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A Geodetic-based Estimate of Groundwater Storage Variations in Balaka, Malawi

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Abstract

Ground water is the main source of water for domestic and agricultural purposes in rural areas in Malawi. Continued exploitation of the ground water for domestic, agricultural, mining and other industrial purposes results in continued temporal changes in its levels. Understanding changes in the Groundwater Storage Capacity is crucial in development and in improving the livelihoods of people. Attempts to study groundwater storage have been made in Malawi. However, the lack of groundwater data, triggered by scarcity of ground observation facilities, hampers water resource management efforts. In this paper, the Gravity Recovery and Climate Experiment (GRACE-FO), supported by Global Land Data Assimilation System (GLDAS), has been used to determine variations in Terrestrial Water storage capacity levels, which combine the surface moisture, groundwater, snow and canopy water conditions in Balaka district, in Malawi, over a period of ten years (2012-2022). Owing to the fact that Balaka does not register any snowfall, only the surface moisture anomaly was considered in reducing the terrestrial water storage anomaly to determine the groundwater storage level changes from 2012 to 2022. Since an increasing trend, declining to levels as low as 0.002mm/year, was determined, the GRACE-based groundwater storage anomalies revealed no significant changes in groundwater levels. Influencing factors for the increasing trend were not addressed in this paper. Nonetheless, the results of this paper can contribute positively to the effective management of groundwater resources and promote the use of geodetic gravity data in water resource management.

Keywords: *Terrestrial Water Storage (TWS), Surface Moisture, GRACE-FO, GLDAS*

1. Introduction

Water reservoirs play a vital role in human life and the dynamics of the Earth's system. Owing to a wide range of changes in the lithosphere and atmosphere over time, water in the Earth's system redistributes itself in a variety of ways (UNAVCO, 2012). In many countries, including Malawi, ground water constitutes a significant proportion of the water that is readily available for use. Many people in the rural areas of Malawi, including Balaka, depend on groundwater for different purposes (Mapoma & Xie, 2014). Groundwater aquifers supply water for domestic and agricultural use, just to mention a few. In rural Malawi, ground water from dug wells and hand pumped boreholes is estimated to supply 3 million people (Hellens, 2013).

As a consequence of exploitation, changing weather patterns and climate change, ground water storage (GWS) levels continue to vary in various regions across the globe. Another important component that is crucial in defining the global hydrological cycle is terrestrial water storage (TWS). TWS is the total amount of water stored on the Earth's surface and sub-surface and includes, amongst others, ground water, soil moisture, lakes, rivers and glaciers (Humphrey, Matthew, & Eicker, 2023). The depletion of TWS and GWS contributes to the droughts and continued crustal deformations that are prevalent in various parts of the globe (Wang, et al., 2022; Seka, et al., 2022). The depletion of ground water leads to water insecurity and could threaten agricultural productivity and hydro-electric production (Frappart & Ramillien, 2018). Considering the crucial role that ground water plays in economic development and the growth of countries such as Malawi, the depletion of this vital natural resource poses a danger to the livelihoods of people. In this regard, it is necessary to monitor the levels of terrestrial and groundwater storage.

Geodesy has provided different ways of monitoring water levels on the Earth's surface and has made huge amounts of hydrological data available. Satellite Geodesy provides valuable Earth Observation data for modelling the size, shape and gravity field of the Earth, as well as its rotation, which are fundamental properties of the Earth (Böhm & Schuh, 2013). Further applications in modelling the different dynamic properties of the Earth have been developed. Of paramount importance in modelling the Earth is space-based geodesy, which makes use of different satellites that have been launched into space and are orbiting around the planet Earth. The launching of modern satellites such as GRACE-FO and GPS into orbit marks the advent of modern geodesy. Satellite geodesy has become an interdisciplinary science that has found important applications in different scientific fields, including hydrology, climate change and meteorology, among others (Herring, 2007; Suya, et al., 2022; Ikuemonisan & Ozebo, 2020). Among many space-geodetic missions, the Gravity Recovery and Climate Experiment (GRACE-FO) satellites, as well as the Global Positioning System (GPS), provide the means to monitor water levels on the surface of the Earth.

Balaka is one of the driest areas in Malawi. In some areas, efforts to exploit groundwater prove futile and many water sources run dry during significant periods of the year. Attempts to study groundwater storage using remote sensing have been made in Malawi. However, the focus was only on the use of normalized difference indices for vegetation and water (NDVI and NDWI) which measure only the water content of water bodies without measuring the levels of terrestrial water storage. Traditional methods to study variations in ground water have also been used. These include the use of *in-situ* observations and hydrological modelling. However, these methods offer a limited point scale (Han, et al., 2023). In addition to that, the lack of groundwater data, triggered by the scarcity of ground observation facilities, hampers water resource management efforts. This results in a poor understanding of the changes in the groundwater storage levels. In this study, solutions focusing on measuring the water levels on both the surface and sub-surface by employing geodetic methods have been employed to analyze the current water storage levels in Balaka, Malawi. Time series analyses of TWS capacity changes have been employed, and the results have been validated with the aim of determining the GWS variations.

This study focuses on measuring water levels on both the surface and sub-surface. GRACE-FO provides data on a wide range of temporal variations or changes in surface mass with a centimeter-equivalent water high precision with a spatial resolution of approximately 400 km and a monthly temporal resolution (Li, Zhong, Li, & Liu, 2022). GRACE-FO offers important tools for the analysis of groundwater levels and has been used for tracking changes in water storage and monitoring drought and groundwater inversion (Seka, et al., 2022). GRACE-FO also serves as a reliable substitute of the costly groundwater observation wells. It provides uniformity in scale and spatial distribution and provides reliable results, even in the absence of hydrological and meteorological data (Shao & Liu, 2023). On the other hand, there is a correlation between changes in groundwater levels and vertical displacements of the Earth's surface (Liu, et al., 2022; Khorrami, et al., 2023); hence, GPS measurements have the ability to track changes in GWS levels.

Dwindling levels of ground water in the wake of climate change and the continued exploitation of ground water pose a threat to the water security of people, especially in developing countries such as Malawi. They also jeopardize agricultural productivity. Therefore, having accurate information on groundwater levels is important in making informed decisions. This study provides information on the levels of groundwater in Balaka district and provides a track of water level changes. This will ensure that proper decisions are made in tackling the problem at hand.

2. Space Geodetic Techniques for Estimating Changes in TWS Levels

There are numerous space geodetic techniques. Those that are relevant for this study have been briefly discussed.

2.1. Global Navigation Satellite Systems (GNSS)

GNSS is a highly precise geodetic positioning technique that has become crucial in surveying and navigation. Its high level of precision and the ease of acquiring its data have made GNSS crucially important in geophysical studies (Herring, 2007). Different studies in measuring TWS levels have employed GNSS. Owing to the correlation between vertical displacement of the land mass and extraction of ground water, GNSS has been used to detect changes in groundwater levels. It has in fact been established that vertical displacements of continuously observing GNSS stations indicate changes in the water levels of aquifers (Liu, et al., 2022). Nonetheless, to provide definitive results, there is a need to have a network of permanent GNSS stations that continuously observe vertical displacement in the study area. Cumulative vertical displacement time series of longer periods need to be obtained to ascertain land subsidence due to water level changes (Ikuemonisan & Ozebo, 2020).

In Shaan-Gan Ning region in China, post-processed GNSS data obtained from 77 evenly distributed permanent GNSS stations were used in estimating groundwater levels (Li, Zhong, Li, &

Liu, 2022). In Beijing, China, a network of 36 Continuously Observing Reference Stations (CORS) were used to correlate crustal deformation data and station velocity data to groundwater storage changes (Li, et al., 2022). In groundwater level and land subsidence studies, a well distributed network of GNSS CORS was used to provide definitive vertical displacements in Lagos and the United States (Ikuemonisan & Ozebo, 2020; Wang, et al., 2022). However, in Malawi and Balaka in particular, there is no proper distribution of the CORS network. There are only 10 GNSS stations, and four of them are decommissioned (Suya, et al., 2022). This would not serve as a good basis for making observations since the study area does not have any GNSS station. The nearest station is the Zomba GNSS station (labelled number 11 in Figure 1), which is over 80km from the study area.

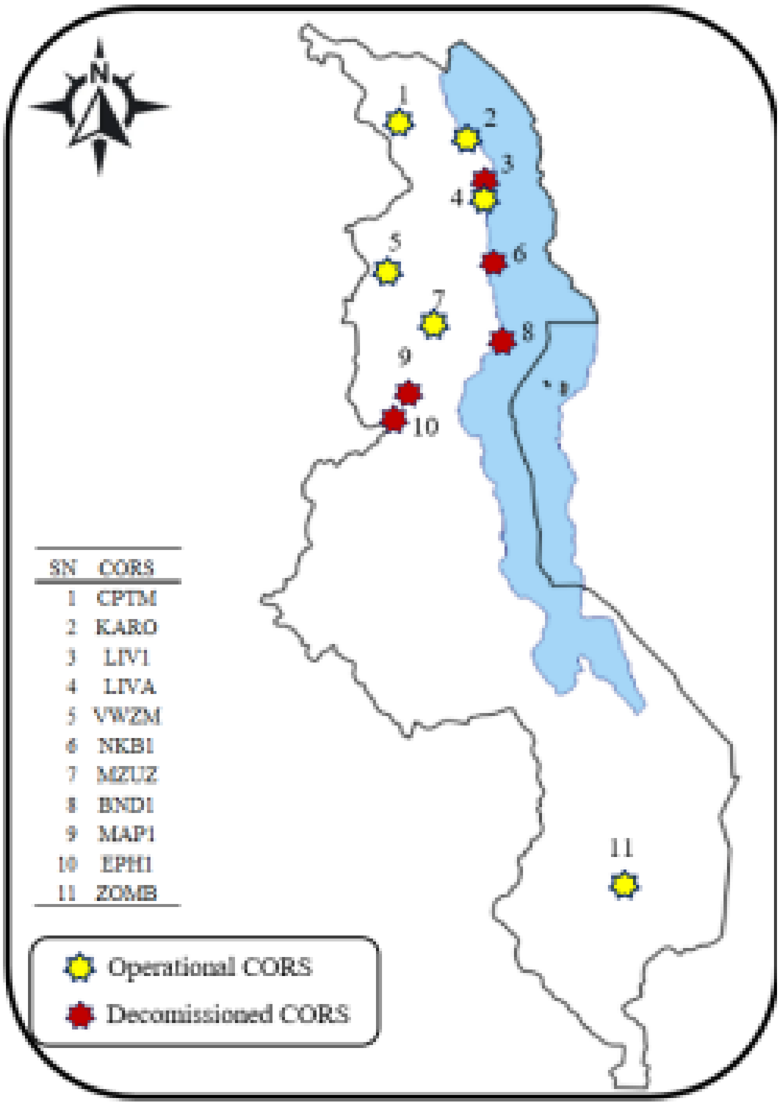


Figure 1: Distribution of permanent GNSS stations in Malawi. Source (Suya, et al., 2022)

Li, Zhong, Li, & Liu (2022), stated that good quality GNSS permanent stations that are evenly distributed should be selected as fixed reference stations. Their data should be employed and jointly adjusted with those of other datasets to obtain the final vertical displacement time series of the GPS stations relative to the International Terrestrial Reference Frame (ITRF). Owing to the uneven distribution of GNSS stations in Malawi, GNSS was not used for the purposes of this study as the uneven distribution could lead to biased results.

2.2. GRACE-FO

The main purpose of the GRACE mission is to measure time-varying anomalies in the gravity field of the Earth which is one of the fundamental properties of the planet (Humphrey, Matthew, & Eicker, 2023). It was jointly launched in 2002 by the National Aeronautics Space Agency (NASA) and the German Aerospace Centre (Frappart & Ramillien, 2018). It consists of two identical satellites, following each other at 220km and are orbiting the Earth at an altitude of 500km. The two satellites use microwaves to accurately monitor their separation distance and they have on-board accelerometers that minimize the distance problems resulting from the atmospheric drag that is caused by the low altitude of the identical orbits. The distance between the two identical satellites varies with time as they fly through spatial gradients in the gravity field, and so, by monitoring those changes, the gravity field can be determined (Herring, 2007). Using the microwave ranging instruments on board, the satellites create maps of the Earth's changing gravity fields which are primarily caused by fluctuations in the water mass on Earth (Mucia, 2018).

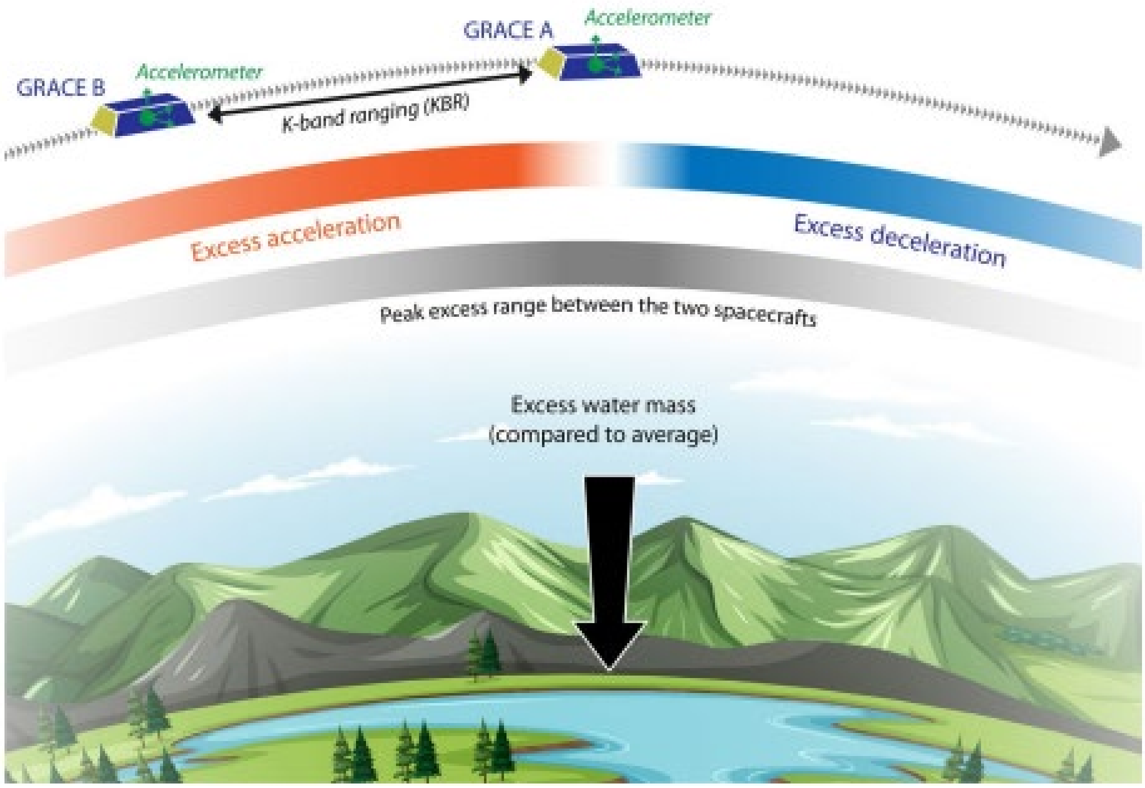


Figure 2: View of the GRACE-FO mission. Source (Humphrey, Matthew, & Eicker, 2023)

Following a battery failure in the satellites, the GRACE mission came to an end in 2017. A follow-on mission, GRACE-FO, launched in 2017, would continue the mission of its predecessor. The GRACE-FO provides high resolution monthly models of the Earth's gravitational field. The models have been used to analyze TWS with higher accuracy and precision where it has been shown that there is a strong interrelation between hydrology and gravity (Creutzfeldt, Güntner, Klügel, & Wziontek, 2008). In an area where there is excess water, a stronger gravitational acceleration is experienced, while in areas experiencing drought, a weaker gravitational acceleration is registered. GRACE has been proven to answer hydrogeological questions with reliability and accuracy. The GRACE mission has been applied in determining changes in the mass distribution of the Earth (Döhne, Horwath, Groh, & Buchta, 2023). Changes in terrestrial water storage redistribute the mass of the Earth; hence water storage can be modelled using GRACE and GRACE-FO data. Since the launch of GRACE in 2002, the monitoring of water storage over large areas has been made possible and its data have been made available (Li, et al., 2022). In hydrological modeling, it has been established that there is a correlation between GRACE load deformation (hydrosphere) and the vertical seasonal changes of GPS stations (Bian, et al., 2023). GRACE-FO has been proven to provide reliable results in estimating terrestrial water storage levels as it was found that there is a good association between GRACE-derived and water balance-based terrestrial water storage change (Huang, et al., 2023). Owing to this, and coupled with the uneven distribution of GNSS CORS stations and the unavailability of reliable hydrological data, GRACE has been used for the purposes of this study.

2.2.1. TWS

Total water storage combines all water that is stored on the land (surface and sub-surface) and includes components such as groundwater and soil moisture. The GRACE mission satellites accurately detect gravity anomalies that are caused by changes in TWS. Positive or negative change in TWS levels is linked to changes in lake levels and droughts and is highly responsive to different atmospheric dynamics triggered by climate change. The lack of hydrological data and the challenges in determining all the components of TWS have hindered an understanding of the spatial and temporal TWS changes (Seka, et al., 2022). However, GRACE-FO provides vital datasets of hydrology that can be used to model changes in TWS.

GRACE and GRACE-FO provide TWS hydrological data, reported in metres, centimetres or millimetres, monthly. The TWS changes are reported in the form of grid anomalies. They indicate the quantity of the water mass that is needed at the surface of the Earth's ellipsoid to best explain the observed gravity field anomaly (Humphrey, Matthew, & Eicker, 2023). Such anomalies are obtained by subtracting the current terrestrial water storage and the long-term TWS averages derived from satellite observations. As such, it is important to note that GRACE does not provide TWS data, but only anomalies in TWS obtained from the deviations from the long-term mean. According to Fatolazadeh, Eshagh, & Goita (2022) the hydrological model can be expressed as:

$$TWS = SM + SWE + CAN + GW + SW \quad [1]$$

Where $SM,\ SWE,\ CAN,\ GW\ and\ SW$ are soil moisture, snow water equivalent (SWE), canopy water (CAN), groundwater storage (GWS) and surface water (SW), respectively. The same can be expressed in terms of anomalies; hence the terrestrial water storage anomaly (TWSA) contains the surface moisture anomaly (SMA), the snow water equivalent anomaly (SWEA), the canopy water anomaly (CANA), the ground water anomaly (GWA) and the surface water anomaly (SWA).

$$TWSA = SMA + SWEA + CANA + GWA + SWA \quad [2]$$

One of the reliable sources of surface moisture storage data is the Global Land Data Assimilation System (GLDAS). GLDAS provides a wide variety of land surface information that includes soil moisture, storm water runoff, total precipitation, wind speed and air pressure. It can provide stable and a long time series model of land surface information. This makes the GLDAS hydrological model, combined with GRACE data, suitable for assessing GWS levels under all terrestrial conditions (Wang, et al., 2023). GLDAS gathers data from a few satellite platforms and uses such data to estimate TWS anomalies. In Chad, GRACE products were integrated with GLDAS data analysis results to estimate and analyze spatio-temporal TWS changes and to estimate groundwater storage anomalies (Mohamed, Abdelrady, Alarif, & Othman, 2023). In the GWS levels study in North America, it was discovered that, not including surface water storage data from GLDAS, the data results led to contradictory findings (Wang, et al., 2023). In this study, surface wetlands have been subtracted from TWS signals provided by the GRACE data to correct for the errors caused by disregarding GLDAS.

3. Study Area, Datasets and Methods

3.1. Study Area

The study area is located between latitudes 14°40’S and 15°20’S, and longitudes 34°50’E and 35°20’E in Balaka district of Malawi which covers a surface area of $2133.84\ \mathrm{Km}^2$. The study area is characterized by a tropical climate and experiences two main weather seasons, namely, the rainy season that spans from November to April and the dry season that extends from May to October. Malawi’s climate is dominated by the north–south migration of the inter-tropical convergence zone (ITCZ), which is marked by the convergence of the northeasterly monsoon and southeasterly trade winds (Ngongondo, Xu, Gottschalk, & Alemaw, 2011). Balaka is one of the hottest districts in Malawi but it has in recent years experienced heavy rains brought by Cyclones Anna and Idai.

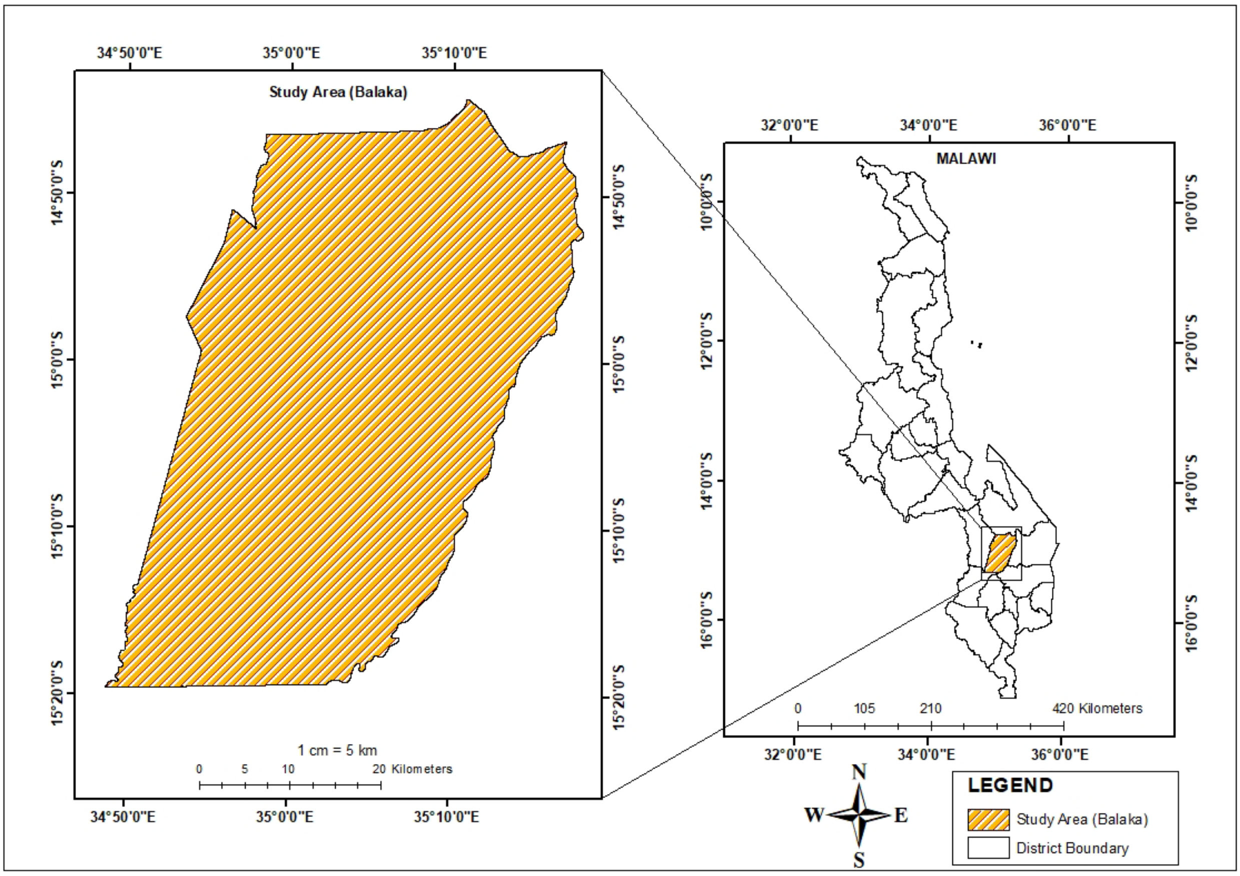


Figure 3: Study area map

3.2. Data set

3.2.1. GRACE Data

In this study, gravity data based on monthly time varying solutions from GRACE processing centres were used. Monthly Mass Grid-Global mascons (JPL RL06.1_v03) and CSR GRACE/GRACE-FO RL06 mascon solutions (version 02) provided by NASA's Jet Propulsion Laboratory (JPL) and Centre for Space Research (CSR), respectively, were used. The gravity data had a resolution of 1°×1° grid. Mass concentration blocks (mascons) offer advantages over spherical harmonic solutions in such a way that with mascons, geophysical constraints can be implemented much more easily. These *a-priori* constraints help to filter out noise from GRACE/GRACE-FO observations. Mascons serve as alternatives to spherical harmonics for processing GRACE-FO data. A mascon corresponds with a small predefined region on the Earth's surface and serves to quantify a local mass anomaly other than spherical harmonics, the latter being a representation of the global gravity field (Humphrey, Matthew, & Eicker, 2023). The datasets were not smoothed nor scaled for post processing. This was the case because scaling techniques, spectral de-striping and smoothing filtering are not necessary when working with mascon solutions (Alshehri & Mohamed, 2023). The missing monthly data in the datasets were determined through interpolation. A linear trend of the anomalies was determined from the variations in the TWS time series. The JPL and CSR dataset also had monthly surface moisture anomalies (SMA) with 1° × 1° grid resolution.

Monthly land mass grids provided by JPL and CSR contain land water mass anomalies provided in terms of water equivalent thickness (WET). The WET given by GRACE-FO has already been corrected for glacial isostatic adjustment (GIA) and correction filters have already been added. The WET represents the TWS.

3.2.2. GLDAS

To understand the fluctuations of TWS and surface moisture (SM), the Global Land Data Assimilation System (GLDAS) dataset was used. The GLDAS dataset contains no gaps and was used to fill in the missing gaps in the GRACE data. TWS data from the CLSM025 model of GLDAS, with a $0.25° \times 0.25°$ spectral resolution and daily temporal resolution, was used. The dataset was retrieved from GIOVANNI, NASA's open data portal (https://doi.org/10.5067/SXAVCZFAQLNO). The GLDAS offers good spatial and temporal resolution and the dataset was applied to study the time series of TWS. The GLDAS dataset provides all components of the water balance equation (Fatolazadeh, Eshagh, & Goita, 2022). For this study daily, the $0.25° \times 0.25°$ model was used to determine variations in terrestrial water storage capacity levels. The GLDAS data were used to validate the results and offer a comparison of the results generated from the GRACE-FO solutions.

The soil water data of the GLDAS MERRA-2 model was also used. The data had a monthly temporal resolution and a $0.5° \times 0.625°$ spatial resolution. GLDAS NOAH-10 model surface moisture data with a $1° \times 1°$ spatial resolution and a one-month temporal resolution was used as well. Another dataset that was used was the GLDAS NOAH025 surface plant canopy water, with a temporal resolution of one month and a spatial resolution of $0.25° \times 0.25°$ grid.

3.3. Methods

GLDAS-derived TWS was provided in mm/grid, SW was provided in kg/m^2, SM in kg/m^2 and CAN in kg/m^2. These were pre-processed to convert the units to cm/grid, which is the scale used by GRACE data. This was done by determining the cm/grid-level equivalent of kg/m^2 of water. In pre-processing, the gaps in the GRACE data were filled and others were ignored because they could not have an impact on the results. The TWS data of GLDAS which are provided with a daily temporal resolution were also pre-processed by grouping them in monthly averages so that they would conform to the other datasets provided with monthly temporal resolutions.

Changes in the GWS anomaly were monitored by using the changes in the other components obtained from the GRACE-FO data. The climate conditions of the study area are mostly dry and no snowfall has ever been recorded in its history. Therefore, the snow water equivalent was not considered for the purposes of this study. Other components, such as the biomass anomalies, surface water storage, surface canopy water and runoff-water anomalies were also not considered. A study on the groundwater changes in China indicated that runoff-water and biomass anomalies have a negligible impact on terrestrial water storage (Shao & Liu, 2023). Hence, a change in ground water can be expressed as:

$$\Delta GWS = \Delta TWS - \Delta SM \quad [3]$$

Where ΔGWS is the change in groundwater storage, ΔTWS is the change in terrestrial water storage.

However, for the GLDAS data, only the snow water equivalent was dropped from [1equation [1 to give equation [7. To validate the GRACE data, the results of the GRACE analysis were compared to the results of the analyses obtained from the GLDAS data set.

3.3.1. Trend Analysis

A simple ordinary least squares linear regression analysis was conducted to determine the trend of the components over the study period. The linear trend slope represents the rate of change in the levels of water storage in the area for the study period. To determine the significance of the trend, P-values of change were determined. The analyses were done at a 95% confidence level. If 1 and -1 represent an insignificant difference and a significant difference respectively, the results of P-value (p) can be interpreted using equation [4. The results of the time series have been discussed.

$$p = \begin{cases} 1 \; if \; p > 0.05 \\ 0 \; if \; p = 0.00 \\ -1 \; if \; p < 0.05 \end{cases} \quad [4]$$

The square root of the coefficient of determination denoted by R of GWA was calculated to determine the correlation between the change in the groundwater anomaly and time and the predicted anomaly levels with respect to time. Standard error was also calculated to measure the accuracy of the data distribution. The quantities were determined using equations [5 and [6 (Bluman, 2007):

$$R = \sqrt{1 - \frac{sum \; of \; squared \; regression}{total \; sum \; of \; squares}} \quad [5]$$

$$Standard \; Error = \sqrt{\frac{\sum_{i=0}^{n} \sigma^2}{n}} \quad [6]$$

Where σ^2 is the variance and n is the number of elements in the population.

$$GW = TWS - (SM + CAN + SW) \quad [7]$$

All analyses in this study were done using Python. The maps were created using ArcMap 10.8.

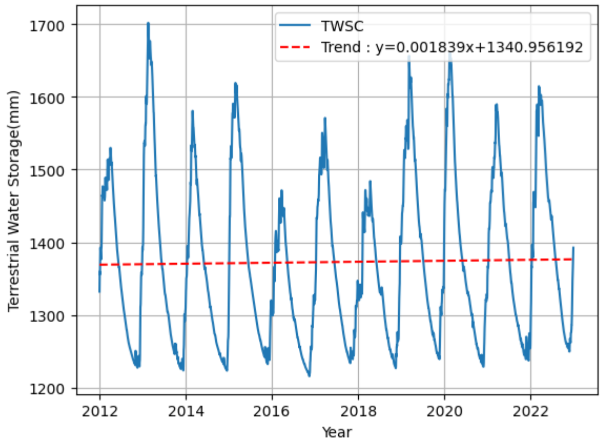
4. Results and Discussions

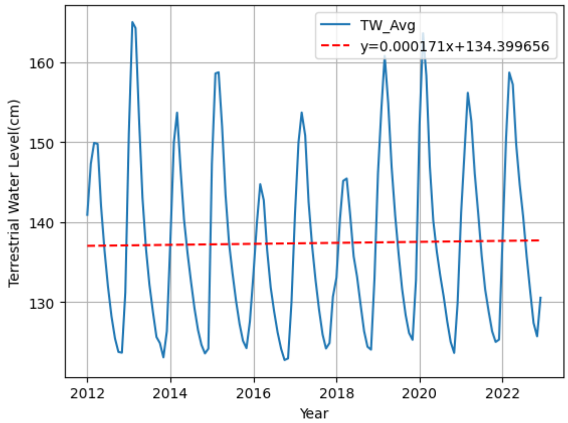
In this work, an independent look at the components of the water balance equation were considered.

4.1. Results

4.1.1. Temporal Variations in Terrestrial Water Storage

Figure 4 illustrates the levels of total water storage from 2012 to 2022, as determined from the GLDAS daily 0.25° × 0.25° data for study area. The figure also shows a slight upward trend of total water storage of +0.002mm/year. In this period, the GLDAS calculation shows a highest total water storage capacity of 1700mm in 2013 and a lowest level of 1240mm in 2014.





(b)

(a)

Figure 4: Monthly TWS estimates from January 2012 to December 2022, as produced from GLDAS. (a) Shows daily levels and (b) shows monthly averages.

Using GRACE observations of TWS changes for the study area, Figure 5 shows the annual fluctuations of TWS anomalies based on the mascons provided by CSR and JPL. A trend based on the monthly averages of CSR and JPL revealed a +0.002mm annual upward trend. CSR and JPL estimates showed negative and positive trends respectively, as presented in **Error! Reference source not found.**. Having determined the separate trends based on the mascons from the CSR and JPL processing centres, an average of the two trends was computed for comparison. The mascons have fewer leakage errors and offer great resolutions over land; hence the averages of the two solutions were used.

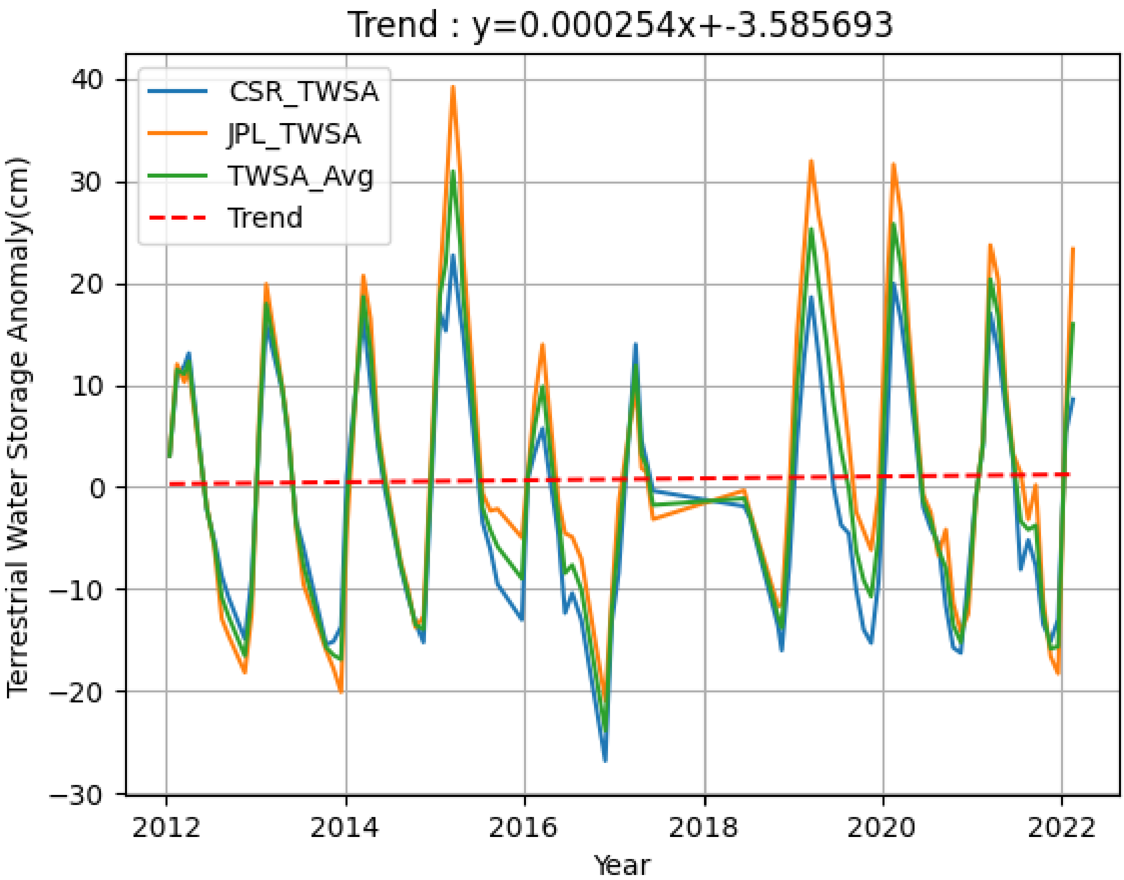


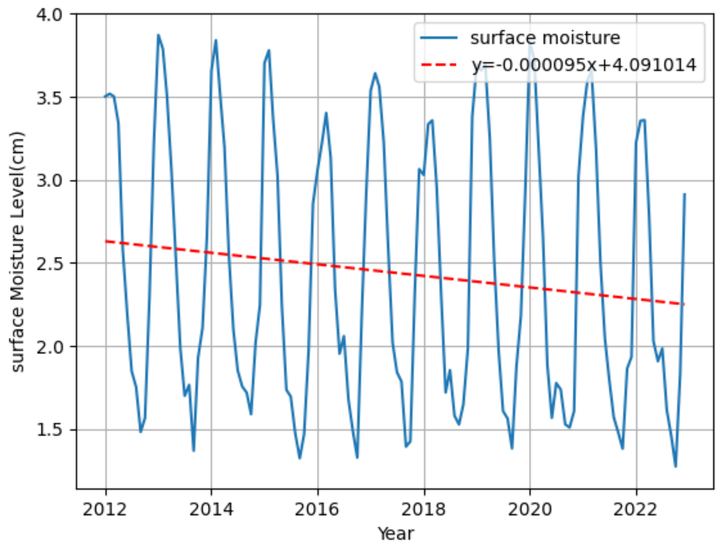
Figure 5: Annual TWS anomaly time series of mascons from CSR and JPL processing centres and their averages.

Table 1: TWS anomaly trends in the study area for the entire period (2012-2022)

Component (cm)	Solution	Trend
Terrestrial Water Storage (TWS) anomaly	CSR	-0.005mm/year
	JPL	+0.012mm/year
	Average	+0.002mm/year

4.1.2. Variations in Surface Moisture

GLDAS-derived surface moisture storage showed a negative trend in the study area for the study period. The estimated annual change determined from the GLDAS NOAH version is -0.008mm per year. This is illustrated in Figure 6(a). Figure 6(b) depicts the spatial distribution of average SMS corresponding with the entire study area over the study period.



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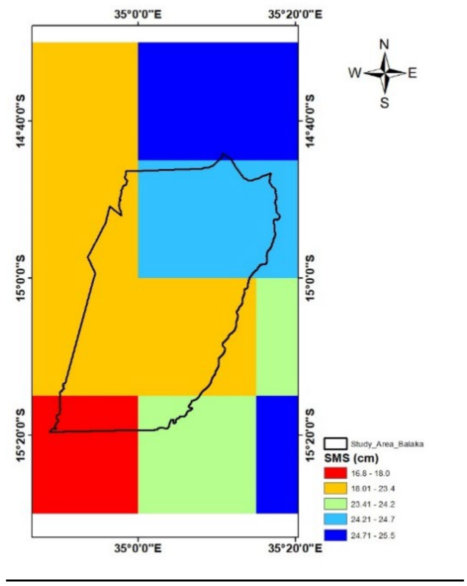
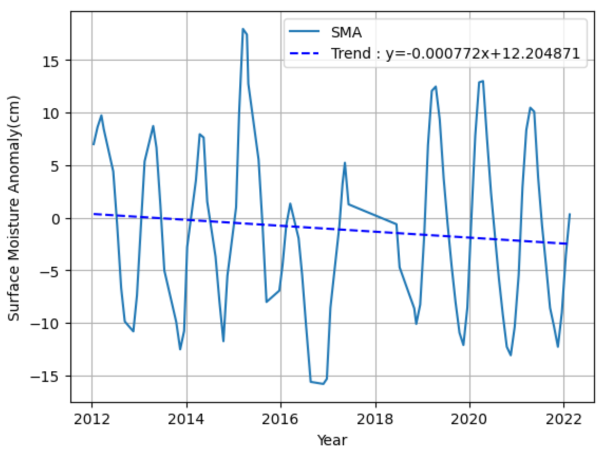


(b)

Figure 6: Fluctuations in SMS, as derived from GLDAS NOAH version data. (a)Time series plot and (b) Spatial temporal illustration

Surface moisture anomalies derived from GRACE CSR and JPL showed different results. There was a negative trend of -0.007mm/year and a positive trend of 0.009mm/year determined from CSR and JPL GRACE products respectively (Figure 7).



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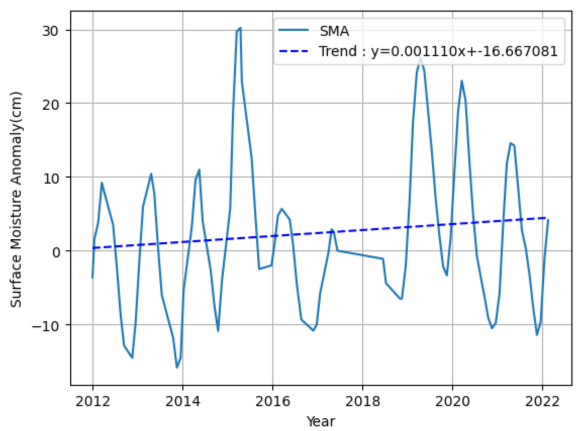


(b)

Figure 7: (a)Time series of SMA for CSR GRACE mascons and (b) Time series of JPL GRACE mascons.

Averages based on CSR and JPL mascons revealed an upward trend of 0.001mm/year, as shown in Figure 8.

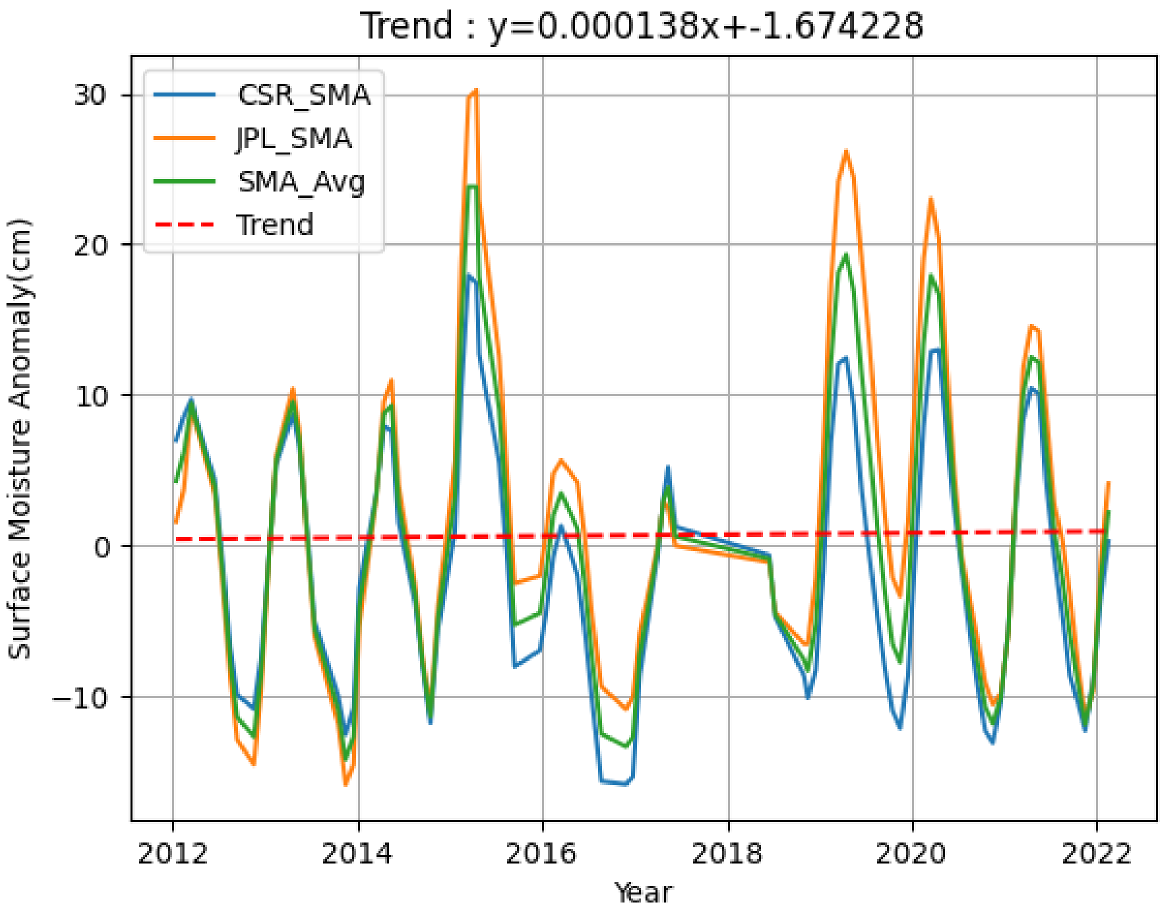


Figure 8: The dotted line in red represents a 0.001mm/year positive trend of SMA based on the CSR and JPL GRACE mascon averages of SMA variations

4.1.3. Variations in Ground Water Storage (GWS)

A time series analysis of all the components showed that SW and CAN are negligible compared to TWS and SM (Figure 9). GWS levels were obtained by applying equation [7. A trend analysis of GWS revealed that there was a slight increase in groundwater levels (Figure 10).

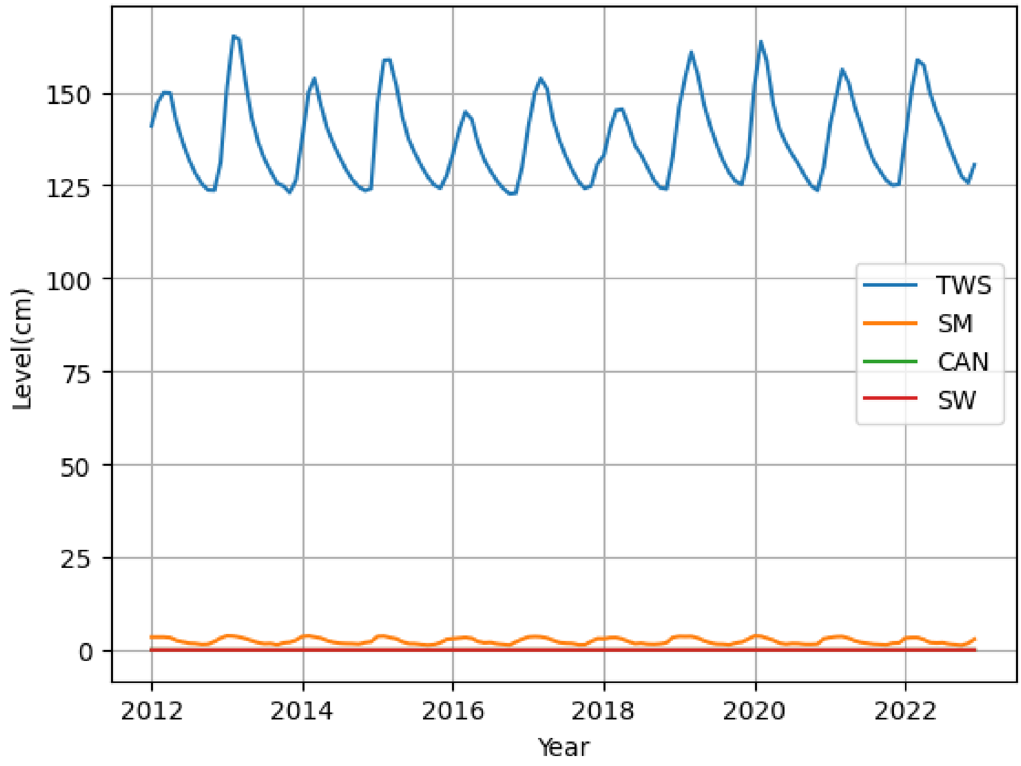


Figure 9: Time series of monthly averages for water balance equation components used in this study

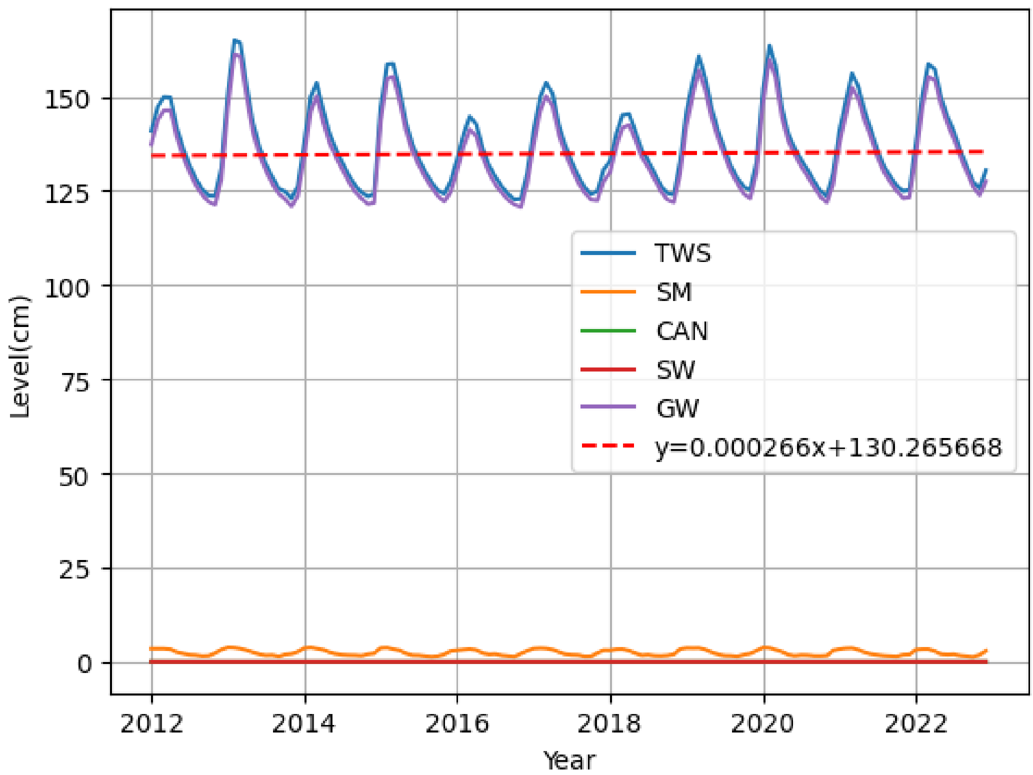


Figure 10: Time series trend analysis of GW determined from GLDAS (+0.002mm/year)

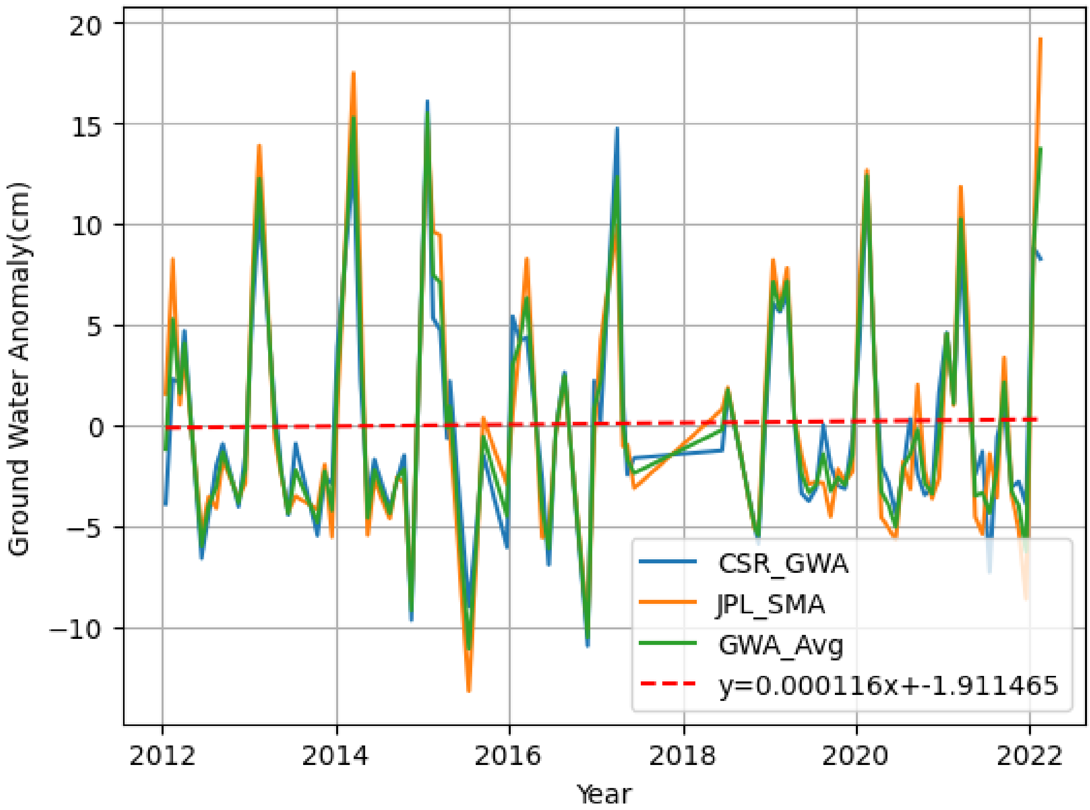


Figure 11: GWA time series with a trend line (red dotted line) representing an upward trend of +0.001mm/year. Average GWA (in green) has been determined from CSR GWA (in blue) and JPL GWA (in orange).

4.2. Discussions

Both GLDAS and the averages of the GRACE mascons for the study area during the study period provided annual variations in the levels of TWS storage. Both solutions indicated a slight increase in the levels of TWS. Both the GLDAS and GRACE indicated an increase of 0.002mm/year in the total terrestrial water storage capacity. There were similarities in the shapes of the TWS trends revealed from both the GRACE and the GLDAS data.

There were differences in the trends of surface moisture revealed by GLDAS data and GRACE mascon averages. Nonetheless, there was also a strong agreement between surface moisture trends of GLDAS and GRACE CSR (Figure 6(a) and Figure 7(a)). Despite the downward trends shown from the GLDAS and GRCAE CSR surface moisture time series, the slight increase in TWS levels can only be explained by increases in the other components (such as surface moisture and ground water).

Based on the GRACE mascons, the levels of groundwater storage were determined in terms of the anomalies. Applying Equation [3, GWA was determined and revealed an almost changeless groundwater storage capacity. Concurring with TWSA and SMA, an upward trend of as little as 0.001mm/year was determined from the averages of the CSR and JPL solutions. Despite a negative trend in the CSR SMA, there was a positive trend in the CSR-derived GWA of 0.001mm/year over the study period. The JPL-derived GWA increased at a rate of 0.01mm/year. Figure 11 shows a combined time series plot of CSR, JPL and an average for the two mascons. There were agreements in the TWS and GWS from both datasets.

Using Equation [5, the R-value was calculated. The R-value of GWA was close to zero (0.025), which indicated that there was no significant correlation between the values of the average anomalies and the time. A standard error of +/-0.0005 was calculated using Equation [6. It indicates the accurate distribution of GWA data derived from JPL and CSR mascons. This is depicted in Figure 12.

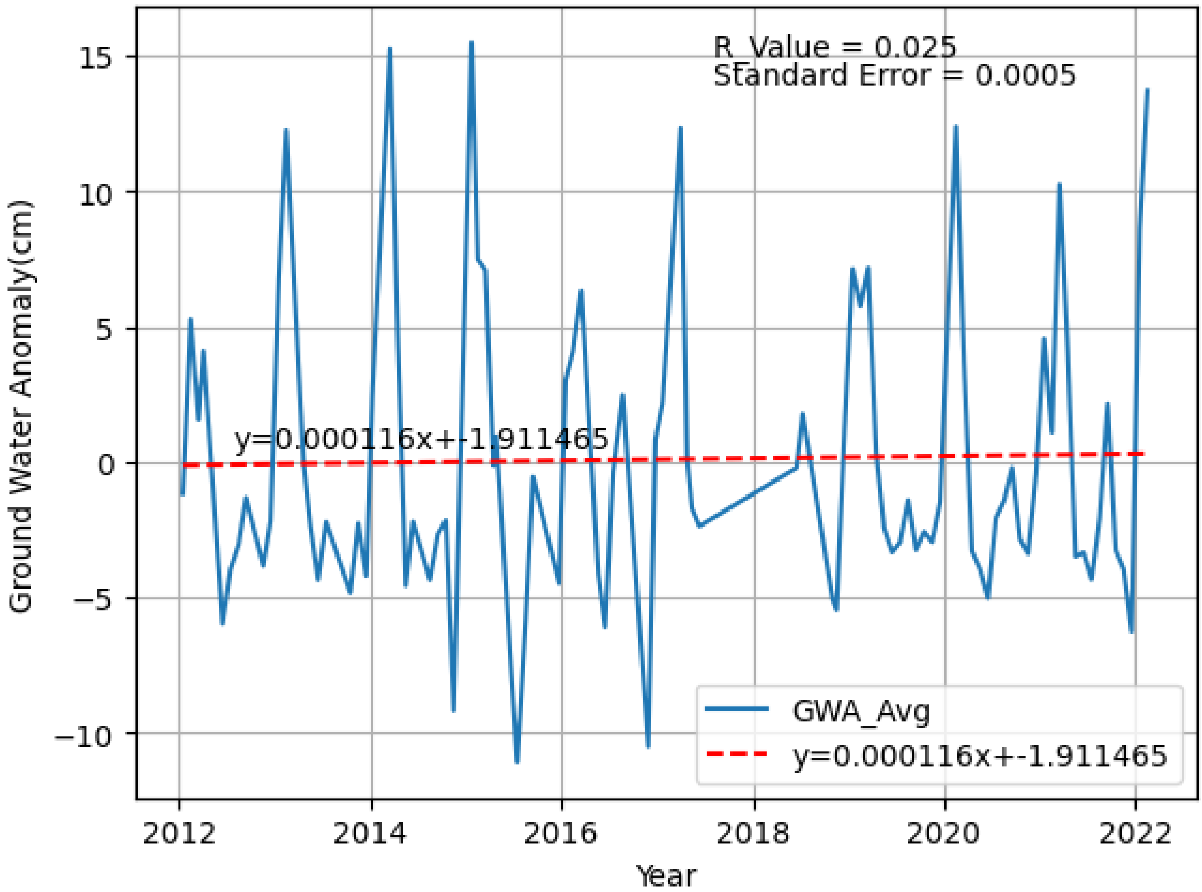
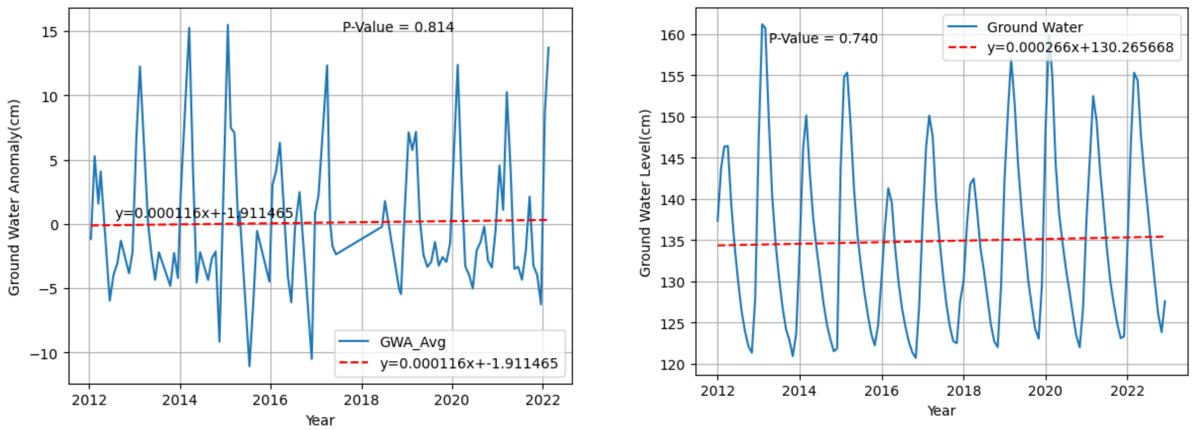


Figure 12: A plot indication of the correlation between GWA and time (R value) and accuracy of the data distribution in the population (standard error)

The P-values of the GWS were calculated to determine the significance of the trends at a 95% confidence interval. For GLDAS and GRACE, the P-values were 0.74 and 0.814 respectively, both being greater than 0.05. It can also be shown that the null hypothesis that there was an insignificant increase in groundwater levels over the period cannot be rejected.



(a) GRACE

(b) GLDAS

Figure 13: (a) Time series trends of GRACE-based GWA and (b) GLDAS-based GWS level with trend P-values.

5. Conclusion

The results of this study indicate that the overall variation rate of the GRACE-based GWSA of Balaka district of Malawi over the period, 2012 to 2022, was +0.001mm per year. The study estimated a groundwater increase of $2000m^3$per year. The GLDAS data analysis revealed a ground water storage level increase of +0.002mm per year, which translates to $4000m^3$ of water per year. The 10-year continued study of terrestrial water storage variations in the area over the period showed an increasing trend in TWS until 2013, followed by a decline until 2017, and then an increase until 2022, representing an average upward trend of 0.002mm year. It can also be concluded that the upward trend in groundwater levels was not significant, as determined from the calculated P-values. This is so because the P-values of the two trends based on the two datasets were both greater than 0.05 at a 95% confidence level.

The upward trend, coupled with the continued exploitation of the ground water in the area, leaves room for an investigation into the influencing factors of the trend and a determination of the possibility of an aquifer recharge in the area. From the calculated R-value and standard error, it can be concluded that time has had no impact on the change in the water levels. As such, there are other influencing factors that have resulted in a minimal increase in the terrestrial water levels. This study is significant because it will help in understanding the trend in groundwater levels which will help in the effective management of water resources in Malawi. It will also promote the use of Geodesy in the management of water resources.

Conflict of interest

The author declares no conflict of interest related to this study.

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6. Data availability statement

The author used the following data:

F Landerer. 2021. TELLUS_GRAC_L3_CSR_RL06_LND_v04. Ver. RL06 v04. PO.DAAC, CA, USA. Dataset accessed [2023-05-15] at https://doi.org/10.5067/TELND-3AC64.

Beaudoing, H. and M. Rodell, NASA/GSFC/HSL (2020), GLDAS Noah Land Surface Model L4 monthly 0.25 x 0.25-degree V2.1, Greenbelt, Maryland, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: [2023-07-29], https://doi.org/10.5067/SXAVCZFAQLNO

JPL mascon solution available at: https://podaac.jpl.nasa.gov/dataset/TELLUS_GRAC-GRFO_MASCON_GRID_RL06_V2

CSR solution available at: http://www2.csr.utexas.edu/grace/RL06_mascons.html

7. References

Ikuemonisan, F. E., & Ozebo, V. C. (2020). Characterisation and mapping of land subsidence based on geodetic observations in Lagos, Nigeria. *Geodesy and Geodynamics*, 151-162.

Alshehri, F., & Mohamed, A. (2023). Analysis of Groundwater Storage Fluctuations Using GRACE and Remote Sensing Data in Wadi As-Sirhan, Northern Saudi Arabia. *Water*, 1-16. Retrieved from https://doi.org/10.3390/w15020282

Bian, Y., Li, Z., Huang, Z., He, B., Shi, L., & Miao, S. (2023). Combined GRACE and GPS to Analyze the Seasonal Variation of Surface Vertical Deformation in Greenland and Its Influence. *Remote Sensing*, 1-19. Retrieved from https://doi.org/10.3390/rs15020511

Bluman, A. G. (2007). *Elementary statistics : a step by step approach* (7th ed.). New York: McGraw Hill.

Böhm, J., & Schuh, H. (2013). *Atmospheric Effects in Space Geodesy.* Berlin: Springer.

Creutzfeldt, B., Güntner, A., Klügel, T., & Wziontek, H. (2008). Simulating the influence of water storage changes on the superconducting gravimeter of the Geodetic Observatory Wettzell, Germany. *Geophysics*, 1-27.

Döhne, T., Horwath, M., Groh, A., & Buchta, E. (2023). The sensitivity kernel perspective on GRACE mass change estimates. *Journal of Geodesy*, 1-20. Retrieved from https://doi.org/10.1007/s00190-022-01697-8

Fatolazadeh, F., Eshagh, M., & Goita, K. (2022). New spectro-spatial downscaling approach for terrestrial and groundwater storage variations estimated by GRACE models . *Journal of Hydrology*, 1-20.

Frappart, F., & Ramillien, G. (2018). Monitoring Groundwater Storage Changes Using the Gravity Recovery and Climate Experiment (GRACE) Satellite Mission: A Review. *Remote Sensing*, 1-25.

Han, Y., Zuo, D., Xu, Z., Wang, Z., Wang, G., Peng, D., . . . Hong, Y. (2023). Attributing the Impacts of Vegetation and Climate Changes on the Spatial Heterogeneity of Terrestrial Water Storage over the Tibetan Plateau. *Remote Sensing*, 1-22. Retrieved from https://doi.org/10.3390/rs15010117

Hellens, A. v. (2013, October 1). Groundwater quality of Malawi – fluoride and nitrate of the Zomba-Phalombe plain. Uppsala, Uppsala, Sweden. Retrieved from http://stud.epsilon.slu.se/

Herring, T. (2007). *Treatise on Geophysics* (Vol. 3: Geodesy). Los Angeles, California: Elsevier.

Huang, Z., Yeh, P. J.-F., Jiao, J. J., Luo, X., Pan, Y., Long, Y., . . . Zheng, L. (2023). A New Approach for Assessing Groundwater Recharge by Combining GRACE and Baseflow With Case Studies in Karst Areas of Southwest China. *Water Resources Research*, 1-25. Retrieved from https://doi.org/10.1029/2022WR032091

Humphrey, V., Matthew, R., & Eicker, A. (2023). Using Satellite-Based Terrestrial Water Storage Data: A Review. *Springer*, 1-29. Retrieved from https://doi.org/10.1007/s10712-022-09754-9

Khorrami, M., Shirzaei, M., Ghobadi-Far, K., Werth, S., Carlson, G., & Zhai, G. (2023). Groundwater Volume Loss in Mexico City Constrained by InSAR and GRACE Observations and Mechanical Models. *Geophysical Research Letters*, 1-11. Retrieved from https://doi.org/10.1029/2022GL101962

Li, M., Sun, J., Xue, L., Shen, Z., Zao, B., & Hu, L. (2022). Characterization of Aquifer System and Groundwater Storage Change Due to South-to-North Water Diversion Project at Huairou Groundwater Reserve Site, Beijing, China, Using Geodetic and Hydrological Data. *Remote Sensing*, 1-23. Retrieved from https://doi.org/10.3390/rs14153549

Li, X., Zhong, B., Li, J., & Liu, R. (2022). Analysis of terrestrial water storage changes in the Shaan-Gan-Ning Region using GPS and GRACE/GFO. *Geodesy and Geodynamics*, 179-188. Retrieved from http://www.keaipublishing.com/geog

Liu, R., Zhong, B., Li, X., Zheng, K., Liang, H., Cao, J., . . . Lyu, H. (2022). Analysis of groundwater changes (2003–2020) in the North China Plain using geodetic measurements. *Journal of Hydrology: Regional Studies*, 1-12. Retrieved from https://www.elsevier.com/locate/ejrh

Mapoma, H. W., & Xie, X. (2014). Basement and alluvial aquifers of Malawi: An overview of groundwater quality and policies. *African Journal of Environmental Science and Technology*, 190-202.

Mohamed, A., Abdelrady, A., Alarif, S. S., & Othman, A. (2023). Geophysical and Remote Sensing Assessment of Chad's Groundwater Resources. *Remote Sensing*, 1-22. Retrieved from https://doi.org/10.3390/rs15030560

Mucia, A. J. (2018). *Analysis of Gravity Recovery and Climate Experiment (GRACE) Satellite-Derived Data as a Groundwater and Drought Monitoring Tool.* University of Nebraska, School of Natural Resources. Lincoln: University of Nebraska.

Ngongondo, C., Xu, C.-Y., Gottschalk, L., & Alemaw, B. (2011). *Evaluation of spatial and temporal characteristics of rainfall in Malawi: a case of data scarce region*, 79-93.

Seka, A., Zhang, J., Gebiaw, A., Demeke, Y., Han, J., & Prodhan, F. A. (2022). Spatio-temporal analysis of water storage variation and temporal correlations in the East Africa lake basins. *Journal of Hydrology: Regional Studies*, 1-20. Retrieved from https://www.elsevier.com/locate/ejrh

Shao, C., & Liu, Y. (2023). Analysis of Groundwater Storage Changes and Influencing Factors in China Based on GRACE Data. *Atmosphere*, 1-20. Retrieved from https://doi.org/10.3390/atmos14020250

Suya, R. G., Kapachika, C. C., Soko, M. O., Luhanga, V., Ogwang, J. B., Chilembwe, H., & Gitau, F. (2022). Applying Malawi Continuously Operating Reference Stations (CORS) in GNSS Meteorology. *South African Journal of Geomatics*, 218-233. Retrieved from http://dx.doi.org/10.4314/sajg.v11i2.4

UNAVCO. (2012). A Foundation for Innovation: Grand Challenges in Geodesy, Report from the Long-Range Science Goals for Geodesy Community Workshop. In J. L. Davis, Y. Fialko, W. E. Holt, M. M. Miller, S. E. Owen, & M. E. Pritchard (Ed.), *UNAVCO.* Colorado: UNAVCO.

Wang, H., Xiang, L., Steffen, H., Wu, P., Jiang, L., Shen, Q., . . . Hayashi, M. (2022). GRACE-based estimates of groundwater variations over North America from 2002 to 2017. *Geodesy and Geodynamics*, 11-23.

Wang, S., Cui, G., Li, X., Liu, Y., Li, X., Tong, S., & Zhang, M. (2023). GRACE Satellite-Based Analysis of Spatiotemporal Evolution and Driving Factors of Groundwater Storage in the Black Soil Region of Northeast China. *Remote Sensing*, 1-19. Retrieved from https://doi.org/10.3390/rs15030704