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# Estimation of Groundwater Storage Change and Groundwater Recharge Using GRACE data in Jedeb Watershed Under the Application of Google Earth Engine

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**ABSTRACT:** Over exploitation of Ground Water (GW) has resulted in lowering of water table in the Jedeb watershed. In this study, water storage changes with GRACE satellite data and total annual precipitation with CHIRPS data in the Google Earth Engine system were investigated for the Jedeb watershed during 2003–2017. The groundwater recharge is estimated from a time series of groundwater storage using the water table fluctuation method. According to the results obtained from the GRACE satellite data on the fluctuations of annual water storage between 2003 and 2017, it was found that the biggest annual increase in water levels (15 cm) occurred in 2008, 2013, and 2015, and the biggest annual decrease (12.5 cm) occurred in 2012. The obtained net recharge rate varied from 18 to 25 cm/year for a 14-year period, and the average was 21 cm/year. This study indicates that the GRACE-based estimation of groundwater storage changes is skilled enough to provide monthly updates on the trend of groundwater storage changes for resource managers and policymakers in the Jedeb watershed.

**KEYWORDS:** GRACE, groundwater storage, CHIRPS, Google Earth Engine, water table fluctuation

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## Introduction

The management of groundwater is essential for maintaining livelihoods because communities all over the world depend on it for everything from drinking water to irrigation (Pulla et al., 2023). Collecting water levels in wells is the most popular method of groundwater resource monitoring (Pulla et al., 2023). The complexity of data collection, sample well site frequency, and other factors make this task difficult even at the aquifer scale, and it becomes significantly more so when viewed regionally. Moreover, a number of factors, including contamination, salinization, climate change, and fast groundwater depletion, are placing severe strain on groundwater supplies in many parts of the world (Liu et al., 2021). Groundwater levels are steadily dropping as a result of excessive extraction and lowered water quality. Aquifer depletion brought on by overexploitation of groundwater has resulted in environmental and geological issues such as land subsidence and wetland damage (Liu et al., 2021; Raza et al., 2019; Seo & Lee, 2016). Developing countries with inadequate infrastructure and training increase these problems even further.

The amount of water that is held in reserve in the aquifer during recharge and outflow is referred to as groundwater storage. Around the world, in arid and semi-arid areas, groundwater storage plays a major role in contributing to TWS (Barbosa et al., 2022; Raza et al., 2019; Seo & Lee, 2016). Depending on the physiographic composition of the basin, the water uses a variety of indirect or direct channels to enter (recharge) and exit (discharge) the groundwater storage. The extra water drains under the force of gravity and enters the groundwater system after the soil moisture is saturated. The aquifer system's recharge and discharge differences over time produce a net gain or deficit in groundwater storage. Groundwater storage rises when recharge exceeds discharge, while groundwater storage decreases when recharge falls short of discharge.

The inability to measure recharge and outflow directly presents the biggest obstacle to calculating changes in groundwater storage. Due to the vast area and lack of hydrological data, it is challenging to evaluate changes in groundwater level and water storage using conventional methods (Shami & Ghorbani, 2019). Using remote sensing technology and satellite observation that can gather data over a large geographic region at both a spatial and temporal resolution, it is possible to monitor and analyze changes in groundwater levels and water storage (Shami & Ghorbani, 2019).

In the downscaling literature, a variety of statistical methods have been used and evaluated. These techniques include Markov chains, empirical and statistical regression models, classification-based methods, and correlative relation methods (Eshagh et al., 2023). For downscaling GRACE observations, machine learning methods including as random forests, support vector machines, artificial neural networks, and multiple linear regression models have been widely used in statistical inversion in recent years (Eshagh et al., 2023). However, statistical techniques require the availability of extensive datasets and depend on assumptions that the dynamics of the system being examined are accurately captured by the observed data and small-scale information and that these dynamics hold true for the duration of the observation period (Eshagh et al., 2023).

The water balance method, hydrological modeling, and in situ observations (such as groundwater level) are examples of the traditional methods for calculating GWS changes (Pulla et al., 2023; Seo & Lee, 2016). Despite the fact that these techniques have been applied in numerous earlier research, they are limited by real-world application conditions like the uneven distribution of observation wells. As a result, fulfilling the demands for timely and dependable managed groundwater resources continues to be a significant worldwide concern. A new technique for downscaling GRACE data has gained popularity (Eshagh et al., 2023; Pulla et al., 2023). The satellites known as the Gravity Field Recovery and Climate Experiment (GRACE) were launched in March 2002 and have the ability to reflect changes in the Earth's gravitational field with a level of spatial and temporal resolution and accuracy never before seen (Barbosa et al., 2022; Raza et al., 2019). According to Liu et al. (2021), they offer a novel approach to the examination of regional water reserves and serve as a reliable tool for tracking alterations in extensive groundwater reserves. The GRACE satellites are among the most sensitive remote sensing satellites available. They provide an estimate of the earth's gravity field, which allows for the establishment of a link between changes in water level and monthly variations in the earth's gravity field (Shami & Ghorbani, 2019). The initial satellite designed to assess subsurface water reservoirs and humidity under various conditions was the Gravity Recovery and Climate Experiment (GRACE) satellite (Mehdi et al., 2021). Utilizing the GRACE satellite data offers the main advantage of being able to spatially quantify the amount of water storage that exists around the globe.

This work aims to address several limitations identified in earlier research. In this study, water storage changes with GRACE satellite data and total annual precipitation with CHIRPS data in the Google Earth Engine system were investigated. GEE has shown itself to be a developing online platform with easy management capabilities for large satellite data. Moreover, GEE is regarded as an interdisciplinary instrument with numerous applications across different fields of study. Furthermore, this research offers conclusions and recommendations for future projects that employ this methodology. In addition, it aims to support scholars in comprehending the developments in this area, recognizing suggested works, and coming up with novel applications in the future. The novelty of this work is to establish that all the codes were developed through GEE for simplicity, ease of use, and shareability. We used the extremely effective computing capabilities of GEE, which is free for non-commercial, educational, and research purposes, to obtain the groundwater storage data (Pulla et al., 2023).

One important connection between surface water and groundwater is groundwater recharge (Wu et al., 2019). In addition to replenishing groundwater reserves, recharge water also transports solutes from higher strata that may contaminate groundwater. Therefore, groundwater recharge affects the quantity and quality of groundwater. Thus, precise estimations of groundwater recharge are necessary for the sustainable management of aquifers (Jeon et al., 2019; Wu et al., 2019).

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 (Barbosa et al., 2022; Jeon et al., 2019). 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 (Barbosa et al., 2022). 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 (Li et al., 2023).

However, these methods have disadvantages. The tritium method is not usable when the unsaturated zone is shallow (Hassen et al., 2021), and the CMB method requires a balance between the input and output of chloride concentrations from precipitation and underneath the root area, respectively. In the vadose zone, this equilibrium frequently takes years or decades to reach equilibrium, and in the saturated zone, it may take up to a century. This indicates that these methods are most helpful in areas where land use and climate have not changed dramatically in the recent past and only yield appropriate findings. Furthermore, these methods rely on in situ measurements and laboratory analysis, both of which are scarce in Ethiopia. An alternative method that does not require chemical data is the Water Table Fluctuation (WTF) method. In order to estimate episodic recharge based on variations in the groundwater table, WTF was created in the early 1920s (Yang et al., 2018). When analyzing seasonal variations in the aquifer's or monitoring wells' piezometric head, WTF classifies the increasing component of the yearly variability as recharge.

A few studies have been made to estimate groundwater recharge using the WTF method with water levels derived from GRACE data. For instance, Barbosa et al. (2022) estimated the groundwater storage anomaly and yearly groundwater recharge from 2002 to 2008 in Mali, Africa, using both GRACE and GLDAS data. These results were then compared to estimates produced via the WTF technique utilizing data from accessible observation wells. Mohamed and Gonçalvès (2021) 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 (2018) in the Nubian aquifer in Egypt. According to their findings, recharge only happens when Lake Nasser levels significantly rise and/or the area has an abundance of precipitation. Finally, Wu et al. (2019) calculated groundwater recharge in the Chinese Ordos

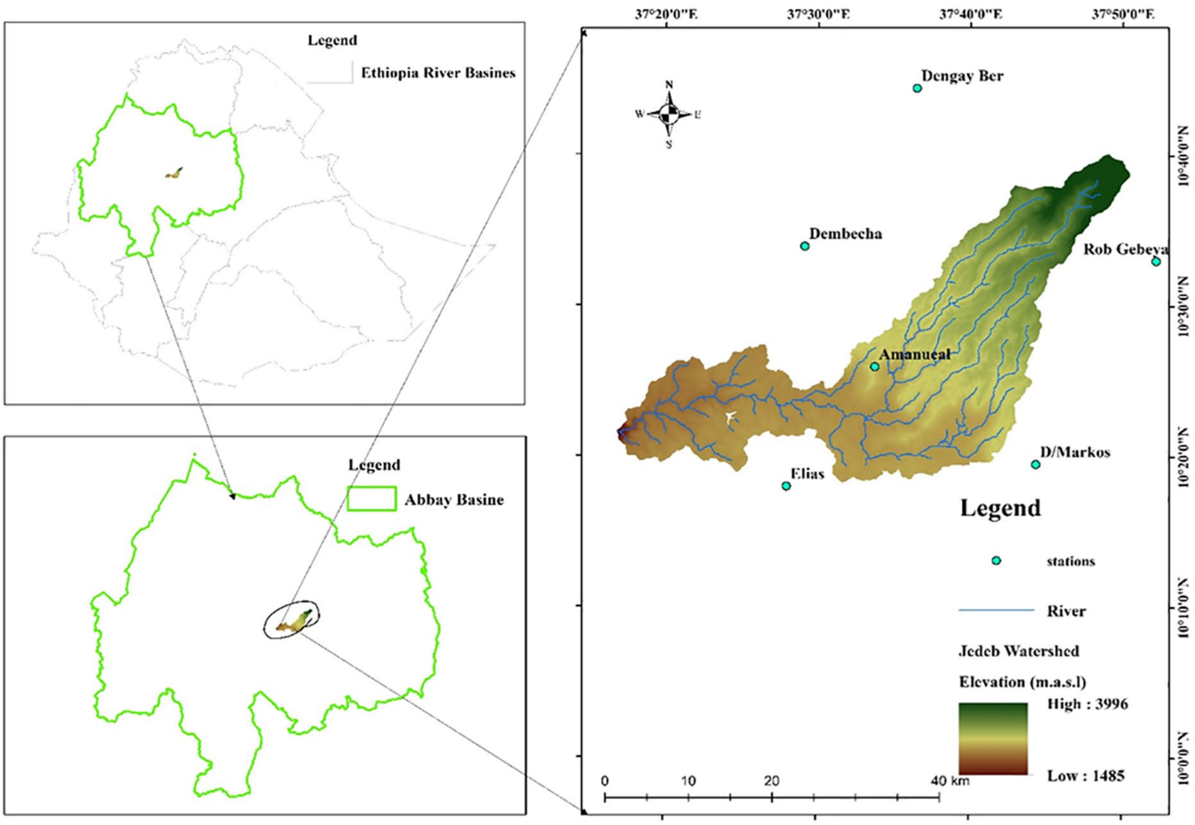

**Figure 1.** Location map of Jedeb watershed.

basin using the WTF approach using GRACE and GLDAS data. The findings showed that there was little difference between the groundwater recharge estimated by GRACE and the values determined using an environmental tracer.

Ethiopia, which has over 252 billion cubic meters (BCM) of water resources, is known as the "water tower of Africa" due to its profusion of rivers, lakes, and groundwater (Berhanu et al., 2024). However, Ethiopian groundwater quantity research revealed that no established amount is currently accessible. For instance, the preliminary water resources master plan study was conducted nationwide by the Ministry of Water Resources (MoWR) in Ethiopia (Woldegebriel et al., 2022), which assessed it at 2.6 BCM. Ethiopia's groundwater resource was estimated by a more recent study to be between 12 and 30 billion cubic meters, or even more (Kedir et al., 2021). These are indications that the amount of groundwater accessible in Ethiopia is not universally acknowledged.

The Jedeb watershed (study area), located in the Upper Blue Nile, has declining groundwater levels due to increased groundwater consumption in various sectors. Thus, lowering the groundwater table damages surface water resources by causing them to dry up and flow less freely, in addition to harming groundwater supplies. In this sense, careful integrated groundwater and surface water development and management sustainably depends on the long-term study of groundwater storage change and its variability (Berhanu et al., 2024). Therefore, the objective of this study is to evaluate the changes in groundwater storage (GWS) and recharge in the Jedeb watershed. The application of GRACE-derived data analysis in the Jedeb watershed under consideration will be the first of its kind in north Ethiopia catchments, and as such, the results of this work will help validate additional investigations conducted at the regional level. Furthermore, understanding the spatial and temporal changes in the GWS in the Jedeb watershed will inform policy for sustainable water resource management in an ecologically important and environmentally sensitive region.

## Materials and Methods

### *Study area*

Jedeb watershed is located in the East Gojjam zone of Amhara Regional State, northwestern Ethiopia. The watershed encompasses four districts: Sinen, Machakel, Debre Elias, and Gozamin. Jedeb watershed is about 20 km from Debre Markos and 320 km from Addis Ababa. It covers an area of 830 km$^2$. It is one of the tributaries of the Upper Abay River basin, and it is located in the northwestern highlands of Ethiopia, within 10°18′N to 10°39′N and 37°20′E to 37°53′E (Figure 1). The average elevation of the catchment ranges from 1485 to 3996 m above mean sea level, with an average annual temperature of 17°C. It is drained by a perennial river called the Jedeb River.

**Table 1.** Data Produced by CSR, GFZ, and JPL.

| NAME | UNITS | MIN | MAX | RESOLUTION |
|---|---|---|---|---|
| CSR | cm | –139.2 | 74.88 | Arc degree 1 |
| GFZ | cm | –145.4 | 70.19 | Arc degree 1 |
| JPL | cm | –137.9 | 71.86 | Arc degree 1 |

The Jedeb River originates from the Choke Mountains at an elevation of 4000 m a.s.l. and drains to the Abay/Blue Nile basin. The watershed receives about 70% of the annual rainfall in the summer (rainy) season (June, July, August, and September) and the remaining 30% in the winter (dry) season, from October to May. According to the Ethiopian geological survey, the lithologic units of the study area include Middle Yujbe basalts, Ignimbrite and tuff deposits, Debre Markos basalts, Lumame basalts, quaternary eluvial deposits, and others that fall in the choke shield volcano group like Rob Gebeya basalt, Arat Mekeraker basalt, and Kutye basalt (Teklebirhan et al., 2012).

### *Datasets*

For this study, the column-integrated water storage anomaly, including surface water, soil moisture, canopy, snow, and groundwater storage data in the Jedeb watershed between June 2003 and December 2017 in the unit of centimeters were obtained from the GRACE satellite. In this study, the following four solutions have been used: (1) GRCTellus Land RL06 release of GRACE data from CSR, JPL, and GFZ (available at https://grace.jpl.nasa.gov/data/get-data/monthly-mass-grids-land/; Alghafli et al., 2023; Jeon et al., 2019; Mehdi et al., 2021; Seo & Lee, 2016; Woldegebriel et al., 2022). The Center for Space Research at the University of Texas, Austin (CSR), GeoForschungs Zentrum Potsdam (GFZ), and Jet Propulsion Laboratory (JPL) provided the algorithms used in the development of the data in the Google Earth Engine (GEE). The information from each of the three centers utilized can differ because each institution generates data on its own. The CSR, GFZ, and JPL research institutes have created the Science Data System (SDS) for the GRACE project. The main function of the SDS is the processing of raw data from GRACE satellite. The raw data is referred to as level zero (L-0) data. During the next stages, the SDS provides two products which are referred to as level one (L-1) and level two (L-2) data. The L-1 data provides information on the distance between twin satellites, accelerometers, GPS, and other similar types of information. The L-2 data, based on adapted and calibrated L-1 data, provides average and monthly information on the gravitational field. The other data sets used in this study were CHIRPS and in situ measurement groundwater levels. The GRACE satellite data was combined with information from the CHIRPS station to determine the total yearly precipitation from 2003 to 2017 and the effect of rainfall on groundwater storage changes and recharge. Table 1 displays the results provided by CSR, GFZ, and JPL in Google Earth Engine.

### *GRACE and CHIRPS data processing using the Google Earth Engine systems*

Google Earth Engine (GEE) is software that offers users a free online tool for processing spatial data. GEE has a petabyte-sized data bank that contains a variety of satellite photos, including MODIS, Sentinel, and Landsat, as well as geophysical and climate data, including DEM and CHIRPS (Mehdi et al., 2021). One benefit of employing GEE is that goods can be ready for use without requiring calculations or processing, and the user is nearly removed from working details in the processing environment (Mehdi et al., 2021; Yousefi et al., 2022). With the ease, effectiveness, and cost- and time-efficiency of processing data from satellite images, Google Earth Engine represents a significant advance in research, particularly in the field of remote sensing. The processing of CHIRPS data from the Google Earth Engine system and GRACE satellite data has been utilized in this work. The benefit of this system is that data does not need to be loaded; instead, it is ready for use and may be processed just through data calls. Furthermore, the data does not require geometric or radiometric modifications. Furthermore, in situations where data volume is significant, a robust processing system is not necessary because the system can call and process all of the current data in a few minutes. The Google Earth Engine system has all commands and programming codes available and ready to be processed.

In order to analyze the GRACE data and to extract the data for the study region, Equation (1) was used to show changes in mass in the form of water layer thickness. Spherical harmonic coefficients, which are expanded to changes in mass, must first be stated according to the GRACE monthly models. Changes in mass according to the equivalent water layer thickness can be stated as follows (Mehdi et al., 2021):

$$\Delta\sigma(\theta,\lambda)=\frac{\alpha^{*}\rho ave}{3}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\frac{2n+1}{1+kn}*\dot{\mathrm{P}}\mathrm{nm}\ (\cos\ (\theta)) \\ *(\Delta \mathrm{J}_{\mathrm{nm}}\mathrm{cosm}\lambda+\Delta \mathrm{k}_{\mathrm{nm}}\mathrm{sinm}\lambda) \tag{1}$$

Where: $\rho_{ave} = 5{,}517\ \mathrm{kg/m^3}$ is the average surface density of the Earth, kn represents Love numbers, $\Delta J_{nm}$ and $\Delta k_{nm}$ are the monthly variations of spherical harmonic coefficients, $\dot{P}nm$ represents normalized Legendre functions, θ is the relative deflection of the vertical axis, $\Delta\sigma$ represents the change of surface density, α is the outer radius of the sphere, λ is the average gravity and n, m are degree and order. The level 2 GRACE data were provided monthly in the form of geopotential models for the Earth's gravitational field. One of the prominent issues in these data is the existence of noise in the harmonic coefficients which increases along with the increase in degree and arrangement. Because of this issue, filters are used to decrease the degree and arrangement coefficients.

### *Estimation of GRACE-derived groundwater recharge*

Estimating yearly groundwater recharge is a crucial component of aquifer sustainability analysis. There are various ways to calculate groundwater recharge, but choosing the best one can be challenging because most methods call for comprehensive data, including precise historical groundwater data (Barbosa et al., 2022; Jeon et al., 2019; Raza et al., 2019). Groundwater recharge is known to be episodic, but only the long-term average of groundwater recharge is reproduced by the tracer methods, giving no information about the temporal evolution of groundwater recharge. Conversely, the groundwater table fluctuation method (WTF), taking advantage of the sharp water table rise in response to a given recharge event, estimates groundwater recharge on a much short time scale, such as the recharge from a rainfall event. Therefore, WTF can be used to capture transient groundwater recharge and is particularly suited for investigating the seasonality and episodicity of groundwater recharge.

Groundwater recharge rate can be computed by multiplying the change in head over a specific time interval by specific yield (Barbosa et al., 2022; Jeon et al., 2019).

$$R = S_{\mathrm{y}} \frac{\Delta h}{\Delta t} \tag{2}$$

Where $R$ is groundwater recharge with units in cm year$^{-1}$, $\Delta h$ is the height of the water table in cm, and $S_{\mathrm{y}}$ is the specific yield in % and $\Delta t$ is the designated time span that was used to measure the change. Seasonality is frequently taken into consideration while choosing the time frame. The water table fluctuation, $h$, is typically recorded at specific wells. The primary advantage of the WTF method is that this method requires no assumptions on the mechanisms for water movement through the unsaturated zone; thus, it can be applied to a variety of recharge mechanisms, including direct recharge from precipitation or irrigation, indirect recharge from flood channels, or local recharge through preferential flow paths (Wu et al., 2019).

An important distinction between GRACE data-based WTF and other WTF applications is how to define recharge episodes. A recharge episode is defined as a period during which the total recharge significantly exceeds its steady-state condition in response to a substantial water-input event (Wu et al., 2019). In the saturated zone, WTF recognizes a recharge episode by water table fluctuation following a storm (Wu et al., 2019; Yang et al., 2018). In a thick unsaturated zone, recharge is also episodic, particularly for recharge due to preferential flow and focused recharge. The episodic recharge event may be short in duration, relative to the measurement interval of GRACE, and can be randomly distributed over space. However, all recharges in an area add to soil water and groundwater, increasing the mass of the area, and the resulting mass increase from each episode accumulates with time and can be readily detected in the form of mass change in a subsequent GRACE measurement. For a footprint as large as what GRACE has, a wet season (summer in the Jedeb watershed) consisting of a series of storm events results in a series of recharge episodes that accumulate over time, creating GRACE-measurable storage increases. This is analogous to tree growth measurements: tree growth has diurnal and seasonal variability; monthly measurements may not detect daily variability, but can capture the salient feature of the growth rates over the season. Therefore, the convolution of these recharge episodes may be considered a response to a large storm (convolution of rainfall events minus evapotranspiration) and can be detected by GRACE as the total storage increment.

Consequently, a recharge episode appears from the trough of decline SB (tB) and finishes at the peak of the rise SP (tP) (Figure 2). Additionally, the recessions continue after tB, while recharge causes the GWSA rise. This part of the recession is called unrealized recession. To obtain recharge from the curve, one approach is to assume that unrealized recession is negligible, while the second approach estimates and corrects for it episode by episode, and the third approach quantifies the system behavior with a functional relationship between the water level and the decline rate (Wu et al., 2019). Here, we adopt the second method by estimating and correcting for the unrealized recession on an episode-by-episode basis. The antecedent recession curve was obtained by linear fitting GWSA as a function of time during the seasonal recession from the peak in the previous year Sa (ta) to the trough of decline SB (tB), and then the obtained linear equation was extrapolated to the time of the peak tP. Finally, we obtain the SL (tP), which is the GWSA extrapolated from the antecedent recession curve (solid line) at the time of the peak (tP). The dashed line from SB (tB) to SL (tP) is the unrealized recession (Figure 2).

Because $\Delta \mathrm{GWSa} = S_{\mathrm{y}} \times \Delta h$, the GR rate may be calculated by the following formula:

$$R = \frac{\Delta GWSA}{\Delta t} = \frac{Sp - SL}{\Delta t} \tag{3}$$

Where SP the peak of the rise and SL is the GWSA extrapolated from the antecedent curve to the time of peak. The conceptual diagram showing the groundwater storage anomaly (GWSA) and the proposed method for groundwater recharge estimation are shown in Figure 2.

Sa (ta) is the peak in the previous year; SB (tB) is the trough of decline; and Sp (tp) is the peak of the rise. The solid line is the antecedent recession curve, which is the best fit of GWSA as a function of time between tA and tB. SL (tP) is the GWSA extrapolated from the antecedent recession curve at the time of peak (tp). Rs is the change in groundwater recharge, and $R_{\mathrm{D}}$ is

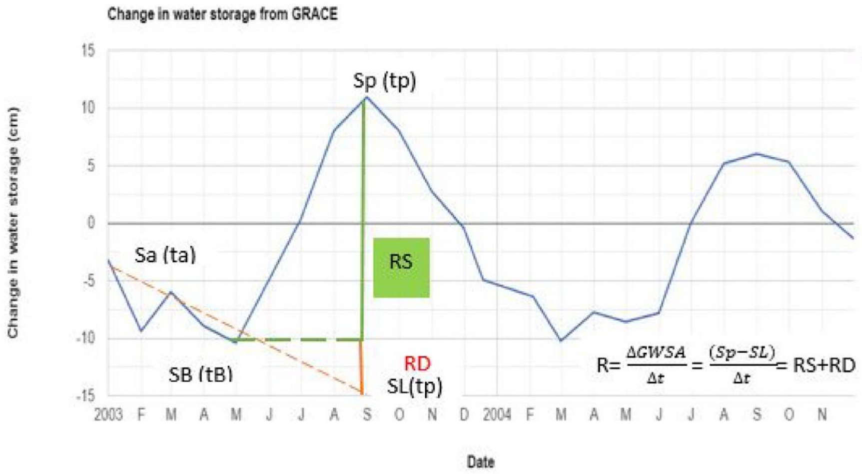

**Figure 2.** The conceptual diagram showing the groundwater storage anomaly (GWSA) from 1/1/2003 to 1/11/2004 and the proposed method for groundwater recharge estimation.

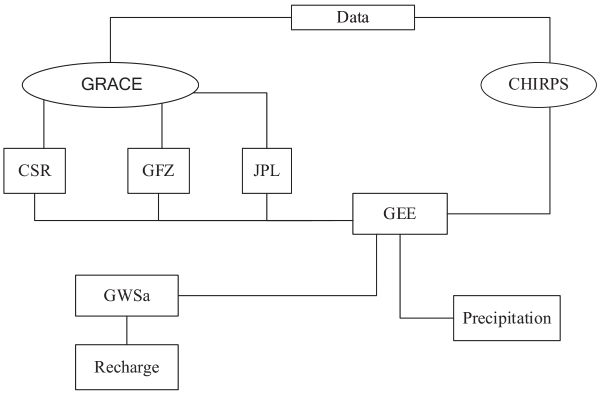

**Figure 3.** The methodological framework of the study.

the recharge that balances the discharge. Figure 3 illustrates the methods of the study.

## Results

### *Results of water storage changes with GRACE data*

The average water storage level changes for the Jedeb watershed using data produced by CSR, GFZ, and JPL institutions after processing with the Google Earth Engine online system are as follows in Figure 4. The investigation of spatial variations in the water storage fluctuation can provide us with a better understanding of this regional data. Among the 15 years that were investigated in this study, 2003, 2004, and 2012 were found to be the driest years with the most decrease in water storage, while 2007, 2008, 2013, and 2015 were relatively wet years with the most increase in water storage. The observed negative GWSa values are indicative of groundwater depletion in the basin, whereas positive GWSa values denote groundwater recharge. The total volume gained in groundwater storage over a 15-year period (2003–2014) was 2.5, 0.8, and 3.6 $\mathrm{Mm}^3$ in CSR, GFZ, and JPL, respectively. A positive total volume gained storage (55.1, 55, and 53 $\mathrm{Mm}^3$), and the highest volume losses were 45, 42, and 45 $\mathrm{Mm}^3$ in CSR, GFZ, and JPL, respectively. Due to the production of data by the three different institutions, the results are slightly different. Therefore, the results were compared with each other.

### *Groundwater storage estimation and comparison with in situ measurements*

The groundwater storage anomalies were calculated as a component by deducting canopy water, snow water equivalent, and soil moisture storage from the TWS of GRACE. However, because there aren't enough boreholes in the research region, it's difficult to validate the projected groundwater storage. Six borehole data sets were used to verify the accuracy of the calculated GWSA. The values of GWSA are recovered from the raster surfaces using extraction by points, accounting for the well locations. Figure 5 shows the time series of monthly groundwater storage from GRACE and measured groundwater levels from wells. The comparison between the estimated groundwater storage changes and the changes from measured well levels shows a similar long-term trend. The measured groundwater level variability is consistent with the estimated groundwater storage. The peaks and the trough of the plots match with a slight variation.

### *Evaluation of the effect of rainfall on GRACE-based groundwater storage anomalies*

A crucial component of the water cycle, precipitation is essential for replenishing groundwater reserves. Due to the limitations of using observation wells, data provided by the GRACE satellite was utilized in order to assess the fluctuations and variations in the water storage of the Jedeb watershed. To compare data from the three institutions (CSR, GFZ, and JPL), linear regressions were made on the processed GRACE data from each institution with CHIRPS results from 2003 to 2017. Precipitation is one parameter that controls the water storages in the Jedeb watershed. It was found that the GRACE data

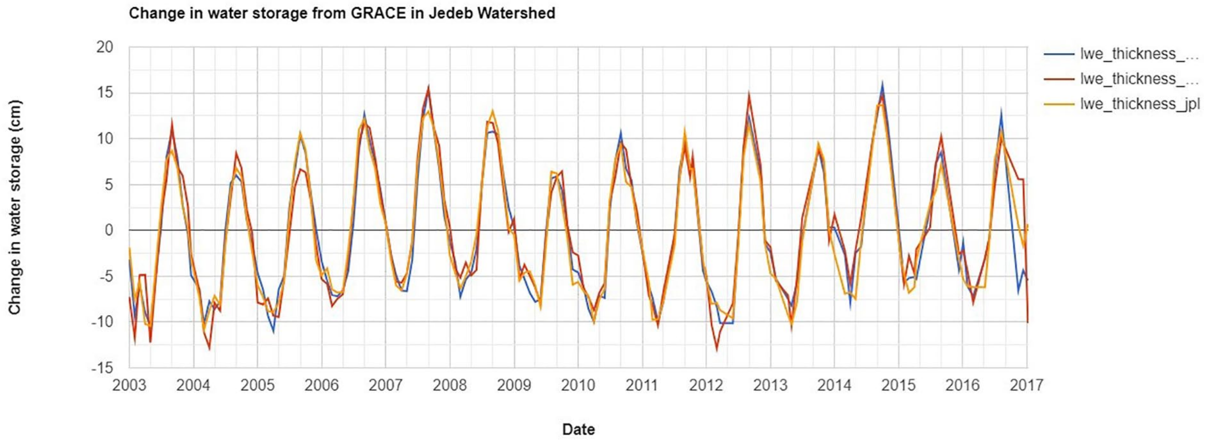

**Figure 4.** Data from CSR, GFZ, and JPL showing groundwater level changes.

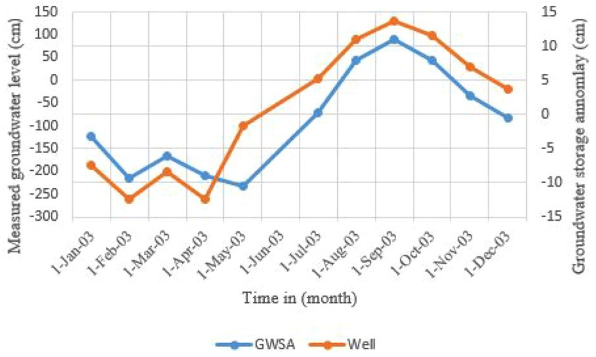

**Figure 5.** Comparison of estimated GWSA with measured GWL from well in the year of 2017.

processed by the three algorithms (CSR, GFZ, and JPL) and the CHIRPS rainfall data have a comparatively high correlation coefficient of about 0.86, showing that in this area, the decline in precipitation paralleled the decline in water storage. Figure 6 shows a seasonal and monthly time series of GRACE-based groundwater storage and the average monthly precipitation in the basin, exhibiting clear seasonal amplitude and phase changes. Similar, during the rainy season, the groundwater level rises due to net recharge, and during the dry season, we anticipate a reduction in groundwater levels. The results show that precipitation is the main hydrologic contributor in the basin for groundwater storage.

### *Results of groundwater recharge with GRACE data*

There was a recharge season in each year from 2004 to 2014 as can be shown in Figure 7. The GWSA monthly mean points in each recession curve as shown in Table 2 used to estimating groundwater recharge.

The obtained net recharge rate varied from 18 to 25 cm/year for a 14-year period, and the average was 21 cm/year. During the summer and wet periods, the groundwater recharge is high because the plants are dormant and the evapotranspiration and evaporation are at their lowest. However, during the winter and dry months when temperatures are high, the evapotranspiration rate exceeds the moisture from precipitation, resulting in negligible recharge to the aquifers and groundwater levels declining. It is important to reduce the uncertainty in groundwater recharge estimations; this can be achieved by accurately measuring precipitation, irrigation, evapotranspiration, and soil moisture content (Barbosa et al., 2022).

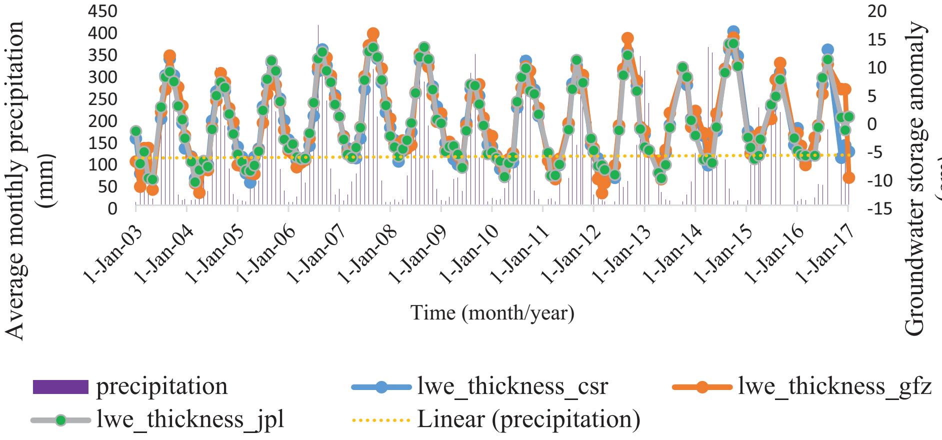

**Figure 6.** Monthly groundwater storage anomaly comparison with monthly average precipitation.

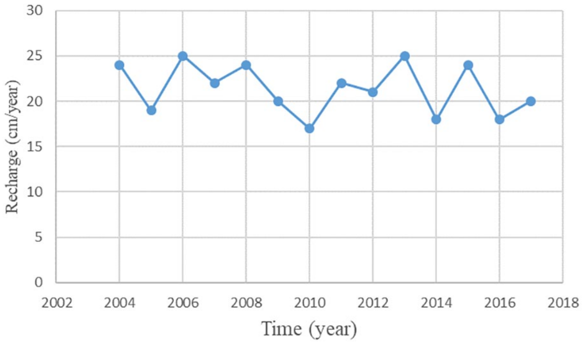

**Figure 7.** Estimated recharge values in the Jedeb watershed.

**Table 2.** The Variables Used in Estimating Groundwater Recharge From Groundwater Storage Anomaly.

| YEAR | SP | SL | ST | RS | RD | RECHARGE (CM/YEAR) |
|---|---|---|---|---|---|---|
| 2004 | 10 | –14 | –10 | 20 | 4 | 24 |
| 2005 | 5 | –14 | –10 | 15 | 4 | 19 |
| 2006 | 10 | –15 | –11 | 21 | 4 | 25 |
| 2007 | 12 | –10 | –8 | 20 | 2 | 22 |
| 2008 | 14 | –10 | –6 | 20 | 4 | 24 |
| 2009 | 10 | –10 | –8 | 18 | 2 | 20 |
| 2010 | 5 | –12 | –10 | 15 | 2 | 17 |
| 2011 | 10 | –12 | –9 | 19 | 3 | 22 |
| 2012 | 9 | –12 | –10 | 19 | 2 | 21 |
| 2013 | 10 | –15 | –10 | 20 | 5 | 25 |
| 2014 | 8 | –10 | –8 | 16 | 2 | 18 |
| 2015 | 14 | –10 | –7 | 21 | 3 | 24 |
| 2016 | 7 | –11 | –5 | 12 | 6 | 18 |
| 2017 | 10 | –10 | –8 | 18 | 2 | 20 |

### *Groundwater recharge rate comparative with annual precipitation*

Rainfall is the major source of groundwater recharge in the basin. Other possible sources of recharge could be induced by reservoirs and along local streambeds. The comparison between the average annual precipitation over the Jedeb watershed from 2004 to 2017 and the groundwater recharge rate is depicted in Figure 8. The annual precipitation histogram exhibits significant variability, with the highest precipitation occurring in 2006 and 2013. The lowest precipitation occurred in 2012. An increase in precipitation during the preceding year's rainy seasons is the cause of this yearly increase in groundwater recharge. Because of the recharge changes with decreasing or increasing total annual precipitation, this indicates that recharge is regulated by precipitation in the Jedeb watershed. Subsequently, the basin experienced an increase in groundwater storage and precipitation, with the biggest recharge occurring in 2006 and 2013. Many similar researchers reported a higher correlation between groundwater recharge and precipitation (Liu et al., 2021; Mehdi et al., 2021; Shami & Ghorbani, 2019).

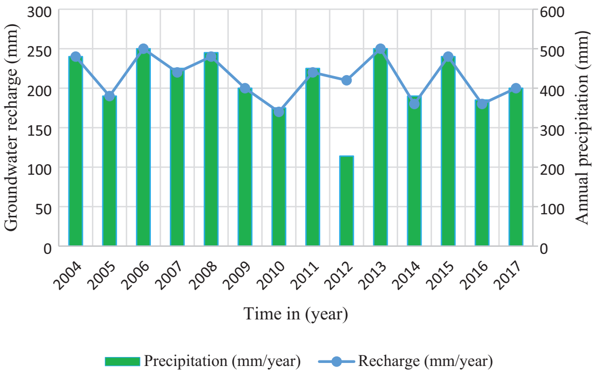

**Figure 8.** Comparative evaluation of estimated groundwater recharge and annual precipitation in the watershed.

## Discussion

Groundwater is the primary supply of water for all human purposes in the study area, including residential, agricultural, and livestock feeds. Accurate understanding of groundwater storage variation (DGWS) is essential for assessing the state of groundwater resources. This is because these factors are primarily caused by excessive groundwater extraction under conditions of insufficient water supply, and they pose a threat to land subsidence, declining crop productivity, and salinity in the soil. Limited groundwater data can make managing groundwater resources difficult, especially over the longer time periods required to evaluate aquifer sustainability (Barbosa et al., 2022; Jeon et al., 2019; Raza et al., 2019). Groundwater monitoring is expensive in terms of money, technology, and time since it requires setting up various monitoring wells and continuously collecting, storing, and evaluating data on water quality and level over an extended period of time (Barbosa et al., 2022). Groundwater demand is increasing, with a 3% annual growth in groundwater use globally from 1990 to 2010 (Barbosa et al., 2022; Jeon et al., 2019; Raza et al., 2019). Because of a lack of finance, technology, and logistics, developing countries often lack data; nevertheless, the GRACE satellite can supply crucial hydrological data to these countries. At regional scale, such as in the Jedeb watershed, water stress is a major risk. The need for fresh water has increased as a result of population development, urbanization, and an increase in industrial and agricultural activity (Liu et al., 2021; Wu et al., 2019). There was less heterogeneity and less reliable validation of the results since the network of observational wells was not dispersed throughout the whole study area. In order to support hydrological assessments and environmental and water management decisions, our work emphasizes the significance of GRACE satellite data. Any significant attempt to create integrated water resources management strategies at the national or catchment level requires the availability of such data. GRACE provides a novel and significant method for calculating changes in groundwater storage. The findings show that the GRACE satellite, which was employed in this investigation, has a strong capacity to compute groundwater variations and precipitation values with a high degree of reliability. A similar conclusion also found by (Alghafli et al., 2023; Barbosa et al., 2022; Jeon et al., 2019; Raza et al., 2019; Seo & Lee, 2016) in United Arab Emirates, in Niger West Africa, in Korea, and in agricultural basin of Korea, in South Korea precipitation has a great influence on groundwater storage changes.

Many validation studies at the regional level have been carried out now that there is a long enough series of GRACE data available. Acceptable agreement between GRACE-derived and total water storage fluctuation has been found through comparisons between predicted outputs and measured data. For example, (Ali et al., 2021; Ghosh & Bera, 2023; Liu et al., 2021; Sun et al., 2022; Wu et al., 2019) found good agreement between monitored groundwater levels and GRACE-derived values in the Northwester China, SRB, Loss Plateau, Indus Basin irrigation system, and Mississippi River basin. It was found that the GRACE data and the CHIRPS rainfall data have a relatively high consistency with the estimated groundwater recharge.

The findings show that the accuracy of this enhanced approach is tolerable. In contrast to other approaches, the improved approach described in this work can be used to estimate total groundwater recharge at regional scales. It may also be useful in areas with continental, Mediterranean, monsoon, and alternating wet-dry season cycles worldwide. In order to manage and budget groundwater resources more effectively, the improved approach is expected to produce reasonable groundwater recharge estimates at regional scales.

The application of GRACE-derived data analysis in the Jedeb watershed under consideration will be the first of its kind in north Ethiopia catchments, and as such, the results of this work will help validate additional investigations conducted at the regional level. GRACE data enable general conclusions on watershed water mass change based on findings from this study and other studies. This offers a chance to research places where there is little or no in situ data accessible. These data are critical for integrated water resource management in the region, where groundwater is regarded as the most precious resource. In addition, the current study aims to discover new areas of interest, promote cooperation between countries and authors, and make relevant data on a certain subject field easier to access. Lastly, researchers might use this work as a guide for their future studies.

## Conclusions

In this study, GRACE satellite data and the improved WTF method were used to estimate the regional groundwater storage and recharge in the Jedeb watershed. The other data sets used in this study were CHIRPS and in situ measurements of groundwater levels. Due to the limitations of using observation wells, data provided by the GRACE satellite was utilized in order to assess the fluctuations and variations in the water storage of the Jedeb watershed. Based on the GRACE satellite data on the fluctuations of annual water storage between 2003 and 2017, it was found that the biggest annual increase in water levels (15 cm) occurred in 2008, 2013, and 2015, and the biggest annual decrease (12.5 cm) occurred in 2012. The obtained net recharge rate varied from 18 to 25 cm/year for a 14-year period, and the average was 21 cm/year. The estimated annual average recharge rates are consistent with groundwater storage changes for the study region. On the other hand, the input of water storage is due to rainfall, so increasing or decreasing rainfall has a direct effect on water storage level changes and recharges. However, reducing rainfall can reduce water storage levels significantly, but other factors, including the contribution of human resources, should be carefully discussed. In this way, appropriate and new methods should be applied to the management style of groundwater resources in the study area.

GRACE offers an innovative and important approach to estimating groundwater storage changes. However, there are still some limitations include its inability to solve GRACE's shortcomings, such as the leakage factor, validate in data-sparse locations, and handle advanced bias correction. The framework's future development may involve creating an assembly process for an ensemble model. More reliable and accurate downscaled GRACE data can be produced by combining the advantages of several machine learning techniques and incorporating data-driven methodologies with physics-based models. In order to better represent the complexity of the underlying hydrological processes and lessen the constraints of individual models, ensemble and hybrid approaches can be used. We highly advise against using such a downscaling approach unless there is an easy way to obtain high-quality regional data. By using auxiliary datasets of worse quality, this method reduces biases or uncertainties and guarantees that the resulting high-resolution terrestrial water storage estimations appropriately reflect the underlying hydrological processes.

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## Author Contributions

TA has made considerable contributions in designing the study, data acquisition, data collection, analysis, interpretation, and manuscript writing; MK and NA have made a significant contribution in designing and analysis of data, in commenting, suggesting ideas, and editing the manuscript. All authors read and approved the final manuscript.

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## Data Availability

Datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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