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ORIGINAL ARTICLE

Analysis of spatio-temporal variability of groundwater storage in Ethiopia using Gravity Recovery and Climate Experiment (GRACE) data

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Abstract

The spatio-temporal variability of groundwater storage cannot be well understood without proper groundwater monitoring schemes. Since 2002, the launch of the Gravity Recovery and Climate Experiment Satellite (GRACE) mission has served to monitor Groundwater Storage Anomaly (GWSA) and filled the observational data gap on a regional scale. This study aimed to estimate the spatio-temporal GWSA in Ethiopia using GRACE satellite data. GWSA was calculated by disaggregating GRACE estimation of Terrestrial Water Storage Anomaly (TWSA) using auxiliary soil moisture and surface runoff data obtained from the Global Land Data Assimilation System. GWSA was decomposed using the Seasonal-Trend decomposition method, LOESS (STL). The results depicted an increasing variability of TWSA and GWSA over various regions of the country. Ethiopia experienced an increase in TWSA (3.8 mm yr^{-1}) and GWSA (4.6 mm yr^{-1}) between the years 2003 and 2021, with GWSA contributing primarily to the TWSA. Greater contributions to the rise in groundwater storage come from the Rift Valley, Omo Gibe, Baro Akobo, and a portion of the Genale Dawa, Awash, and Wabi Shebelle Basins. Except for the lowlands (Northwestern, Northeastern and Southeastern), most regions showed an average increase in GWSA per annum at varying rates. Precipitation, temperature, and evapotranspiration have a significant influence on the spatial variability of GWSA. The impact of precipitation on GWSA reached its maximum after a 2-month lag (correlation coefficient $(R) = 0.62$). GRACE captured the seasonal GWSA of Ethiopia reasonably well and can be used as a guide for a more detailed evaluation of the groundwater potential.

Keywords GRACE · Terrestrial water storage · Groundwater storage · STL method · Ethiopia

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Introduction

Groundwater is a primary source of fresh water in many parts of the world (Rodell et al. 2009). It is also the largest and major source of drinking water in Africa (Macdonald et al. 2012). Groundwater has been overexploited (Frappart and Ramillien 2018) and its utilization has been projected to rise due to the rapid increase in population and abstraction for various needs (Pavelic et al. 2012). The stress created by the continuous abstraction of groundwater resources is exacerbated by climate change and variability (Taylor et al. 2013; Scanlon et al. 2022).

In Ethiopia, groundwater extraction is mainly for domestic water supply in rural and most urban centers, and its use for irrigation has been increasing (Ministry of Water and Energy (MOWE) 2013; Kebede et al. 2018; Birhanu et al. 2021). The water resource development plan of the country (2015–2025) is also based mainly on groundwater (Mengistu et al. 2019). Yet, groundwater is poorly monitored and there are no national groundwater level monitoring programs in Ethiopia (Kebede et al. 2018). Given, the installation of monitoring well networks is costly and labor-intensive (Rodell et al. 2007), it is difficult to adequately implement groundwater monitoring schemes in Ethiopia soon. Further, even though in situ data are undoubtedly important, it is difficult to apply the groundwater monitoring system at a regional scale and in inaccessible areas. Moreover, the groundwater level measurements made at one site may not accurately reflect the conditions throughout the region of interest (Yin et al. 2018). This is due to the different lithology in the vadose zone and preference flows, and groundwater recharge varies among different regions (Yang et al. 2019). All these aforementioned limitations necessitate the need to apply other tools to monitor groundwater resources in space and time and implement better groundwater management systems.

To this end, the GRACE satellite mission offers the opportunity to record monthly changes in terrestrial water storage since 2002 by converting observed gravity anomalies into changes of equivalent water height (Wahr et al. 2004; Tapley et al. 2004; Scanlon et al. 2015). GRACE provides temporal and spatial records of column-integrated terrestrial water storage components, including snow, surface water, soil moisture, canopy water, and groundwater (Voss et al. 2013; Ali et al. 2021, 2022a). Consequently, GRACE satellite data have the potential to address the observational gap in monitoring regional water storage changes (Strassberg et al. 2009). After the GRACE mission ceased operation in November 2017, the GRACE Follow-On (GRACE-FO) was launched in May 2018 to resume the endeavor; it has a similar satellite orbit configuration but an improved system design. There is a gap of nearly a year (July 2017–May 2018) between the GRACE and GRACE-FO missions, although this will not have an impact on the majority of associated applications that focus on seasonal and long-term time scales (Chen et al. 2022). Spherical harmonic (SH) and mass concentration (Mascon) data versions are included in the latest GRACE TWSA products. Three different processing centers, which are the Jet Propulsion Laboratory (JPL), GeoforschungsZentrumPotsdam (GFZ), and the Center for Space Research at the University of Texas, Austin (CSR), release different solutions by using different approaches and parameters.

Globally, many studies have been conducted for various purposes using the data retrieved from the GRACE satellite mission. For instance, the estimation of global and regional TWSA (Longuevergne et al. 2013; Long et al. 2015; Zhu et al. 2021), drought assessment (Houborg et al. 2012; Kenea et al. 2020; Nigatu et al. 2021; Ali et al. 2022b) and analysis of GWSA (Rodell et al. 2007; Strassberg et al. 2009; Abou Zaki et al. 2019; Salam et al. 2020; Ali et al. 2021). The GWSA can be isolated from GRACE data using auxiliary information on the other components of TWS, either from land surface models (LSM) (Rodell et al. 2007) or in situ observations (Yeh et al. 2006). The NOAH model, within the framework of the Global Land Data Assimilation System (GLDAS), is a common LSM that has been used in many studies to derive soil moisture storage (e.g., Rodell et al. 2007; Awange et al. 2014; Yin et al. 2017). The GRACE-GLDAS approach for estimating GWSA is more skilful for larger regions (Rodell et al. 2007). It can be effectively applied for regional scale—areal coverage of ~200,000 km^2 (Long et al. 2015; Miro and Famiglietti 2018; Shamsudduha and Taylor 2020). The larger the study area is, the higher the accuracy of the data (Swenson et al. 2003). Many studies confirmed that GRACE-derived GWSA agreed well with available in situ records (e.g., Strassberg et al. 2009; Huang et al. 2015; Rateb et al. 2020; Ali et al. 2021). Therefore, it is capable of investigating variability in GWSA in data-poor regions (Skaskevych 2014; Mistry et al. 2019). On top of that, some studies indicated the importance of downscaling GRACE data to study GWSA at the local scale (e.g., Yin et al. 2018; Ali et al. 2021). According to Pascal et al. (2022), the downscaling approach generally improves the temporal agreement of GRACE GWSA with in situ measurements when compared to the non-downscaling situation. Besides, the accuracy and reliability of GRACE-based GWSA estimation are directly related to a range of errors (Kiss and Foldvary 2017). The error comprises the inherent measurement errors (Chen et al. 2004), the North–South striping errors (Swenson and Wahr 2006), leakage error (Swenson and Wahr 2002), filtering error

(Eicker et al. 2012), and uncertainty contribution of the non-groundwater storage component data used in terrestrial water storage decomposition (Li et al. 2023).

In Ethiopia, previous studies utilized different remote sensing and geospatial techniques for the exploration and potential assessment of groundwater resources (e.g., Fenta et al. 2015; Bashe 2017; Anteneh et al. 2022). On the other hand, many conventional hydrogeological field investigations and modeling have been conducted in different parts of the country at the local scale (e.g., Kebede 2013; Ayenew et al. 2008; Kebede et al. 2018; Tigabu et al. 2020; Birhanu et al. 2021; Sisay et al. 2023). The previous studies revealed the variation in groundwater potential and yield of groundwater wells in different parts of Ethiopia (Moges 2012). According to Mengistu et al. (2019), there is no agreement on the nation-wide estimation of groundwater potential. Besides**,** a few studies utilized GRACE data to estimate groundwater storage in the region (Bonsor et al. 2010; Melesse et al. 2010; Awange et al. 2014; Kenea et al. 2020; Nigatu et al. 2021). For instance, Awange et al. (2014) have applied 4° × 4° NOAH LSM soil moisture and SH GRACE data (2003–2011) to characterize mega hydrogeological regimes of Ethiopia. However, as compared to the continuing improved resolution of GRACE data, a very coarse resolution with a limited record period lacks the advantage of characterizing the trend of regional GWSA within the context of longer-term hydro-climatic records. Moreover, the Mascon solution offers significantly improved spatial localization and more accurate amplitude measurements of changes in recovered TWSA (Wang et al. 2020). According to Save et al. (2015) and Watkins et al. (2015), the CSR Mascon solution is considered to have a higher signal-to-noise ratio, higher spatial resolution, and reduced error. Hence, it provides accurate surface-based gridded information that can be used without further processing (Save et al. 2016). This GRACE data have been widely used in previous studies (e.g., Xie et al. 2019; Scanlon et al. 2015). Moreover, the GRACE RL06 solutions show significantly smaller root mean square error than those from RL05, benefitting from improved geophysical background models and data processing procedures.

In this study, a longer (2003–2021) 0.25° × 0.25° CSR GRACE and GRACE-FO RL06 Mascon data and GLDAS NOAH soil moisture and surface runoff dataset were used to characterize GWSA in Ethiopia. The temporal trend was evaluated using the Mann–Kendall (MK) trend test and Sen's slope estimator, and time-series components of GWSA were also decomposed using STL. The spatio-temporal variability of GWSA is determined and the impact of climate variables on Ethiopia's groundwater storage was evaluated. Finally, the GRACE-based GWSA was validated by analyzing precipitation data.

Materials and methods

Study area

Ethiopia is geographically located in the eastern part of Africa between 3° to 15° latitude and 33° to 48° longitude, with a total area of 1.13×10^6 km^2. Ethiopia has an extremely varied topography featuring elevation ranging between two extremes from 120 m below the mean sea level (e.g., Dallol depression) to 4620 m above the mean sea level (e.g., Ras Dashen, northern mountains) (Fig. 1a). The main Ethiopian Rift Valley, part of the East African Rift system, separates the western highlands from the eastern highlands of the country. The climate of Ethiopia is highly variable and diverse and is influenced by altitude. The highlands in the central, west, and southwest regions are temperate (humid and warm), with distinct dry and wet seasons. The lowland areas are arid with significantly hotter and drier climates (Kebede et al. 2018). Over the last decades, the average temperature has significantly increased over the past 40 to 50 years, rising by 0.20 to 0.28 °C per decade (Eshetu et al. 2014). The lowlands, southeast and northeast parts of the country, are vulnerable to increased temperature and prolonged droughts (McSweeney et al. 2008; Ministry of Foreign Affairs of Ethiopia (MOFA) 2018). On average, the analysis of ERA 5 temperature data showed the rise and decline of temperature in the wet and dry periods of the country, respectively (https://cds.climate.copernicus.eu/ accessed online on 10 May 2022). The lowest mean annual evapotranspiration is recorded in the central highlands (620 mm) and rises to a maximum (2350 mm) in the southeastern and northeastern lowlands of the country (Berhanu et al. 2013).

Analysis of Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) indicated that the average annual precipitation in Ethiopia over the study period was 830 mm. Precipitation in Ethiopia has uneven distribution both in time and space. Besides, due to strong inter-annual and inter-decadal variability, it is difficult to detect the long-term trends of precipitation (McSweeney et al. 2024). The highlands may suffer from more intense and irregular precipitation (MOFA 2018). The mean annual precipitation ranges from less than 300 mm in the south-eastern and north-western lowlands to over 2000 mm in the south-western highlands (Fig. 1b). Most of the country experiences one main wet season (locally known as "Kiremt") with precipitation up to 350 mm per month. Sections of north and central Ethiopia have Kiremt and a second smaller rainy season, "Belg" (February–May). The southern part has two distinct wet and dry seasons, a bimodal precipitation pattern (Berhanu et al. 2014); and the Belg and "Bega" seasons (October–December) (MOFA 2018).

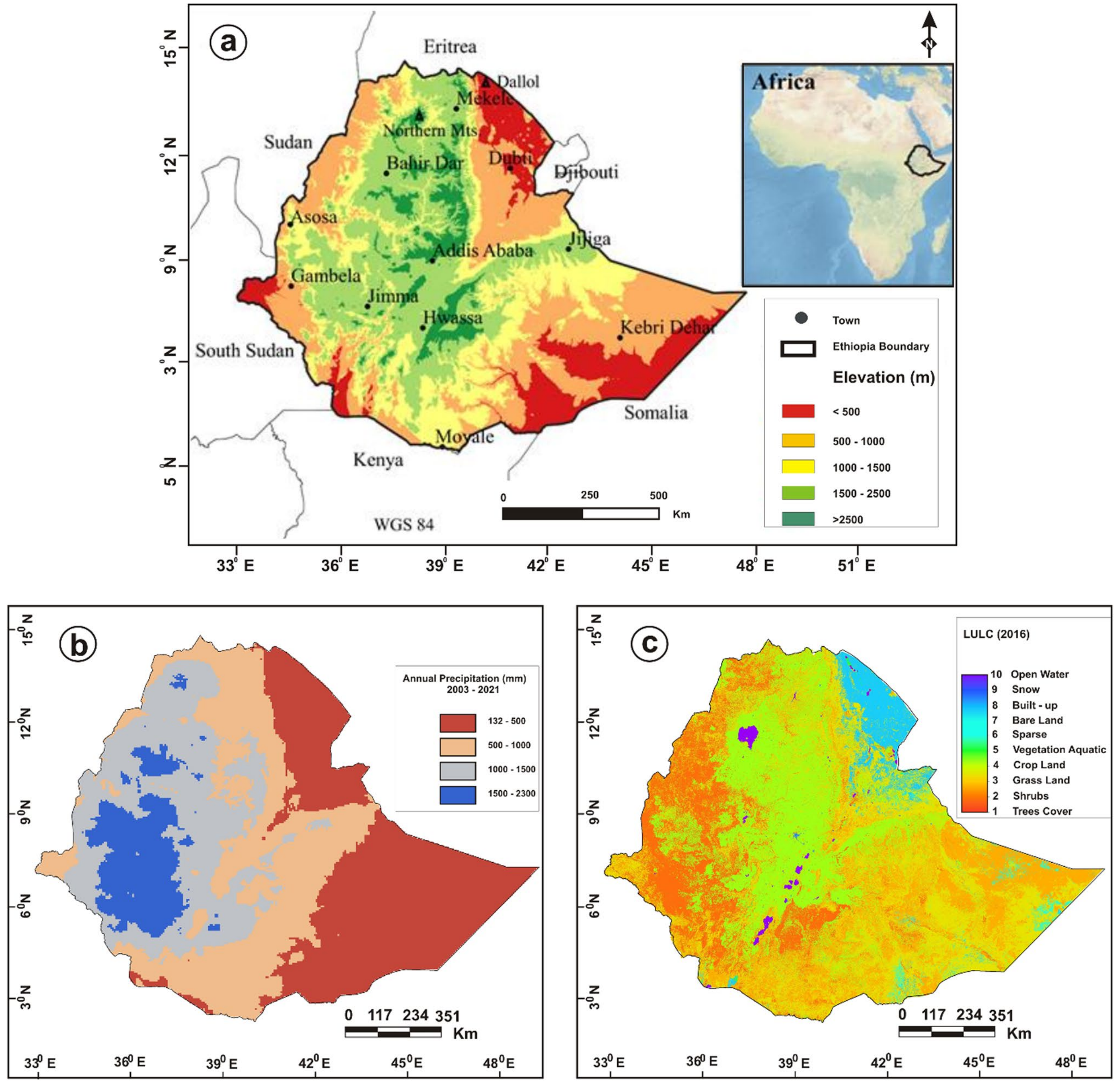

Fig. 1 Description of the study area: **a** location of Ethiopia including a 90 m digital elevation model derived from Shuttle Radar Topographic Mission (SRTM); **b** the amount of annual precipitation in major river basins; and **c** land use land cover

The easternmost corner of Ethiopia receives very little precipitation throughout the year (McSweeney et al. 2024).

Furthermore, topographic variation and regional and global changes in the weather systems caused the spatial variability of precipitation in Ethiopia (National Meteorological Agency 1996; Abiye 2006). The variability in the duration and intensity of the main rainy season is influenced by the intertropical convergence zone (ITCZ), tropical easterly jet (TEJ), winds from the Atlantic and Indian Ocean, and the East African low-level jet (EALLJ) (Endalew 2007; Zeleke et al. 2013). Besides, the El Nino Southern-Oscillation (ENSO) extremes of El Nino and La Nina are the main drivers of climate-related hazards in Ethiopia (Wolde-Giorgis et al. 2022). For example, the 2015/16 El Nino triggered drought conditions in the country (Philip et al. 2018). Ethiopia has experienced around 22 droughts since 1876, with an average cycle of 6 years, demonstrating the long history of the phenomenon (Zegeye 2018). The major drought periods which occurred between 2003 and 2021 include 2002/2003, 2004, 2009, 2011, and 2015/2016 (Bayissa et al. 2015; Mera 2018; Kenea et al. 2020). Ethiopia's dry land regions in the north, south, and southeast continue to experience an increase in the frequency of meteorological drought occurrences (Eshetu et al. 2014). According to Cherinet et al. (2022), 11 major floods have occurred in the past two decades. In general, the rising frequency and intensity of droughts and floods is hindering the expansion of the water sector (Berhanu et al. 2014). Rapid land use land cover change (LULC) has been recognized in the country (Regasa et al. 2021; Shiferaw et al. 2021), mainly due to anthropogenic influence (Negesse 2021). The 2016 Sentinel 2 land use land cover map was accessed from Ethiopia Sentinel2 Land Use Land Cover 2016—GeoNode (rcmrd.org) on March 2022, and the spatial variability of LULC has been observed. Figure 1c shows that most parts of the highlands were covered by cropland and trees, and the LULC in the lowlands was mainly bareland, shrubs, and grassland. Further, the highland plateau accommodates almost 90% of Ethiopia's population (Robinson et al. 2013).

Ethiopia consists of variable soil cover, geology, and hydrogeology (Shishaye et al. 2020). The proportion of surface cover out of the country's total landmass and a description of the major geological formations are presented in Table 1.

Ethiopia is naturally endowed with water resources and makes one of the largest surface freshwater resources in sub-Saharan Africa (MOWE 2013). Because of the country's varied topography, the components of terrestrial water storage (surface runoff and evapotranspiration) vary greatly from region to region (MOWE 2013). The highlands are the source of major perennial rivers. In places below 1500 m, there are very few perennial surface water flows (Kebede et al. 2018). Twelve river basins (Fig. 1b), 11 fresh and 9 saline lakes, 4 crater lakes, and over 12 major wetlands exist in the country (Awulachew et al. 2007). According to the Ministry of Water Resources of Ethiopia (2002), the Blue Nile, Tekeze, Baro Akobo, and Omo Gibe river basins—where only 30 to 40 percent of Ethiopia's population resides—contain between 80 and 90 percent of the country's water resources**.** However, the country's water resource is not fully utilized and developed due to many factors: inaccessible spatial distribution, limited financial resources, and technical challenges (Berhanu et al. 2014). The occurrence, quantity, and quality of groundwater in Ethiopia are controlled by the variability of geology, geomorphology, tectonic history, and climate conditions (Abiye 2006). Based on their regional extent, lithological homogeneity, and hydrologic properties, the aquifers of Ethiopia are grouped under hard rock aquifers, consolidated sedimentary rock aquifers, and unconsolidated aquifers (Moges 2012). According to Kebede et al. (2018), the recharge in Ethiopia varies from 0 to 300 mm per year and nearly 60% of aquifers receive both quick recharge from heavy precipitation events and indirect recharge from floods and mountain runoff. As indicated, the major sources of groundwater in Ethiopia consist of boreholes, hand-dug wells, and springs.

Dataset

GRACE data

The monthly estimates of TWSA were obtained from GRACE and GRACE-FORL06 Mascon solutions provided by the Center for Space Research (CSR), the University of Texas, Austin, from http://www2.csr.utexas.edu/grace, accessed online on March 10, 2022. This data is represented on a 0.25° × 0.25° grid and provides anomalies relative to a baseline mean from 2004 to 2009. This GRACE data have already been post-processed (Swenson and Wahr 2006) and expressed in terms of equivalent water height. It was selected over the outputs of other data centers due to its higher resolution. Most of the global studies applied the 2003 to 2016 GRACE data since fewer missing data existed in the GRACE mission period. However, this study intended to investigate the nature of GWSA to date. Thus, the monthly

Table 1 Description of the geological cover in Ethiopia (relevant data were taken from Kazmin 1975; Mohr 1983; Zanettin 1993; Abiye 2006)

Major geological formations	Areal coverage (%)	Description
The basement rocks	18	Exposed in the northern, western, southern, and eastern parts of the country
The Paleozoic–Mesozoic sedimentary rocks	25	The Paleozoic–Mesozoic sedimentary rocks are represented by three distinct sedimentary basins; namely: the Ogaden Basin, the Blue Nile Basin, and the Mekele Basin
Tertiary volcanic rocks	40	The igneous rocks of Ethiopia represented by tertiary and quaternary volcanic rocks are divided into two main series: Trap Series and Rift volcanic, the former are dominantly localized in the highlands of Ethiopia associated with the Afar hotspot
Quaternary sediments and volcanic rocks	17	The Plio-Quaternary volcanic rocks are largely restricted in the Rift Valley, and substantial shield volcanoes consisting mainly of basalt lava developed on the Ethiopian plateau

time series of GRACE data from January 2003 to December 2021 was used. The missing data between 2003 and 2016 were filled using linear interpolation which has been used by many researchers (e.g., Long et al. 2015; Ali et al. 2021, 2022a). This study did not attempt to fill the longer data gap between the GRACE and GRACE-FO missions because it may cause uncertainty in the estimation of GWSA (Zhang et al. 2022).

GLDAS data

GLDAS has been developed by the joint effort of NASA, Goddard Space Flight Center (GSFC), the National Oceanic and Atmospheric Administration (NOAA), and the National Centers for Environmental Prediction (NCEP). It has been utilizing advanced land surface modeling and data assimilation techniques to generate optimal fields of land surface states (e.g., soil moisture and surface temperature) and flux (e.g., evaporation and sensible heat flux) products (Rodell et al. 2007). For large-scale basins, it is difficult to attain in situ soil moisture and surface runoff data. Therefore, soil moisture and surface runoff datasets were derived from the GLDAS (https://disc.gsfc.nasa.gov/datasets/GLDAS_NOAH025_M_2.1, accessed online on 15 March 2022). GLDAS consists of four land surface models namely, NOAH, Community Land Model (CLM), Mosaic, and Variable Infiltration Capacity (VIC). In this study, due to its better spatial resolution, monthly soil moisture (0–200 cm) and surface runoff datasets from 2003 to 2021 were derived from the NOAH land surface model. The soil moisture and surface runoff were converted to anomaly using a long-term average (2004–2009) similar to the GRACE anomaly.

Precipitation data

An analysis of measurements from rain gauges shows that a longer precipitation record is available. However, there is a data gap and inhomogeneity, and the gauge networks are sparsely distributed, especially in the lowland areas of the country. Consequently, they are unable to offer a reliable spatial representation of precipitation, particularly while utilizing the data at a larger scale (Gruber and Levizzani 2008). Therefore, the CHIRPS satellite data were selected over the other remote sensing datasets because of its better performance in recording precipitation in Ethiopia (Taye et al. 2018). Moreover, CHIRPS has a promising potential to be used in hydro-meteorological studies such as water resource assessments (Lemma et al. 2019). Some studies (e.g., Ayehu et al. 2018; Nkunzimana et al. 2020) conducted over different regions of the world also confirmed the better accuracy of the CHIRPS data for analyzing precipitation in time and space. This dataset was downloaded from https://data.chc.ucsb.edu/products/CHIRPS-2.0/, accessed online on 20 April 2022, and the data were resampled from 0.05° × 0.05° to 0.25° × 0.25°, to match with the other dataset (Table 2), using bilinear interpolation.

Precipitation anomaly is computed using a long-term average (2004–2009) similar to the GRACE anomaly. The temporal precipitation variability and the response of GWSA were calculated using the correlation coefficient (R) at different time lags (1–5 months); the lag time refers to the time interval between precipitation and consequent rising of groundwater storage.

Methods

Estimation of groundwater storage

GWSA was estimated using a mass balance approach whereby auxiliary data (GLDAS) permitted the isolation of a GWSA signal from TWSA. The approach requires the assumption that the TWSA is composed of changes in soil moisture, snow water equivalent, surface water/reservoir storage, and groundwater (Eq. 1) (Scanlon et al. 2012; Ali et al. 2021, 2022a).

Table 2 Summary of the dataset used in this study with indications of the resolution, data sources and timespan

Dataset	Resolution	Unit	Data source	Data span
TWSA	Monthly, 0.25° × 0.25°	cm	GRACE CSR http://www2.csr.utexas.edu/grace	2003–2021
Soil moisture storage	Monthly, 0.25° × 0.25°	kg/m^2	GLDAS https://disc.gsfc.nasa.gov/datasets/GLDAS_NOAH025_M_2.1	2003–2021
Surface runoff	Monthly, 0.25° × 0.25°	kg/m^2	GLDAS https://disc.gsfc.nasa.gov/datasets/GLDAS_NOAH025_M_2.1	2003–2021
Precipitation	Monthly, 0.05° × 0.05°	mm	CHIRPS https://data.chc.ucsb.edu/products/CHIRPS-2.0/	2003–2021
Evapotranspiration	Monthly, 0.25° × 0.25°		GLDAS https://disc.gsfc.nasa.gov/datasets/GLDAS_NOAH025_M_2.1	2003–2021

$$\mathrm{TWSA} = \mathrm{GWSA} - (\mathrm{SMSA} + \mathrm{SWSA} + \mathrm{CWSA} + \mathrm{SWEA}), \tag{1}$$

where SMSA is the soil moisture storage anomaly, SWSA is the surface water storage anomaly, CWSA is the canopy water storage anomaly, and SWEA is the snow water equivalent anomaly.

Snow and canopy water storage are not considered in this study since there is no snow water storage in Ethiopia (Fig. 1c) and compared to other storage components the change in canopy water is believed to be insignificant. Further, biomass variations have been observed smaller than the uncertainty in GRACE (Rodell et al. 2005). In Ethiopia, the surface water covers 0.7% of the total landmass (MOWE 2013), and the areas of the existing water bodies and their fluctuations levels were quite small (Awange et al. 2014). GLDAS provides surface runoff data that are useful for water resource assessment in ungauged or poorly gauged regions (Bai et al. 2016). Therefore, in this study, surface runoff anomaly (QsA) along with SMSA from GLDAS was used in the estimation of GWSA. The final water balance equation of the area is indicated in Eq. 2 by:

$$\mathrm{GWSA} = \mathrm{TWSA} - (\mathrm{SMSA} + \mathrm{QsA}), \tag{2}$$

where SMSA is the soil moisture storage anomaly, and QsA is the surface runoff anomaly.

Seasonal trend decomposition of GWSA

The GRACE-derived GWSA time series record was decomposed using the STL method in Python programming language. STL is a statistical method of decomposing time series data into components of trend, seasonality, and residual (Eq. 3). It enables the detection of non-linear patterns in long-term trends that cannot be addressed through linear trend analyses. Trend describes the variation of GWSA either increasing or decreasing pattern at regular intervals over a longer period. The continuous upward and downward trends of GWSA that repeat themselves after a fixed interval of time are expressed by the seasonality component. The remaining component is the residual component which is the irregular pattern of the storage, which occurred only for a short period and does not repeat itself after a fixed interval of time, and could not be predictable.

$$\mathrm{GWSA}_t = T_t + S_t + R_t, \tag{3}$$

where GWSA_t is the groundwater storage anomaly at time t, T_t is the trend component, S_t is the seasonal component, and R_t is a remainder (residual or irregular) component.

Trend test and uncertainty analysis

The main idea of trend analysis is to detect whether values of data are increasing, decreasing, or trendless over time (Kisi and Ay 2014). In this study, the most widely used MK test (Mann 1945; Kendall 1975) was employed to detect the existence of a trend in the water balance components. The MK test checks the alternative hypothesis of the existence of an increasing or decreasing trend versus the null hypothesis of no trend. In this study, an alpha value of 0.05 is applied; the underlying premise of this method's technique is that if the computed p-value is higher than the alpha value (0.05), then there is not a significant trend. Theil–Sen's Slope Estimator (Sen's Slope), proposed by Theil (1950) and Sen (1968) is also applied to estimate the magnitude of the slope of trend in the sample of N pairs of data. The efficiency of the MK trend test and Sen's slope estimator were already demonstrated for similar applications (e.g., Ali et al. 2021). According to Wani et al. (2017), the Mann–Kendall statistic (S) is computed as follows in the expression:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sign}\left(y_j - y_i\right), \tag{4}$$

where n is the number of data points, and y_i and y_j are the data values in time series i and j ($j > i$), respectively.

The associated uncertainties of the GRACE-derived GWSA were estimated based on error propagation theory. The estimated errors in the input variables, TWSA, and the GLDAS parameters (SMSA and QsA), contribute to the uncertainty of the resulting GWSA (Li et al. 2023; Khorrami et al. 2023). The overall uncertainty associated with GWSA was calculated according to Eq. 5:

$$\sigma\mathrm{GWSA} = \sqrt{(\sigma\mathrm{TWSA})^2 + (\sigma\mathrm{SMSA})^2 + (\sigma\mathrm{QsA})^2}, \tag{5}$$

where σ stands for the standard deviation of the corresponding parameter.

The general workflow of the study is represented as follows (Fig. 2).

Results and discussion

Spatio-temporal variation of TWSA

The spatial variation of annual TWSA is presented in Fig. 3. TWSA over Ethiopia indicates significant spatial variability. In the southern, southwestern, and central parts of the country, a high TWSA was observed. These areas are prominently characterized by a bimodal precipitation pattern. Therefore, the regions may get significant precipitation during the summer (June, July, and August) and spring (March, April, and

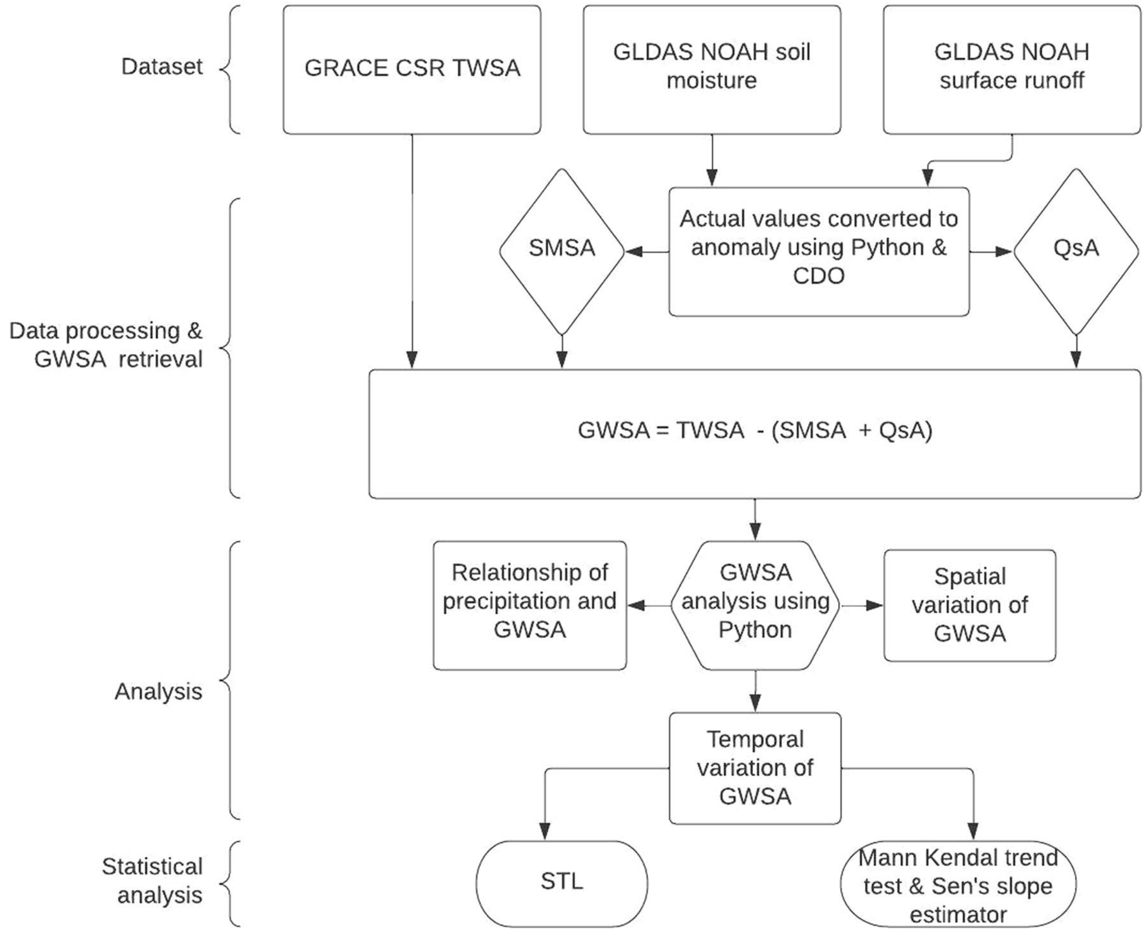

Fig. 2 General workflow of the study: indicating the sources of the dataset, data processing steps and the level of analysis

May) seasons; as a result, the groundwater storage could be improved. Even though the precipitation is dominantly unimodal, a better TWSA is observed in western Ethiopia than in the other regions characterized by bimodal precipitation—the southeastern lowlands and northern Ethiopia. This is due to the existence of abundant precipitation throughout the major rainy period in the former and high annual evapotranspiration rate, low amount of precipitation, and recurrent drought periods in the later.

In Ethiopia, with an average rate of 3.8 mm yr^{-1}, the annual TWSA exhibited an upward tendency (Table 3), which is similar to the findings in the Nile River Basin by Nigatu et al. (2021). The seasonal shift in precipitation is reflected in the monthly TWSA and presented in Fig. 4. On average, the TWSA showed two distinct fluctuation patterns with a high peak in the main rainy months (summer: June, July, and August), and decreased to the minimum in the main dry period (winter: December, January, and February). However, a time lag between TWSA and precipitation is noticeable, which reasonably agrees with the findings of Awange et al. (2014). The TWSA and water reserves raised in the summer due to significant precipitation and decreasing temperature which is analogous to the conclusions of Nigatu et al. (2021). The magnitude of the variation in QsA is very small indicating it has the lowest contribution to the TWSA. Moreover, all the water balance components have a consistent relationship with precipitation. It revealed the water balance in Ethiopia is sensitive to the variation of precipitation. On the other hand, the MK trend test indicated the absence of a significant trend in the annual SMSA, QsA, and precipitation. However, the rising trends in TWSA and GWSA revealed a significant trend at a 0.05 significance level.

Spatial variation of GWSA

The spatio-temporal variation of annual GWSA is presented in Fig. 5. As can be seen there is a high variability in different regions of the country. In most regions, in the years between 2003 and 2006, a negative GWSA is observed, particularly in the northern and central highlands to southern parts of Ethiopia. This might be due to the occurrence of drought periods in the regions

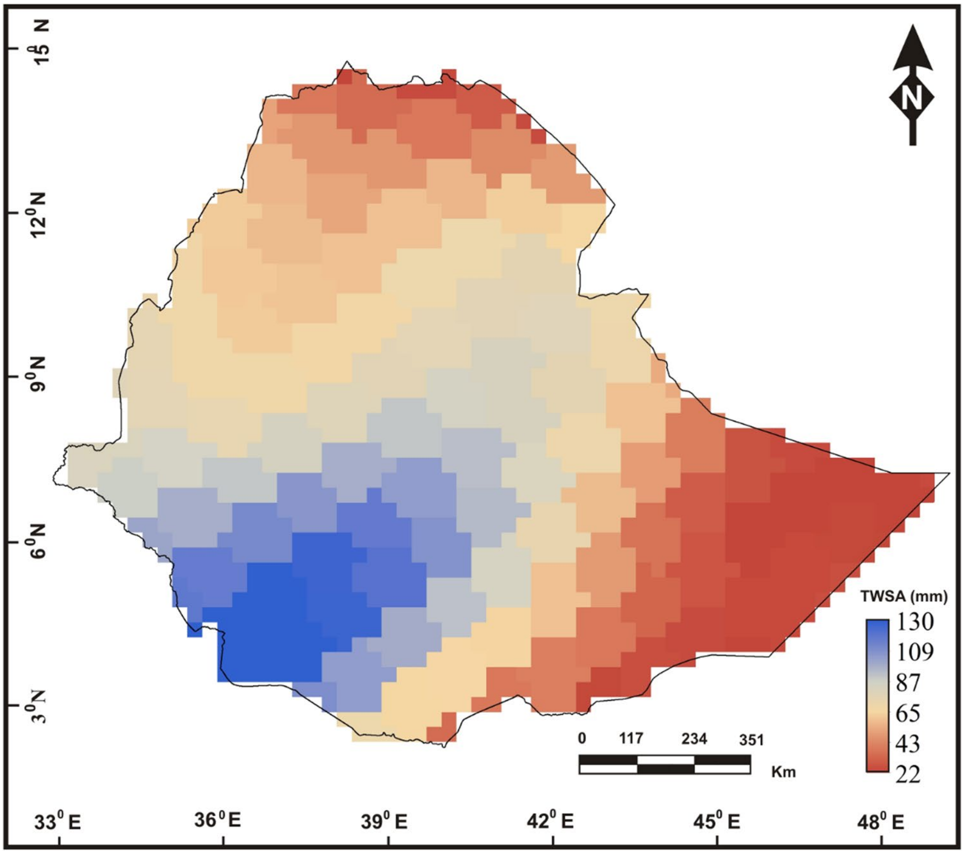

Fig. 3 Spatial variation of annual TWSA (average value of 2003–2021)

Table 3 Statistics of the annual trend and uncertainty values of the hydrological components

Hydrologic components	Trend (mm yr^{-1})	Uncertainty (mm)
TWSA	3.8 ± 4.07	4.07
GWSA	4.6 ± 4.25	4.25
SMSA	No trend	1.25
QsA	No trend	0.09
Precipitation	No trend	3.08

(Gebrehiwot et al. 2011; Bayesa et al. 2015; Tareke and Awoke 2022). For the most parts of Ethiopia, a nearly similar change was detected from 2007 to 2011. Since 2012, there has been a noticeable increase in GWSA, which is apparent in Ethiopia's southwestern part. This is because the area is characterized by a humid climate, i.e., it gets rain for a longer period and to be the least drought-vulnerable region in Ethiopia (Beyene et al. 2023). In contrast, GWSA is not significant in the southeastern and northeastern lowlands. It is due to the lower amount of annual precipitation (< 500 mm yr^{-1}) which leads to a low recharge rate (< 50 mm yr^{-1}) (Kebede 2013). Further, because of rapid evaporation and dry weather in the semi-arid locations, the water content in the vadose zone of the area may only react to significant precipitation amounts (Yang et al. 2019). In the last decade, a record of groundwater depletion is not observed in most regions, which could be due to the minimal usage of groundwater for agricultural practice in the area (Ministry of Agriculture 2011); a very small proportion of irrigation demand, that totals $< 1\%$ comes from groundwater (Kebede et al. 2018). On the other hand, some studies (e.g., Birhanu et al. 2021; Ayele et al. 2023) indicated the risks of groundwater levels and storage depletion in urban centers (e.g., Addis Ababa, Dire Dawa, Harar, Gondor, Mekelle). The coarse resolution of GRACE data did not capture the variations at the local level; moreover, the measurement taken at a single hotspot might not represent the situation at the regional level (Yin et al. 2018). In addition to the amount and fluctuations of seasonal precipitation in different regions of the country, the spatial inhomogeneity of groundwater occurrence is attributed to the variation and complexity of the hydrogeologic setup in the regions (Abiye 2006; Mengistu et al. 2019). It includes the vadose zone thickness as well as significant variations in the aquifers' different hydraulic properties (Mengistu et al. 2019). As a result, the Ethiopian aquifers are classified as one of the most complex and compartmentalized worldwide (WHYMAP 2005).

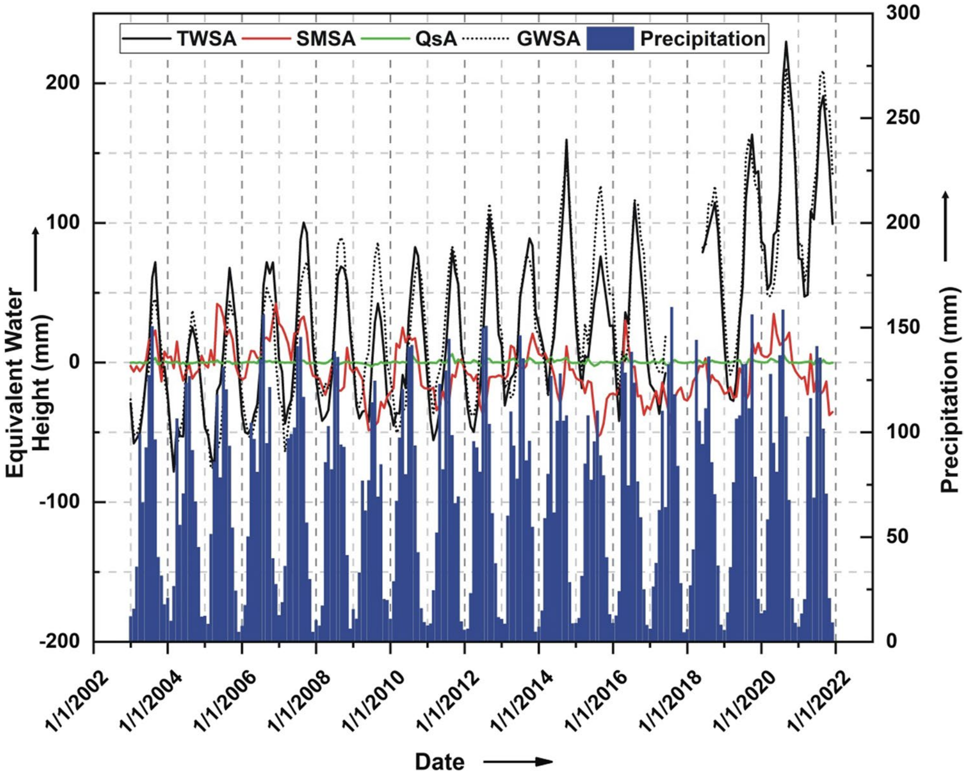

Fig. 4 Relationships among monthly TWSA, QsA, SMSA, GWSA and precipitation of Ethiopia (2003–2021)

Temporal variation of GWSA

The trend and seasonality were the dominant time-series components explaining variance in GRACE-derived GWSA. The overall trend is non-linear and rising (Fig. 6a). Moreover, the MK trend test revealed that GWSA has a positive slope and Sen's slope estimator indicated that the rate of the annual increase in GWSA was approximately 4.6 mm (Table 3). The seasonality of GWSA was also observed, rising in the wet and declining in the dry months of each year following precipitation and temperature discrepancies (Fig. 6b).

The amplitude of the temporal variation of GWSA is consistent with TWSA. On average, the change is marked in the two seasons, i.e., rising in the wet and declining in the dry periods (Fig. 7). It indicated that groundwater is the dominant component of TWSA in Ethiopia, which is consistent with the findings of Awange et al. (2014). The pattern of GWSA was uniform with precipitation and evidenced that the temporal discrepancies of GWSA were triggered by the amount of precipitation that occurred in different seasons of the country.

The correlation between precipitation and GWSA, and the lagged effects are presented in Fig. 8. As can be seen, the correlation coefficient (R) equals 0.23 (Fig. 8a) and it is evident that the impact of precipitation was not uniformly reflected on GWSA at the same time in all places. The R values for the lag times of 1 to 5 months are 0.5, 0.62, 0.6, 0.45, and 0.14, respectively (Fig. 8b–f). There is a 2-month lag between the precipitation and its significant influence on GWSA (Fig. 8b), which is nearly similar to the findings in the Nile River basin by Nigatu et al. (2021). The heterogeneous lagged effect of precipitation on GWSA is due to the variability of soil types, geology, and recharge mechanisms in the different regions of the country (Awange et al. 2014; Kebede et al. 2018). The lag time reflects the response of aquifers to precipitation and the recovery time needed in a dry climate where recharge is low (Li and Rodell 2021). In general, precipitation has both direct and indirect impacts on Ethiopia's groundwater dynamics.

Seasonal variation of GWSA

The long-term average of each month was calculated to observe and analyze the seasonal variations of GWSA in different regions of the country. The seasonal variation of GWSA is distinctly observed. In the western parts of Ethiopia, where the precipitation pattern is unimodal, GWSA increases in the main rainy months (July to November; maximum at September) (Fig. 9). In contrast, it decreased in the severity of dry months and reached its maximum in May. In the southern part where the bimodal precipitation pattern is prominent, GWSA starts rising in May and goes up to November. On the other hand, in northeastern, eastern,

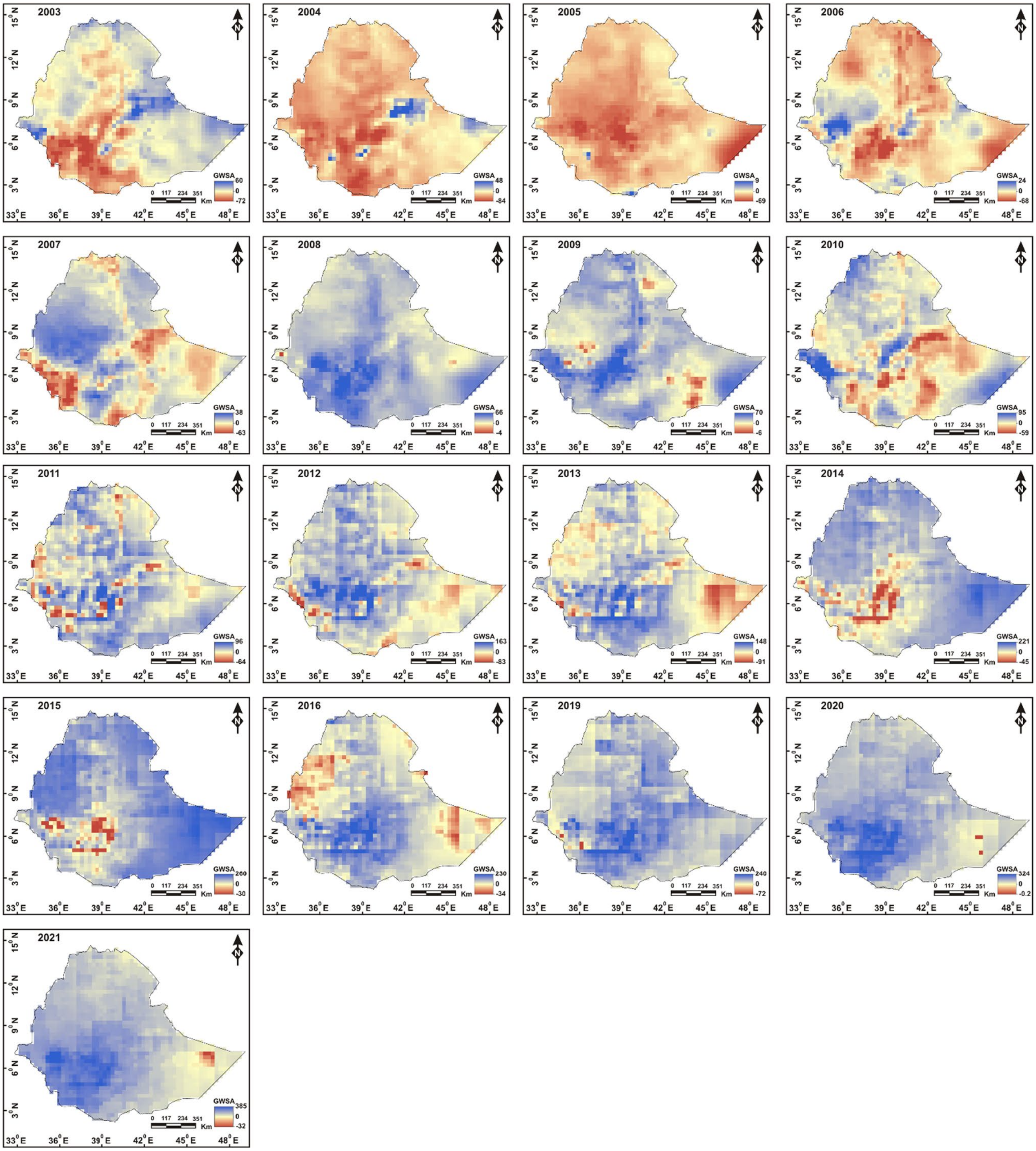

Fig. 5 Spatio-temporal variation of annual GWSA over Ethiopia (2003–2021); the annual GWSA in 2017 and 2018 were not calculated due to the missing GRACE data between January 2017 and June 2018

and southeastern parts of Ethiopia where low precipitation was recorded, GWSA did not show a significant variation in different seasons.

Annual average GWSA (2003 to 2021)

The relationship between annual average GWSA and precipitation anomaly is presented in Fig. 10 and side-by-side comparison clearly shows the impact of precipitation

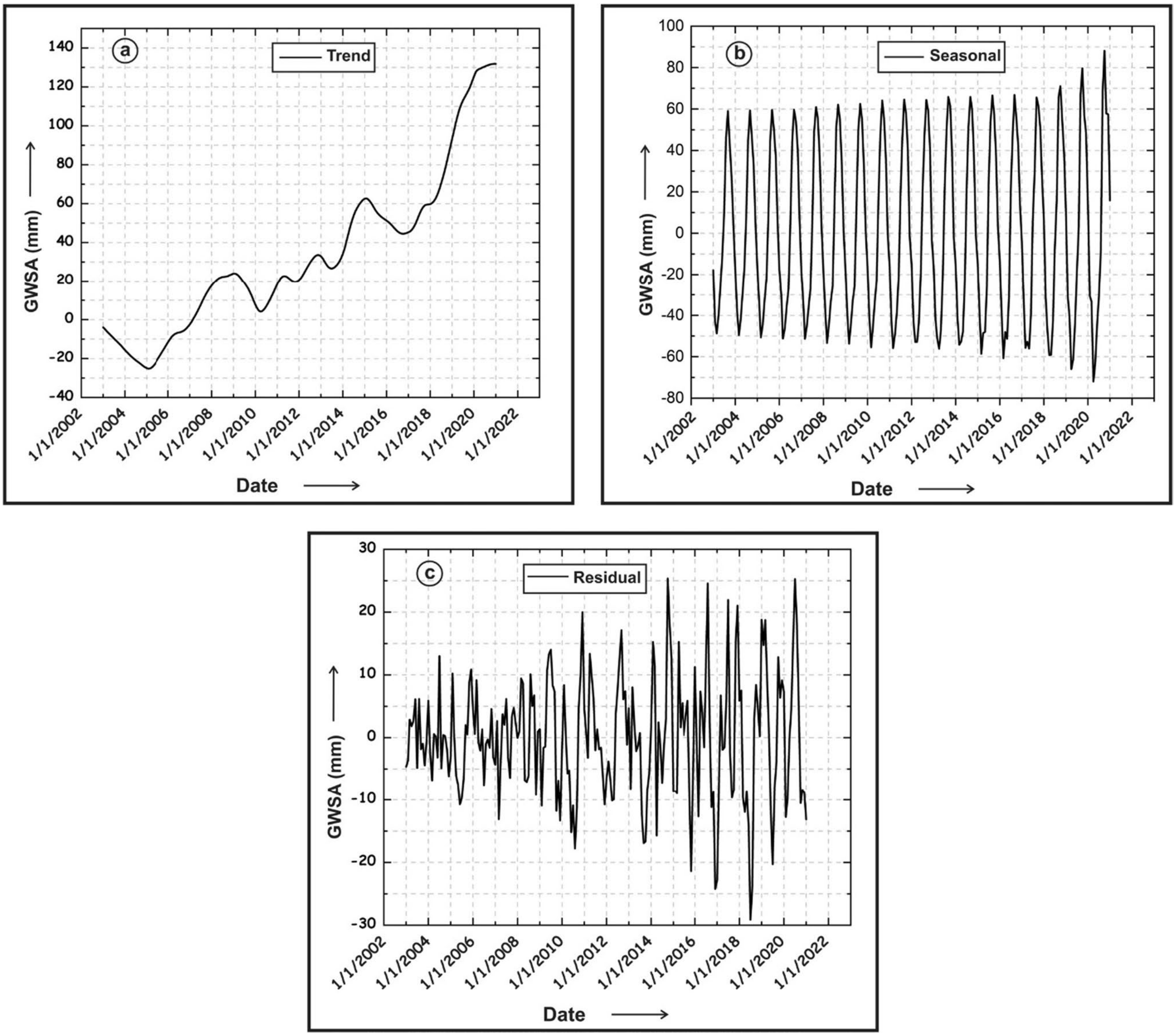

Fig. 6 Time series decomposition of GWSA: **a** trend, **b** seasonality, and **c** residual

climatology on spatial variation of GWSA. A depleted and small positive rise of GWSA was observed in the lowlands of the country (Northeastern, Northwestern, and Southeastern) where smaller precipitation anomaly is detected, this can be also caused by the vulnerability of the region's to the increased temperature, high evapotranspiration and prolonged drought. Most of the southwestern part of the country gained a higher GWSA than the other regions (Fig. 10b). This is due to the presence of the region's substantial amount of precipitation and longest rainy periods per annum, and it is similar to the findings of Awange et al. (2014). In contrast, a positive GWSA was recorded in some parts of the upper and middle Awash though the regions gained a negative precipitation anomaly. Moreover, in the upper awash where a high groundwater abstraction is experienced, a declining water level and potential impact on groundwater storage were predicted (Birhanu et al. 2021).

The variation of GWSA in the major basins of Ethiopia

The spatio-temporal variability of GWSA in the major river basins of the country was classified into four (4) arbitrary regions regarding the storage dynamics. The distinct nature of GWS in each basin could be triggered by the variation in altitude, hydrogeological setup, climate, surface water availability, population, and urbanization. River basins that host abundant surface water and reservoirs (e.g., Gilgel-Gibe hydropower projects in the Omo-Gibe River basin) and

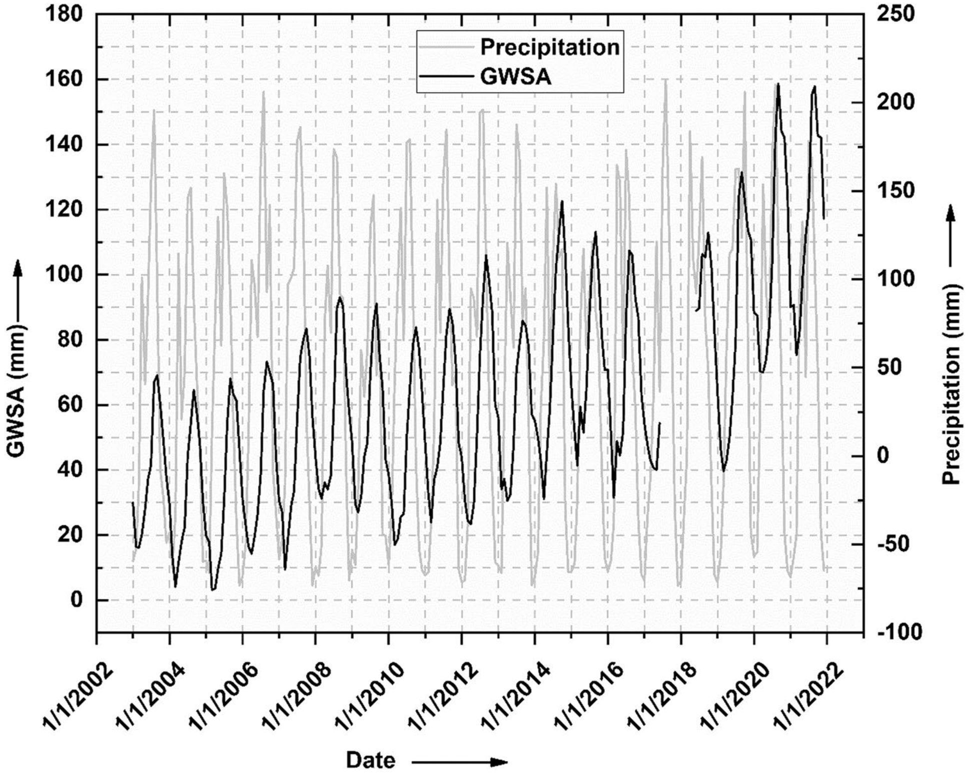

Fig. 7 The monthly time series of GWSA and precipitation (2003–2021)

their change in storage may contribute to the uncertainty of GRACE-derived GWSA (Rodell et al. 2007).

The trend of the hydrologic components and the temporal description and comparison of the major river basin are presented in Table 4 and Figs. 11 and 12, respectively. All regions show an increasing trend of TWSA and GWSA; however, precipitation, soil moisture, surface runoff, and evapotranspiration did not show a significant trend (alpha = 0.05). In regions 1 (Abay and Tekeze basins) and 2 (Omo-Gibe, Rift Valley, Baro-Akobo, and parts of Awash, Wabishebele and Genale-Dawa basins), which contain the highlands of the country, a significant amount of annual precipitation was observed whereas the region 3 (Lower Awash and Denakl basins) and 4 (Ogaden, and lower parts of Genale-Dawa and Wabishebelle basins), at lowlands, have been characterized by smaller amount of precipitation (< 400 mm) (Table 4).

Region 1 shows distinct amplitude of GWSA in the main wet and dry periods (Fig. 11); it raised in all rainy months and declined in the dry months. Such effects are due to both regions are gaining a considerable amount of precipitation in the main rainy season and are being dry for the rest of the months. Moreover, the smallest rise of TWSA was observed due to the increasing of evapotranspiration during 2003–2021 (Table 4). The groundwater storage of the region was not depleted despite the region, particularly northern Ethiopia has been affected by droughts (Gebrehiwot et al. 2011).

A sharply increasing monthly GWSA was observed in region 2 with a maximum rise and decline of more than 250 mm and 70 mm, respectively. In this region, the average annual precipitation exceeded 1000 mm and caused a significant rise of GWSA during the main rainy season in particular. Moreover, the SMSA showed a decreasing trend (-2.3 mm y^{-1}). A smaller upward and downward GWSA was observed in region 4. In the arid areas of the country (significant in regions 3 and 4), GWSA shows an erratic pattern (Fig. 11). In general, the low precipitation and the presence of only a few perennial rivers in the arid and semi-arid river basins could minimize both the direct and indirect recharge. Consequently, it could affect groundwater which gets replenished annually. Moreover, the erratic distribution and smaller amplitude of GWSA in the southeastern lowlands reveal the impact of recurrent drought periods. However, surface runoff, which mostly may come from the highlands, shows a rising trend in the region 3 and 4 (Table 3). Therefore, the flood water could trigger an indirect recharge of groundwater in these areas (Kebede 2013).

The highest monthly fluctuation indicates the greatest contribution of region 1 for the decreasing and increasing of GWSA during the dry and wet periods of the country, respectively. However, the arid and semi-arid regions of the country (region 4) revealed an irregular variation and have a minimum stake to the monthly GWSA of Ethiopia (Fig. 12a).

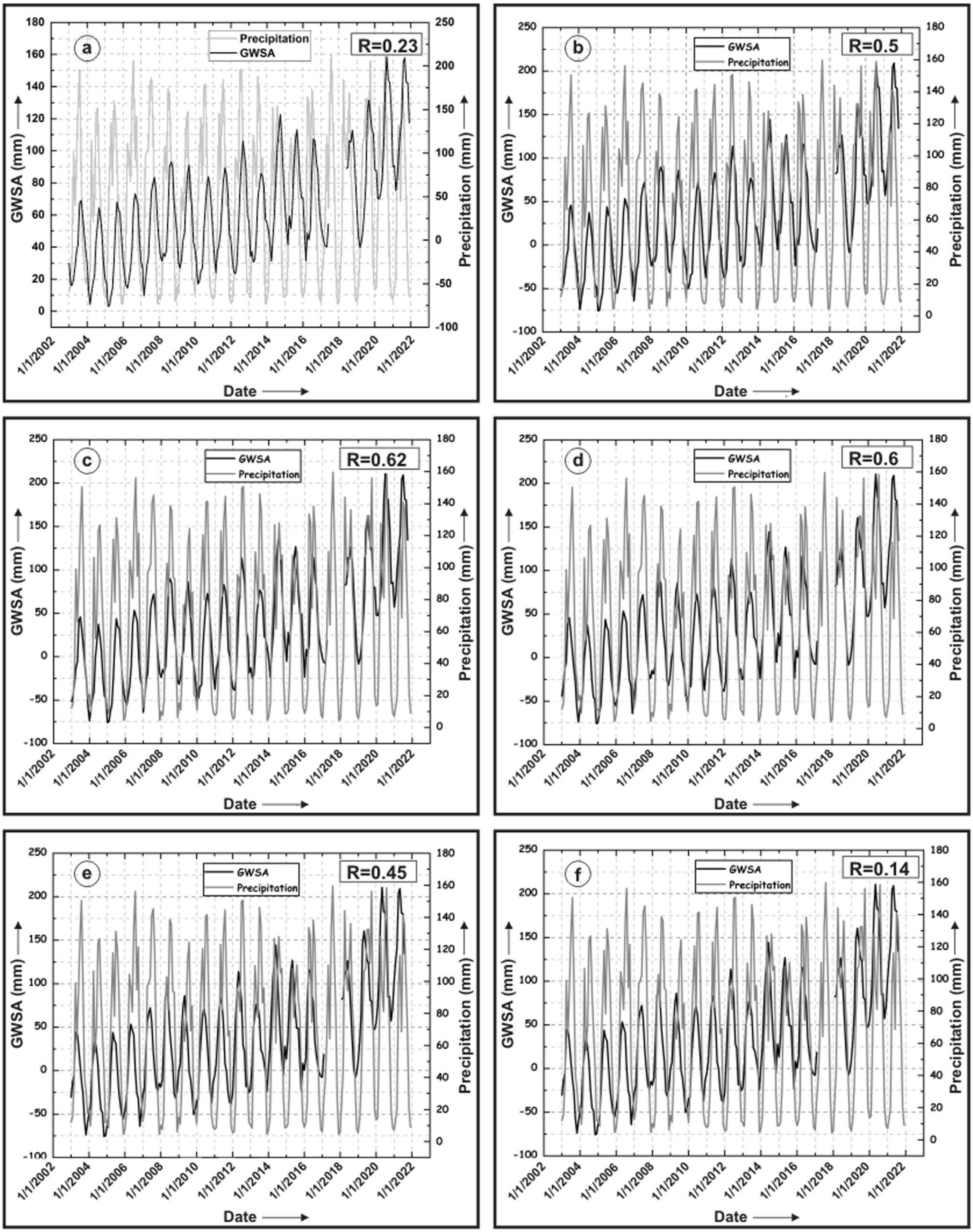

Fig. 8 The relationship between monthly GWSA and precipitation: **a** zero time-lag and **b**–**f** different lag times (1–5 months)

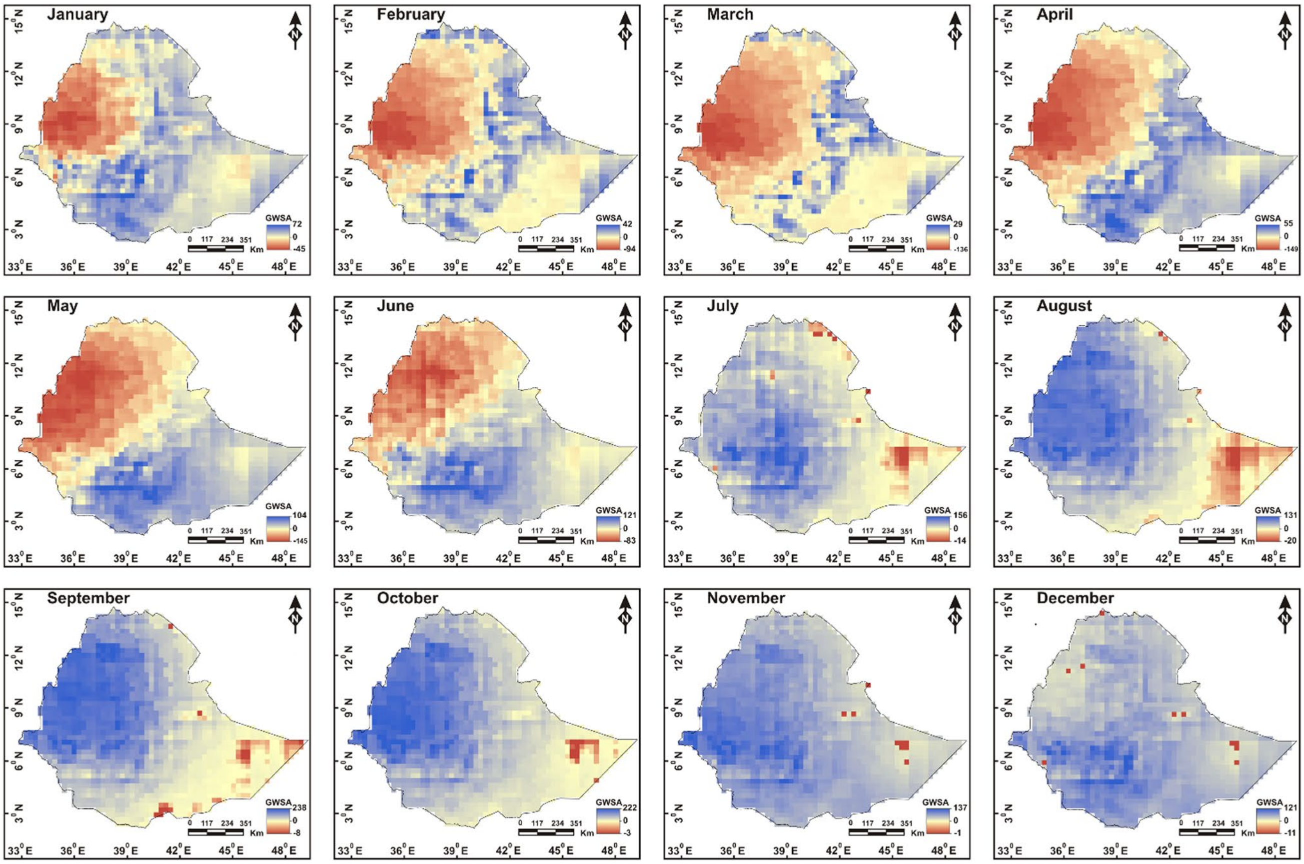

Fig. 9 Monthly variation of GWSA: average value of each month (January to December) in 2003 to 2021 time period

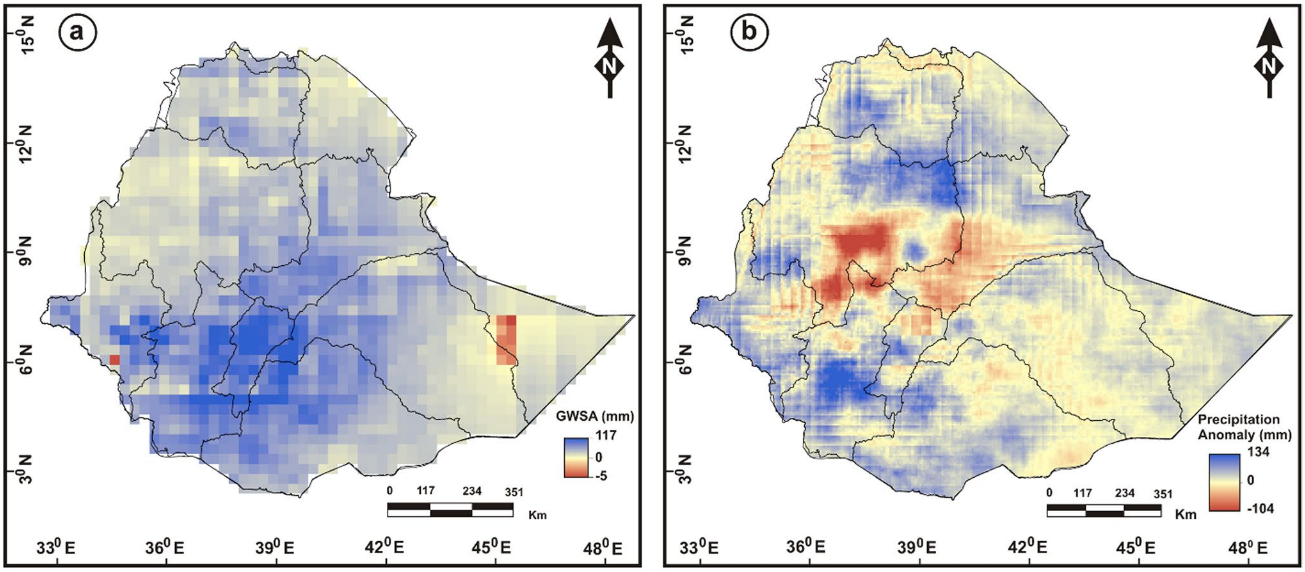

Fig. 10 The relationship of GWSA and precipitation anomaly: **a** annual average GWSA and **b** precipitation anomaly

Table 4 Annual trends of water balance components in the major river basins of the country

Regions	Annual trend (mm yr^{-1})						Average annual precipitation (mm)
	TWSA	QsA	SMSA	GWSA	Precipitation	Evapotranspiration	
Region 1	2.7	No trend	No trend	3.4	No trend	2.5	768
Region 2	3.07	No trend	−2.3	4.34	No trend	No trend	1008
Region 3	3.2	2	No trend	2.7	No trend	No trend	364
Region 4	3.6	2.02	No trend	3.9	2.09	No trend	341

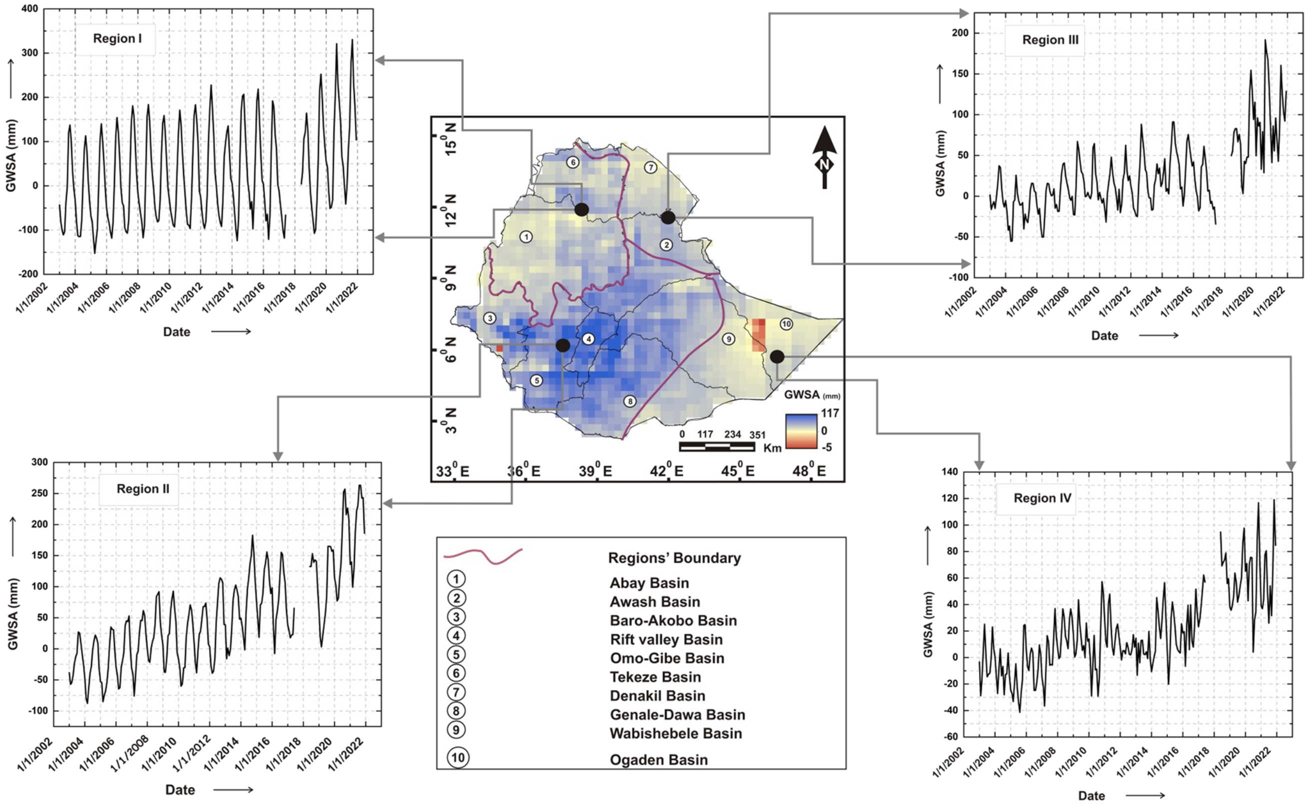

Fig. 11 The temporal variation of GWSA: an arbitrary four regions classification framework, based on the similarity of average spatial GWSA variation, drawn over the major river basins

In Region 1, the greatest increase and decrease of GWSA during the wet and dry periods could offset each other in the calculation of the annual GWSA. Therefore, the annual GWSA showed the major influence of region 2 for the fluctuations of the nation's groundwater storage (Fig. 12b).

Validation of GRACE-based GWSA

The long-term GRACE-derived GWSA was validated by analyzing the precipitation data in Ethiopia, as per the suggestion made by Chen et al. (2016). The result showed a good agreement between the temporal and seasonal fluctuations of precipitation and its impact on groundwater storage (e.g., Figs. 7, 9). The maximum rise was observed at the end of the main rainy periods and declined to its lowest near the closure of the dry months. Further, in regions characterized by a lower amount of precipitation and recurrent droughts (e.g., southeastern, eastern, and northeastern lowlands), the change in GWSA is very small, or depleted in some instances (Fig. 11). However, a disagreement between GWSA and precipitation anomaly was observed in some areas of central Ethiopia, which the GWSA showed a small rise despite the negative precipitation anomaly (Fig. 10). This could be due to the aquifers in this region be also recharged from domestic wastewater and leakage from water mains and reservoirs (Demlie et al. 2007). In general, the relationship between temporal and seasonal precipitation and GWSA showed a reasonable consistency and the lagged

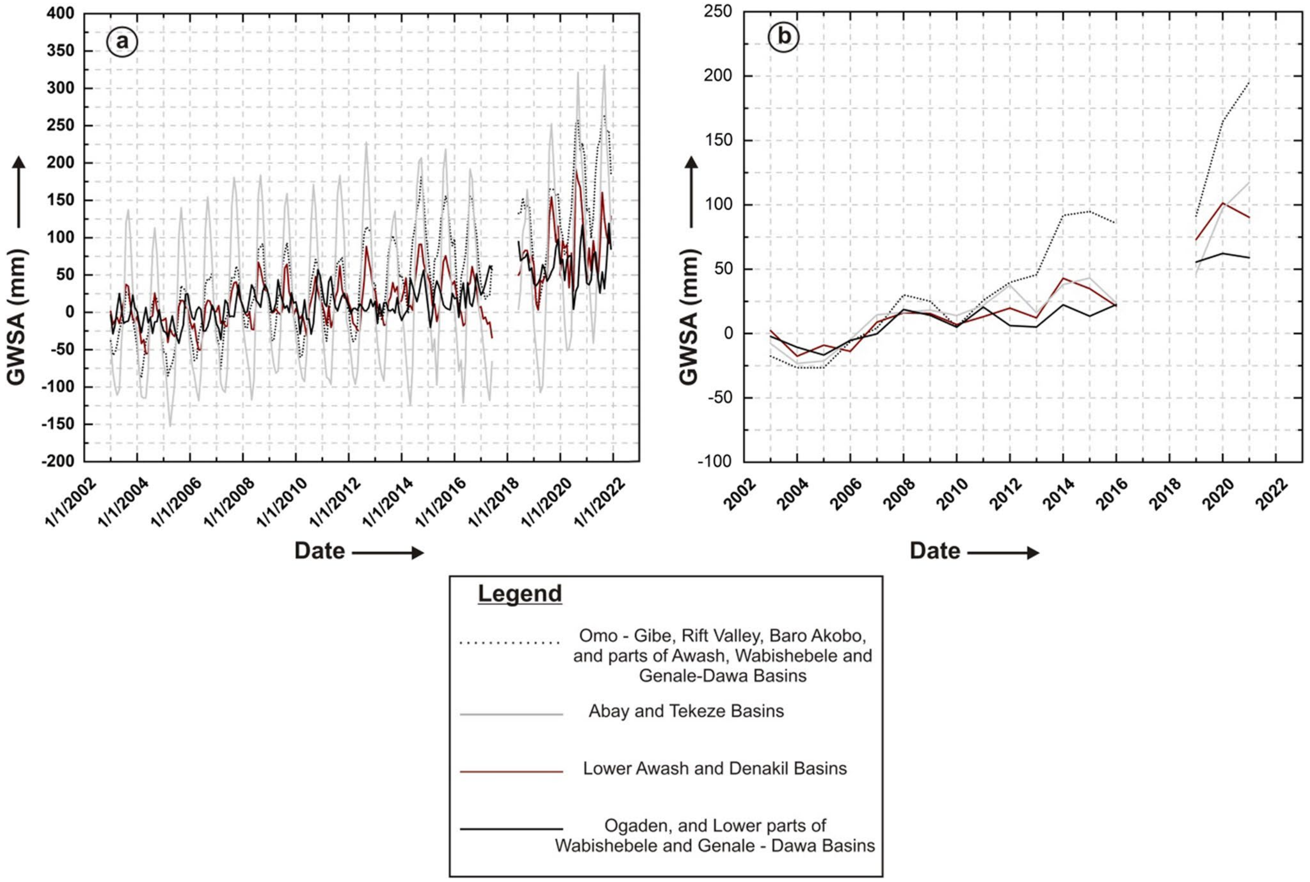

Fig. 12 Comparison of temporal variation of GWSA over the river basins: **a** monthly and **b** annual

effect also demonstrated the influence of the heterogeneity of the hydrogeologic setup in different regions (Fig. 8).

Conclusion

GRACE time-variable gravity data provide a means for detecting water mass movement and redistribution at the regional scale—it offers a unique tool for monitoring and understanding the long-term variation of GWSA, particularly in a place where in situ groundwater level observations are scarce. Taking the benefits of GRACE data, the spatio-temporal variations of TWSA and GWSA over Ethiopia were retrieved. The impact of precipitation variability on GWSA was also addressed. Further, the accuracy of GRACE data was validated by analyzing precipitation data, and uncertainty analysis was performed.

The spatio-temporal variabilities of TWSA and GWSA were assessed using the GRACE-GLDAS approach. The result showed heterogeneous storage dynamics over different regions of the country. Most portions of the country, particularly the western region showed a high monthly variability of GWSA. The average annual GWSA was increased in most regions at varying rates. Abay and Tekeze basins have a major influence on the monthly fluctuations of GWSA. Rift Valley, Omo Gibe, Baro Akobo, and parts of adjacent basins gained the largest contribution to the annual storage variability in the country. On average, TWSA and GWSA show an increasing trend. It indicated that the magnitude of the GWSA was a dominant component depicted to the TWSA in Ethiopia.

The effect of precipitation on TWSA and GWSA was investigated in time and space through correlation analysis. The result showed that the erratic distribution of precipitation has a major influence on the variability of TWSA and GWSA over Ethiopia. GWSA raised to the maximum in the main rainy period and declined more in the severity of dry months. In areas where precipitation is characterized by unimodal pattern, the annual GWSA is highly affected by the fluctuation of precipitation. There is a 2-month lag between the precipitation and its significant influence, and the variation of GWSA witnessed the impact of major drought periods in the country. Therefore, considering this fact is important while using groundwater as a resource for climate adaptation and mitigation.

Even though the result of this study showed the rise of GWSA in Ethiopia, the magnitude of the change is insignificant. Therefore, implementing a sustainable groundwater management system is needed to enhance the use of groundwater for the economic development of the country. The analysis of precipitation data validated that the GRACE reasonably captured the variation of GWSA in Ethiopia. Therefore, this study is one example to show that GRACE, though it has regional application, can be applied to support sustainable groundwater management where the observation data are scarce. However, although the Mascon GRACE data have the best accuracy, the resolution of GRACE still inhibits its use at the local scale; therefore, downscaling of the data to a finer resolution is recommended to improve the result. On the other hand, to apply GRACE in the humid regions of Ethiopia where surface water and reservoirs are abundant and fluctuate in different seasons, special consideration should be given; once the change in the storage of those water bodies may have a significant contribution to the GRACE TWSA. Further, to develop the groundwater resources for climate mitigation and economic practices, the cumulative effects of natural and human activities (e.g., land use and land cover changes, groundwater abstraction, and hydrogeological setup) need to be thoroughly examined.

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Author contributions Kassahun Aweke Arega and Behailu Birhanu: conceptualization, data analysis, and writing of the manuscript. Kassahun Aweke Arega and Shoaib Ali: satellite data computation, writing, and editing. The other authors reviewed and modified the manuscript. All authors read and approved the final manuscript.

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Data availability Data will be made available on request.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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