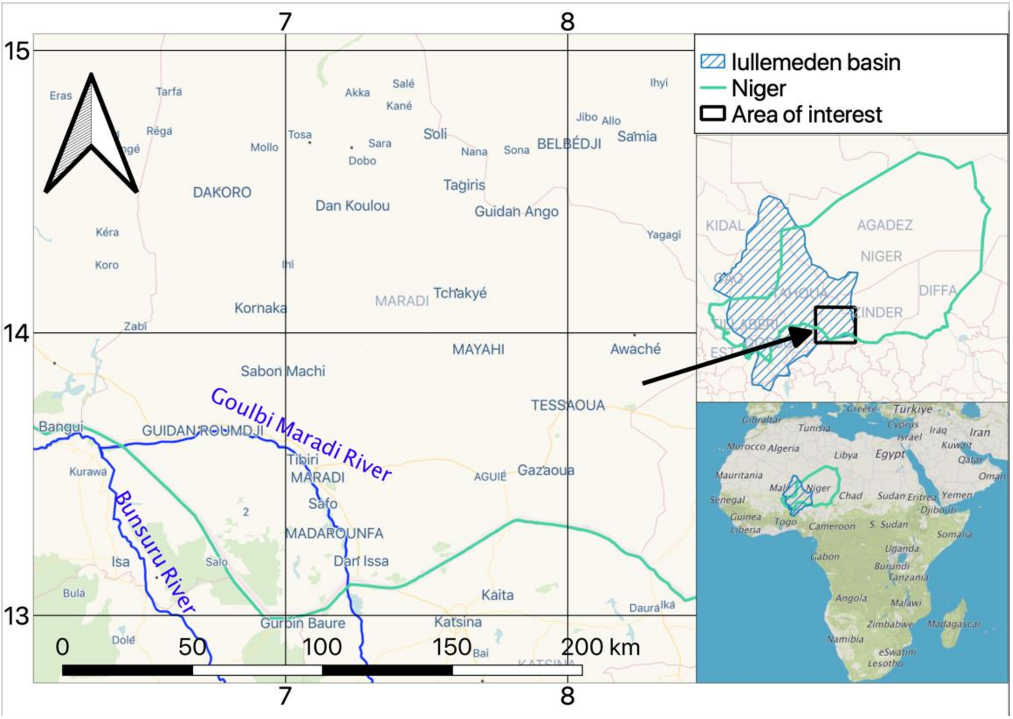

Figure 1. Map of the Goulbi Maradi Region in South Niger.

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 [2].

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 [2].

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 [12]. 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 [2].

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 [13]. 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 [2].

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. [7] 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 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

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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 [14] developed a hydrogeological model for the Iullemeden Aquifer System (IAS) in Niger, Mali, and Nigeria with the goal of improving the assessment of water resources within the aquifer system and identifying hydrogeological risks. They found that withdrawals from the aquifer system have been increasing since the mid-1990s at rates surpassing the available resources. Their simulations suggested 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. [15] 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. [16] used Gravity Recovery and Climate Experiment (GRACE), altimetry, and MODIS satellite data to track different water storage components, including total water storage, reservoir storage, and vegetation indices. The study 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. [17] 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.

1.4. Objective

The objective of this study is to develop a 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.

2. Data

2.1. Well Data

We used data from a well database maintained by the Hydraulic Departmental Direction of Madarounfa in Maradi Niger (**Error! Reference source not found.**). 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.

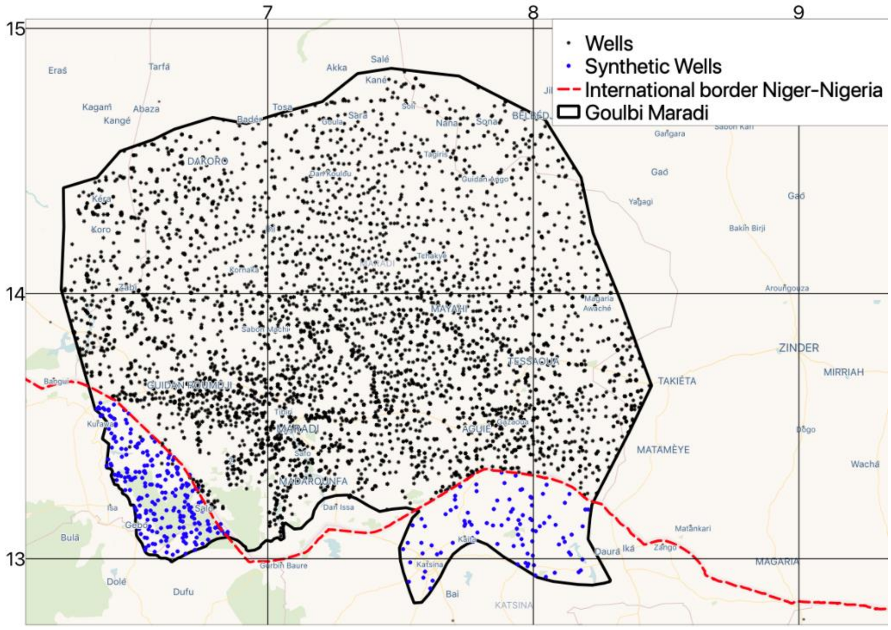

Figure 2. Well Locations in the Goulbi Maradi Aquifer.

2.2. Boheholes

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° (**Error! Reference source not found.**). 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.

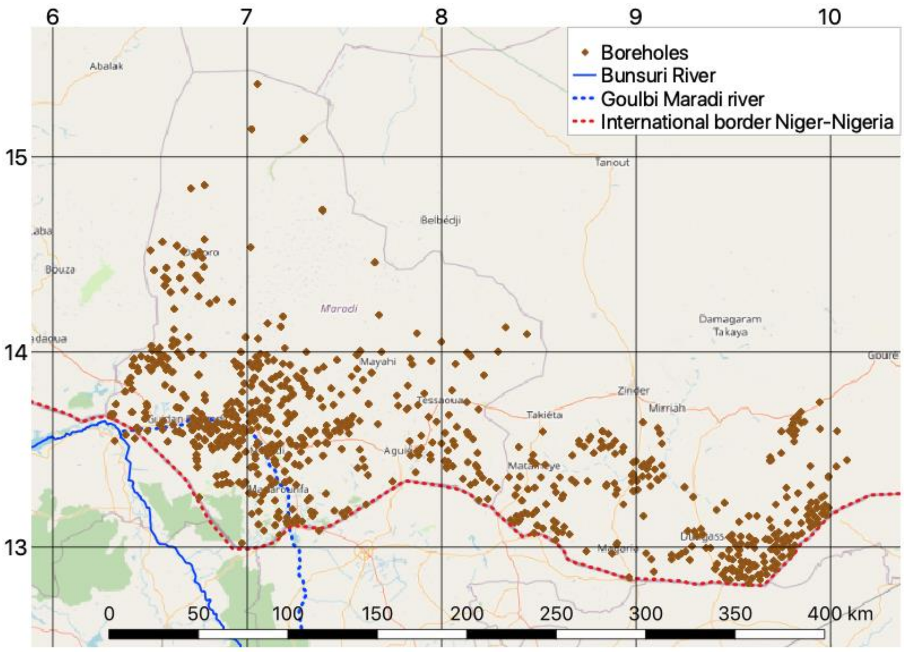

Figure 3. Boreholes Located in Goulbi Maradi and Korama Region.

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

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subsequent GRACE Follow On (GRACE FO) mission, initiated in May 2018, continues to provide monthly gravitational anomaly data to the present [19,20].

The distance between these satellites varies in response to fluctuations in the Earth's gravitational field [21–23]. Precise measurements of these distance changes, are used to quantify gravitational anomalies, indicating variations in mass [22]. 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 [24].

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 [25]. GRACE data have been used for various applications, such as flood studies [26–30], drought studies [31–36] and general hydrologic investigations focusing on regional water storage and trends [37–39]. Recent research has demonstrated the use of GRACE data for monitoring variations in groundwater storage [40–44] including variations in groundwater depletion in arid and semi-arid regions [15,45,46].

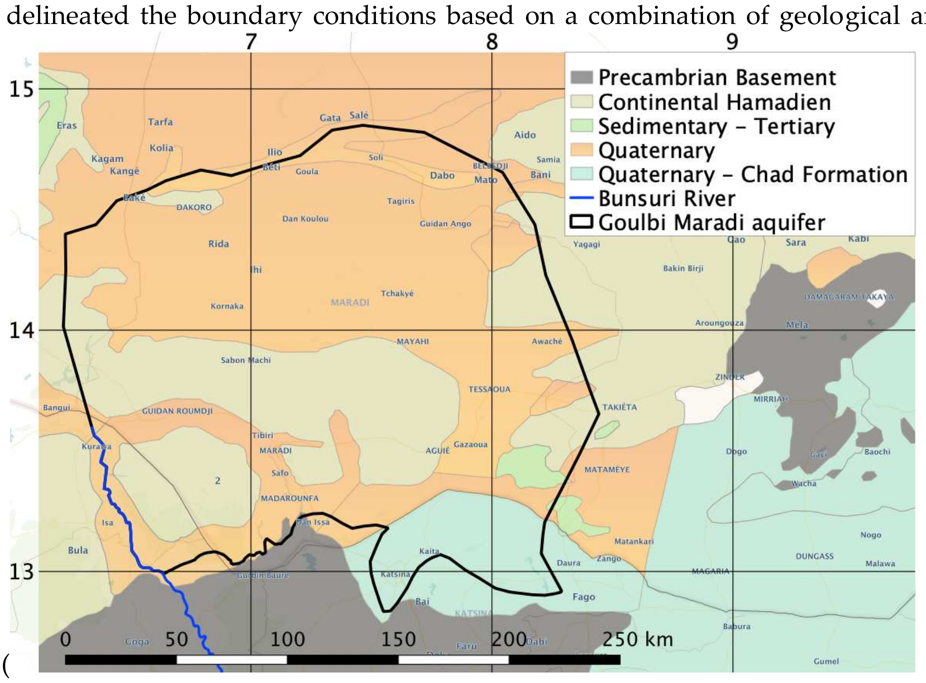
3. Methods

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.

3.1.1. Boundary Conditions

We delineated the boundary conditions based on a combination of geological and hydraulic features (



).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.

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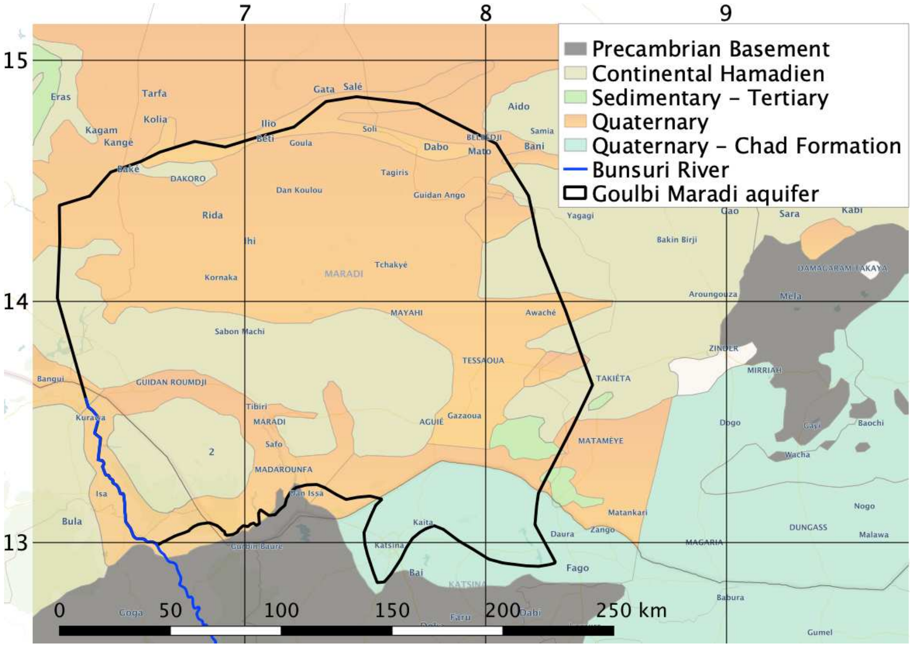
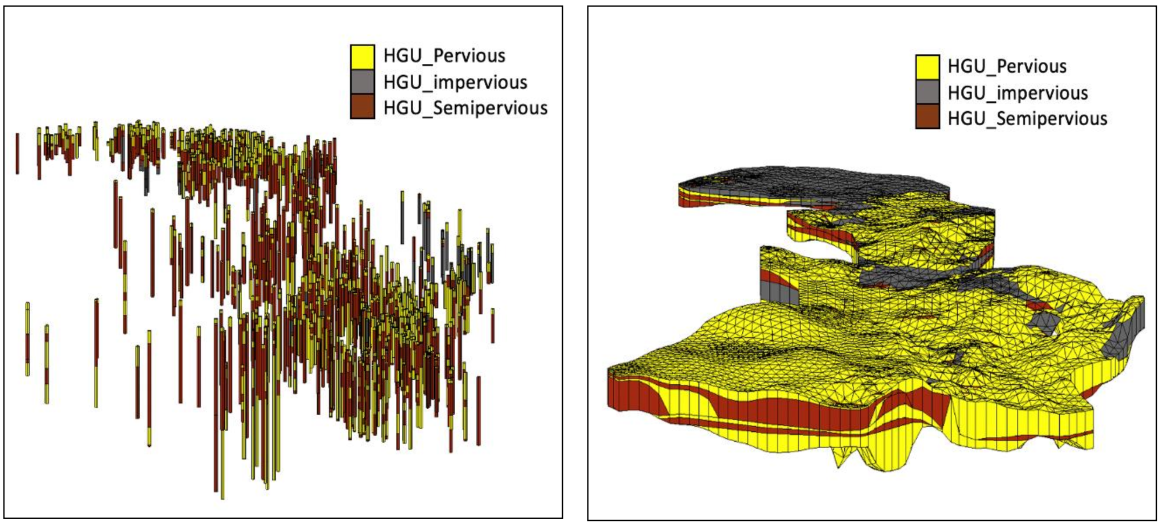


Figure 4. Boundary Conditions in the Goulbi Maradi Aquifer.

3.1.2. Hydrostratigraphy

We used the borehole data described above and applied a "horizons to solids" geometric algorithm described by Lemon & Jones [47] 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 (**Error! Reference source not found.**). We classified the 30 materials into three main hydrogeologic units (HGU's) corresponding to pervious, impervious, and semipervious units.



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

Figure 5. (a) 3D Representation of Borehole Logs (b) Solids Generated by the Horizons-to-Solids Algorithm.

3.1.3. 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:

$$\Delta storage = (inflows - outflows) \quad (1)$$

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

$$\Delta_{storage} = (Recharge + River_{in}) - (River_{out} + ET + Q_{wells}) \quad (2)$$

where:

$D_{storage}$	=	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 (Dstorage). 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, which can be used to derive estimates of changes in groundwater storage [40,42,48,49]. 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 total water storage anomaly (TWSa) [15,40,44,48–59]. For this study, we used data from the NASA's Global Land Data Assimilation System (GLDAS) model for snow water equivalent (SWE), plant canopy (CAN), and soil moisture (SM). We used the GRACE Groundwater Subsetting Tool (GGST) to compute groundwater storage changes [40]. GGST converts the GLDAS data to an anomaly format to obtain SWEa, CANa, and SMa, and then computes the groundwater storage anomaly using Equation 3 [15].

$$GWSa = TWSa - (SWEa + CANa + SMa) \quad (3)$$

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 water to the aquifer is recharge resulting from precipitation. Recharge is notoriously difficult to estimate. It can be estimated with field tests [60], 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 spatial and temporal distribution of recharge [61]. Barbosa et al. [15] and Wu et al. [60] 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 [62] [63].

We estimated groundwater recharge values using the WTF method, which analyzes the seasonal changes in piezometric head at monitoring wells or within the aquifer [62,63]. 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:

$$R = S_y \left(\frac{\Delta h}{\Delta t}\right) \quad (4)$$

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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 [62]. 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 **Error! Reference source not found.**.

Using the WTF approach, 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) [15]. 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) [15].

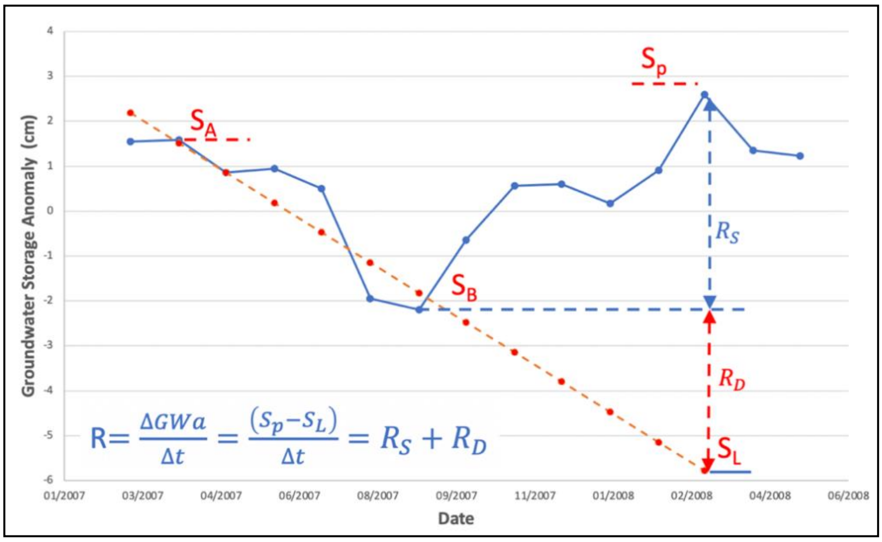

Figure 6. Conceptual Diagram of the Two Approaches of the WTF Method.

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 (**Error! Reference source not found.**). 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 [64,65]. 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.

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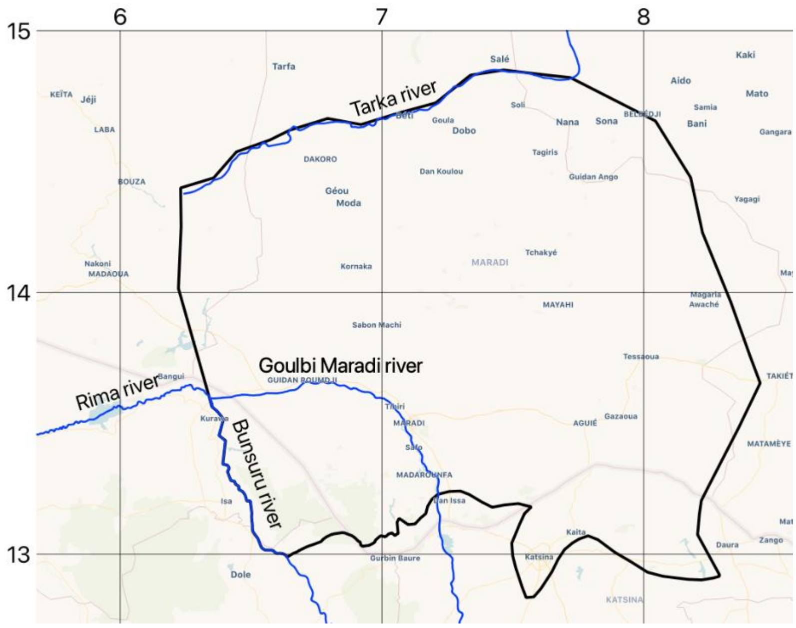

Figure 7. Rivers Located in the Study Area.

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.,[66] 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 3. 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.

3.2. MODFLOW

From the conceptual model we developed a numerical groundwater model using the 2005 version of MODFLOW [67]. 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 [68].

4. Model Development

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 (**Error! Reference source not found.**) on a 1.0-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.

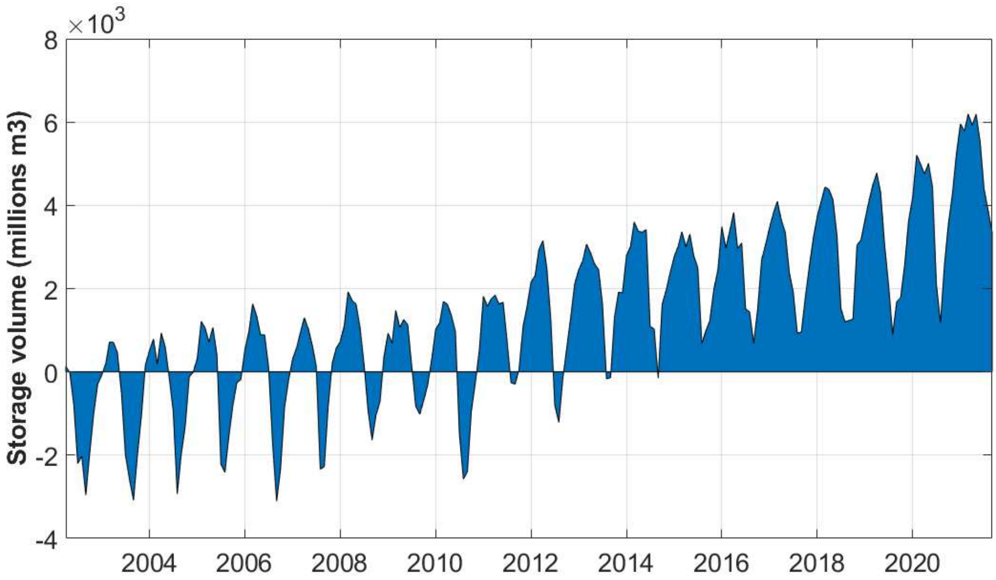

Figure 8. Storage Volume in Millions of Cubic Meters in the Goulbi Maradi Aquifer.

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 **Error! Reference source not found.**. 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 [15].

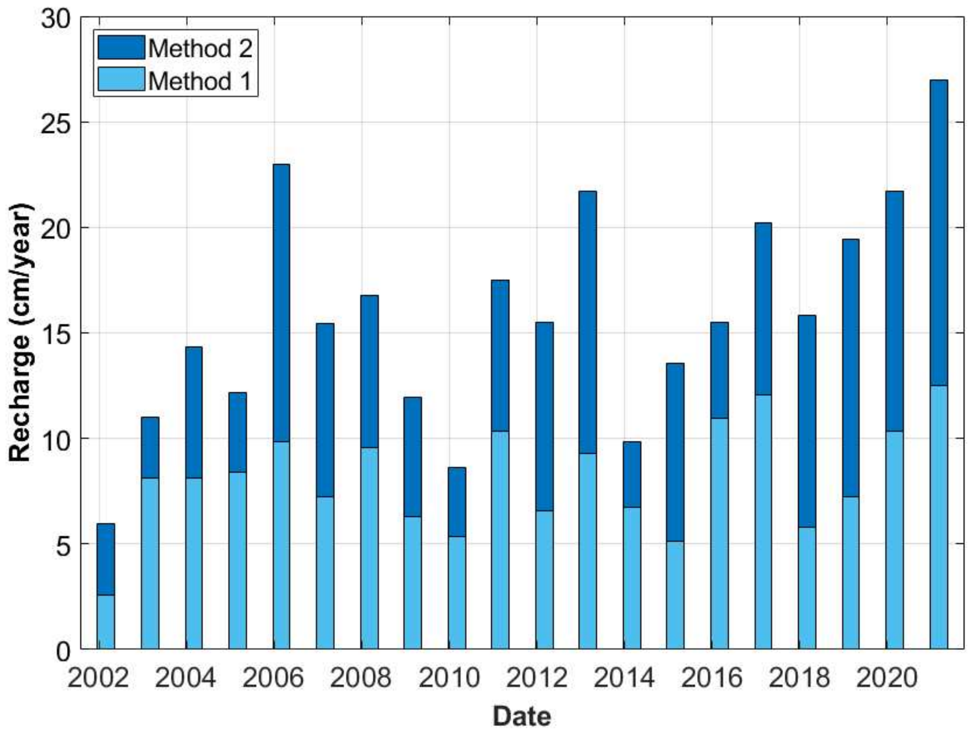

Figure 9. Annual Recharge Values Estimated by the WTF Method for the Iullemeden Basin.

4.3. Computational Grid

We identified two stratigraphically distinct layers by analyzing the borehole data (**Error! Reference source not found.**). 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 (**Error! Reference source not found.**).

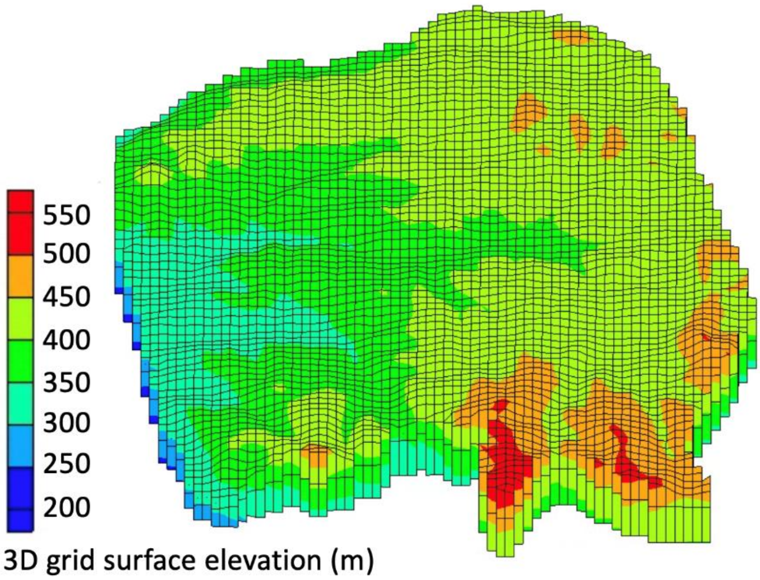

Figure 10. 3D Grid Representation of the Goulbi Maradi Aquifer.

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 a transient model encompassing 40 stress periods, with each stress period comprised of six timesteps, representing monthly time steps from 2002 to 2021. We performed both manual (trial and error) calibration and automated calibration using the PEST utility [69].

4.4.1. Parameters

We assumed recharge was zero during the dry half of the year and at the full rate during the wet period using a range of WTF-derived values (**Error! Reference source not found.**). 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 well 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.

4.4.2. 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 [70] 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.

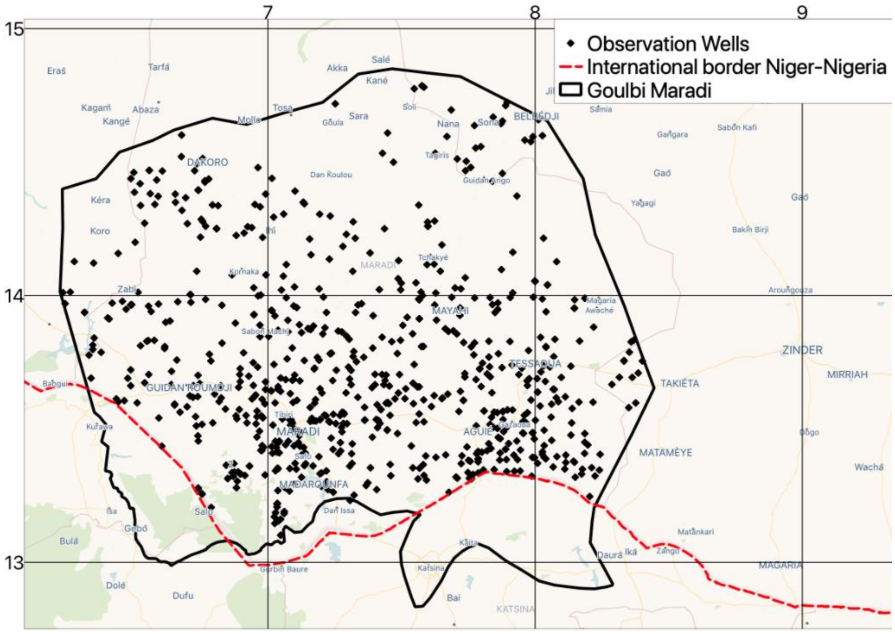

Figure 11. Observation Wells in the Goulbi Maradi Aquifer.

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-derived storage changes 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.

4.5. 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.

5. Results

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.

5.1.1. Optimized Parameter Values

The hydraulic conductivity values for our model of the Goulbi Maradi aquifer that resulted in the best calibration are presented in **Error! Reference source not found.**. The majority of the zones have conductivity values below 40 m/day, indicating the presence of semi-pervious very fine sand materials [71]. 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.

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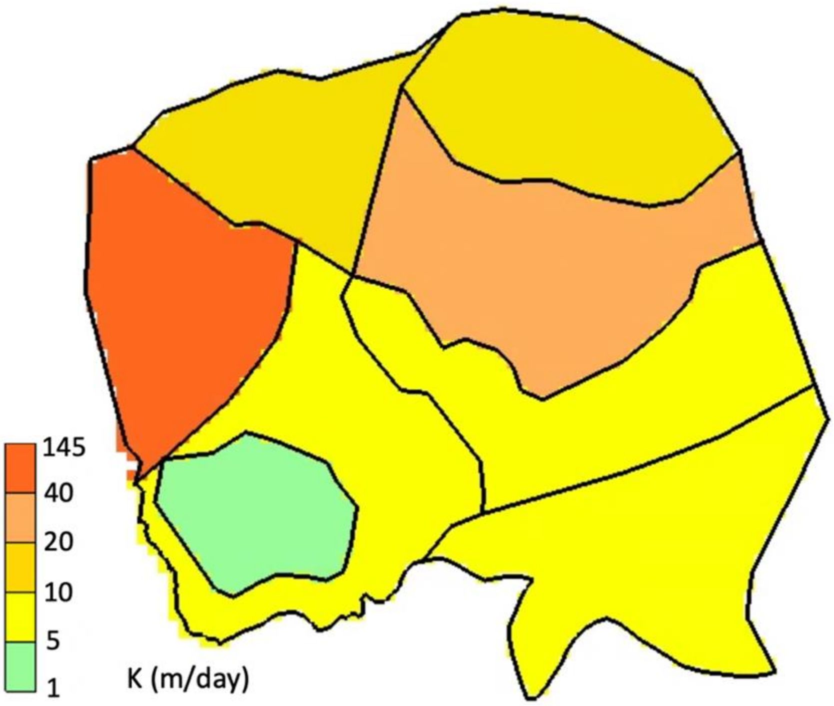

Figure 12. Estimated Hydraulic Conductivity (m/day).

The estimated recharge values based on the best fit to the data are shown in **Error! Reference source not found.**. 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.

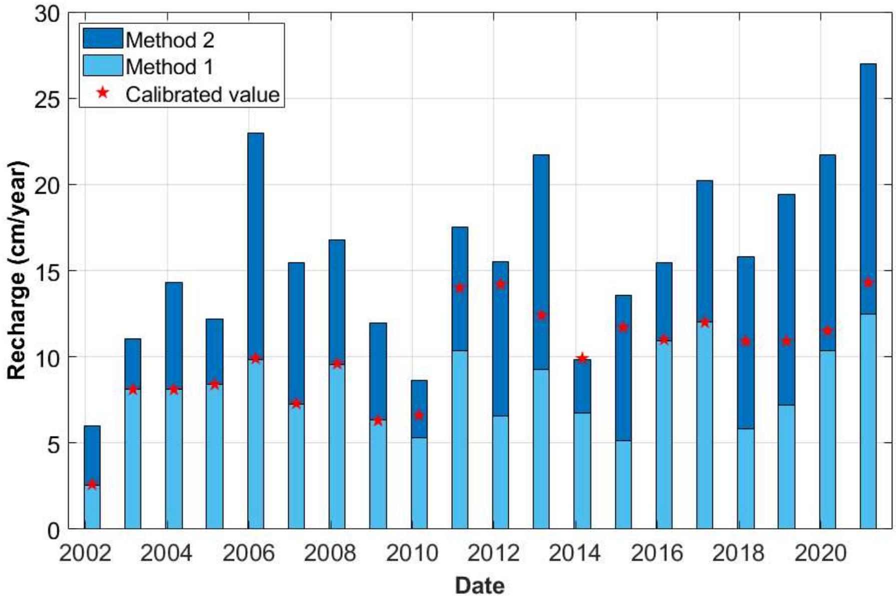

Figure 13. Optimized Recharge Values.

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

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5.1.2. 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: root mean square error (RMSE), mean error (ME), and mean absolute error (MAE) [72,73]. 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. **Error! Reference source not found.** 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.

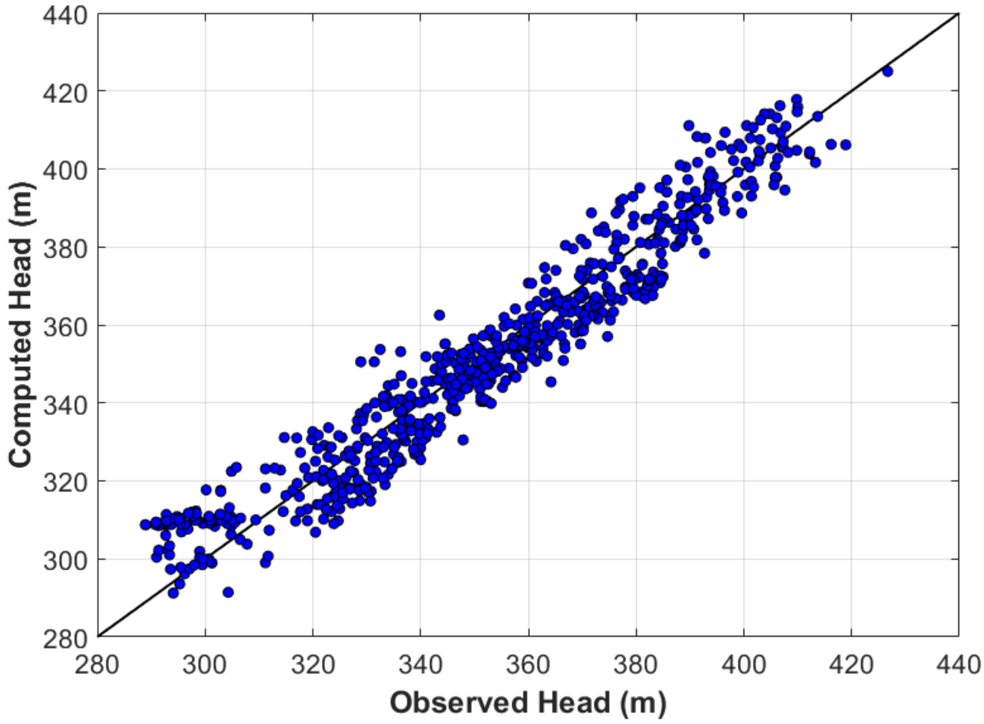

Figure 14. Simulated vs. Observed Head Values in the Goulbi Maradi Aquifer.

5.1.3. Storage Changes

Error! Reference source not found. 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.

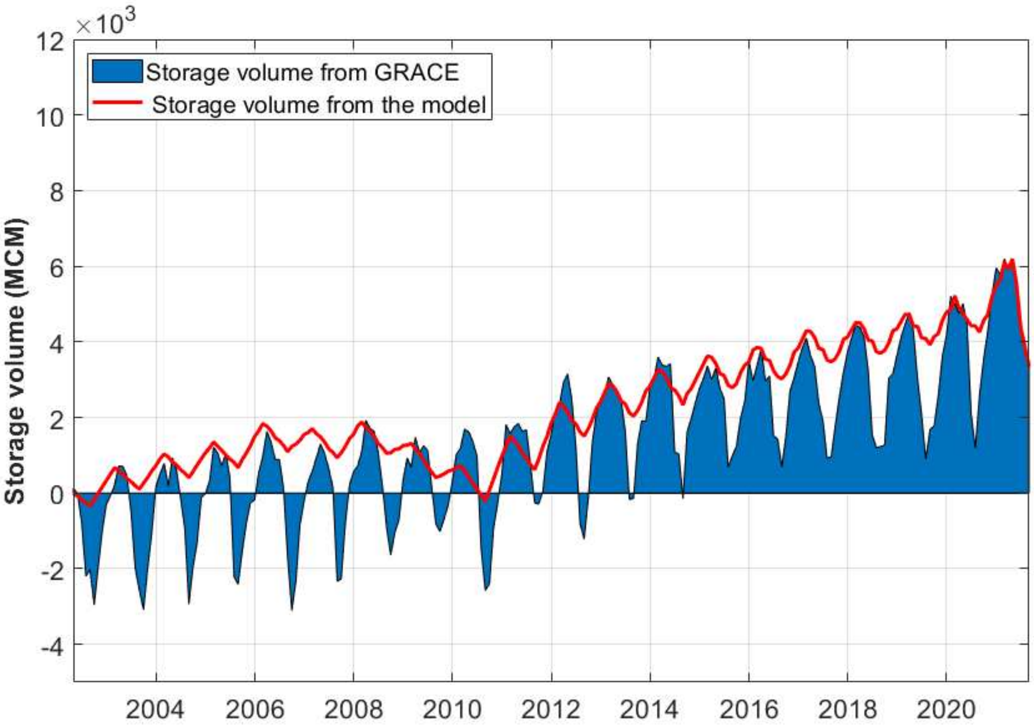

Figure 15. Simulated vs. Observed Groundwater Storage Changes in the Goulbi Maradi Aquifer.

5.2. Predictive model

Following successful calibration, we used the model to predict changes 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 evaluated percentage increases in pumping over the current rates. 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.

5.2.1. 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 assumption. Using this recharge rate, we ran the model iteratively to determine a pumping rate that resulted in a stable water balance.

Error! Reference source not found. 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.

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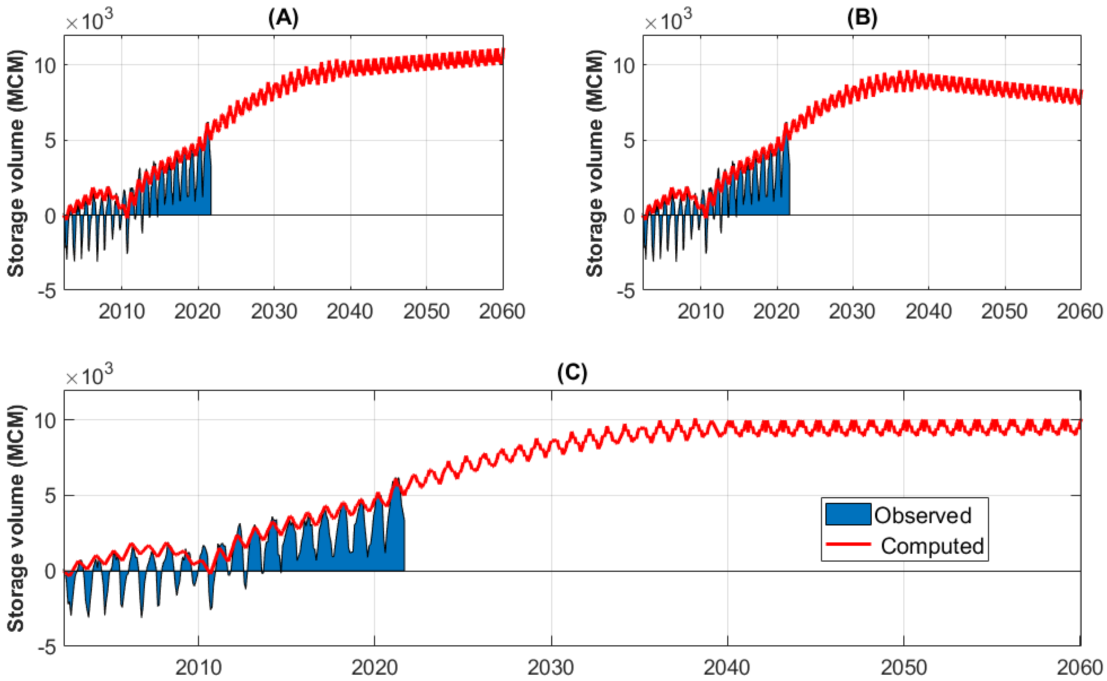

Figure 16. Simulated vs. Observed Groundwater Storage Changes in the Goulbi Maradi Aquifer Using the Last 5 Years Average Recharge Value, with a 20%, 30%, and 22% increase in pumping for Panels A, B, and C, respectively.

5.2.2. Scenario 2: 10-year Average Recharge

For scenario 2, we projected the average recharge rate determined over the last 10 years of the calibration phase into the future. Figure 19 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.

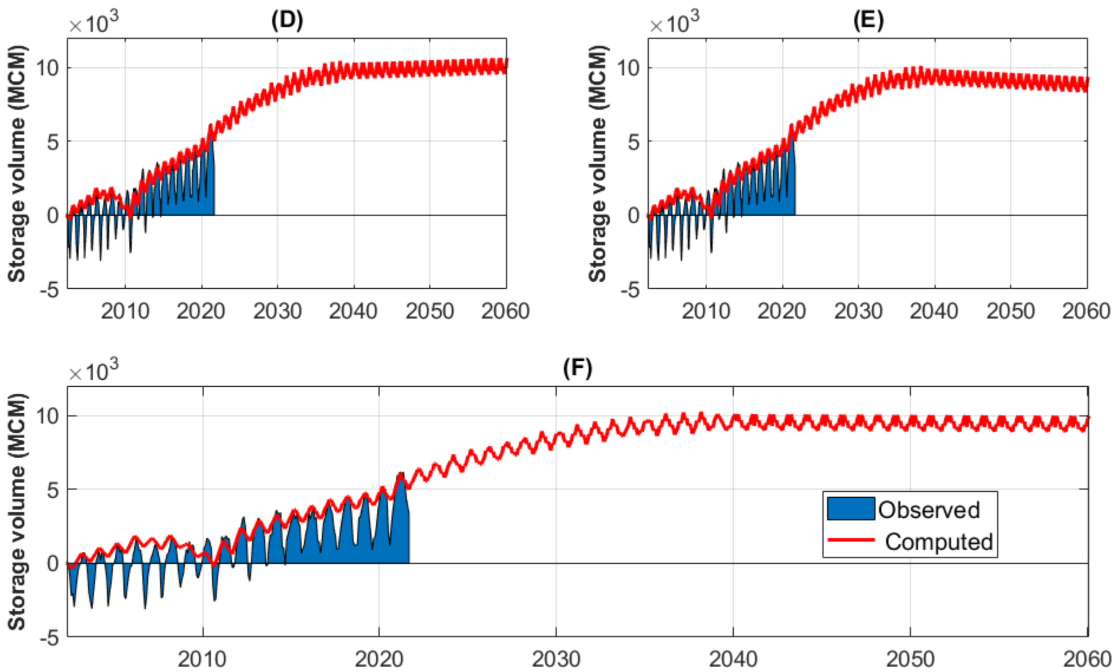

Figure 17. Simulated vs. Observed Groundwater Storage Changes in the Goulbi Maradi Aquifer Using the Last 10 Years Average Recharge Value, with a 20%, 25%, and 24% increase in pumping for Panels A, B, and C, respectively.

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5.2.3. Scenario 3: 20-year Average Recharge

For our third scenario 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 for the next 20 years, 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.

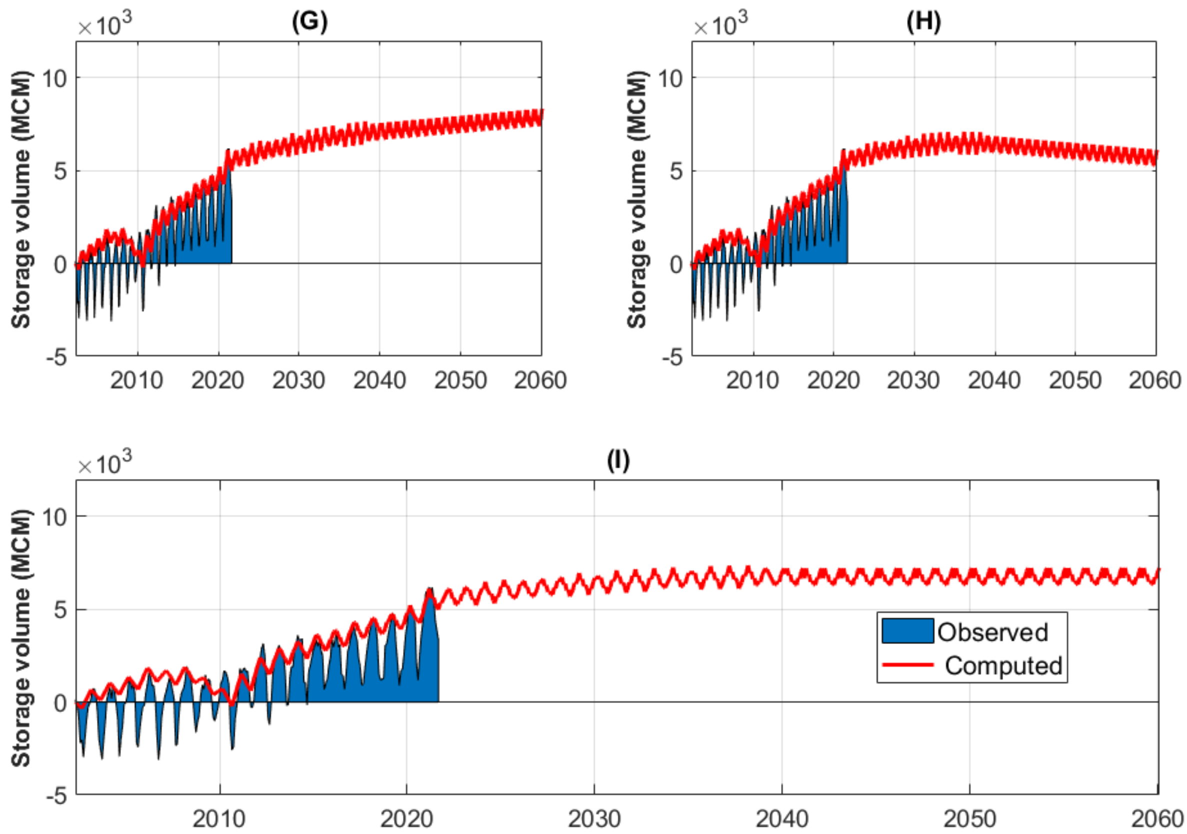

Figure 18. Simulated vs. Observed Groundwater Storage Changes in the Goulbi Maradi Aquifer Using the Last 20 Years Average Recharge Value, with a 5%, 10%, and 7% increase in pumping for Panels A, B, and C, respectively.

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.

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Data Availability Statement: The MODFLOW model files generated in this study are accessible for download at the following link: https://ggst.readthedocs.io/en/latest/. This site also provides comprehensive, step-by-step instructions for adjusting the model inputs to facilitate predictive simulations with diverse assumptions concerning recharge and pumping rates.

Conflicts of Interest: The authors declare no conflict of interest.

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