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Use of GRACE time-variable data and GLDAS-LSM for estimating groundwater storage variability at small basin scales: a case study of the Nzoia River Basin

Yashon O. Ouma[a]*, D.O. Aballa[a], D.O. Marinda[a], R. Tateishi[b], and M. Hahn[c]

[a]*Department of Civil and Structural Engineering, Moi University, Eldoret, Kenya;* [b]*CEReS, Chiba University, Chiba 263-8522, Japan;* [c]*Department of Geomatics, University of Applied Sciences Stuttgart, 70174 Stuttgart, Germany*

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This study integrates time-variable Gravity Recovery and Climate Experiment (GRACE) gravimetric measurements and Global Land Data Assimilation System (GLDAS) land surface models (LSM) in order to understand the inter-annual variations and groundwater storage changes (GWSC) in the Nzoia River Basin in Kenya, using the water balance equation and parameters. From averaged GRACE and GWSC data, the results showed that over the 10-year period, the basin experienced a groundwater depth gain of 6.38 mm year^{-1}, which is equivalent to aquifer recharge of 298 million cubic metres (mcm) year^{-1}. The deseasonalized groundwater variation analysis gave a net gain in groundwater storage of 6.21 mm year^{-1} that is equal to a groundwater recharge gain of 290 mcm year^{-1}. The observed results are comparable to the groundwater safe yield of 330 mcm year^{-1} as estimated by the Water Resource Management Authority in Kenya. Through cross-plotting and analysis with averaged satellite altimetry data and *in situ* measurements from rainfall and streamflow discharge, the total water storage change (TWSC) and GWSC in the basin were consistent and closely correlated in variation trends. The inter-annual standard deviation of groundwater change was determined as ±0.24 mm year^{-1}, which is equivalent to 85% degree of confidence in the obtained results. The results in this study show that GRACE gravity-variable solutions and GLDAS-LSM provide reliable data sets suitable for the study of small to large basin groundwater storage variations, especially in areas with scarce and sparsely available *in situ* data.

1. Introduction

One of the main sources of fresh water globally is groundwater. Groundwater contributes to about half the total global domestic water demands, and is a major contributor to industrial and agriculture and irrigation demands (Xiao et al. 2015). Similar to global trends, the population in the Nzoia River Basin in western Kenya relies on groundwater for domestic, industrial, and agricultural activities. However, no studies have been carried out in relation to the understanding of groundwater variations in the basin. Characteristically, the Nzoia River Basin is one of the basins in western Kenya that is subject to perennial flooding and unstable rainfall patterns due to changes in climate change and human population effects on land use and land cover. Accordingly, a study on groundwater variation and possible prediction for

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*Corresponding author. Email: yashon_o@hotmail.com harvesting budgets is important, especially for planning the present and future demands and the related socio-economic activates in the basin.

Overdependence on groundwater has led its overexploitation, which results in problems related to water resources and environmental issues such as the unremitting reduction in the water table, water resource conflicts, and in some cases land subsidence. In order to monitor the availability and variations in groundwater, water and hydrological scientists in most developing countries still rely on observations from ground wells. In most cases, wells are not only unavailable, but when available they tend to be scarce and sparsely located such that the time and cost required for maintenance and observations are generally high. These *in situ* groundwater monitoring-based measurements tend to result in large-scale and statistically discrete and unreliable observations.

In most areas with scarce and sparse distribution of *in situ* hydrological and meteorological measurements, the causes and impacts of groundwater resources variability remain poorly understood. This implies that is not possible to infer and/or predict phenomena related to flooding and/or drought. This is of particular concern in most parts of Africa, where nearly half of the continent's population rely on groundwater for their daily water supply (Taylor et al., 2013). In these areas, long-term change and the inter-annual variability of water storage are also often lacking. To overcome these data limitations, remote-sensing observations and measurements offer an opportunity to improve hydrological and meteorological data acquisition (Cre´taux 2011).

Advancements in space-based remote sensing have revolutionized the study of water storage variation. Among remote-sensing measurements is included satellite radar altimetry, which can now be used to measure water levels over lakes, rivers, and flood plains. Satellite altimetry data can also provide surface water volume change when combined with surface water area, as summarized in Becker et al. (2010). In addition to altimetry, the Gravity Recovery and Climate Experiment (GRACE) space mission has, since 2002, been measuring spatio-temporal changes in vertically integrated water storage from water balance parameters such as surface water, soil moisture and groundwater, and snow. The combination of altimetric and gravimetric observations has allowed access to a wide range of hydrological products and is thus useful in areas where networks of *in situ* measurements are not only scarce but also encounter maintenance problems (Swenson and Wahr 2009).

Variations in continental water storage can be detected through variation in gravity as influenced by the total terrestrial mass fluctuations from satellite gravimetric measurements. Time-variation GRACE data have been widely used to estimate global and regional groundwater variations by using the components of water balance equations (Hassan and Jin, 2014). Swenson and Wahr (2009) used GRACE to examine trends in lake level and water storage in the Lake Victoria basin over 5 years from 2003, and found that drought and human anthropogenic activities influenced water levels and water storage in the lake and in the basin. Using GRACE data, Becker et al. (2010) analysed the variability in total terrestrial water storage, lake water volume, and rainfall over parts of East Africa from 2002 to 2008, and concluded that the inter-annual variability of total water discharge was due to forcing by the 2006 Indian Ocean Dipole (IOD) on East Africa rainfall. In India, GRACE data have been used to understand regional groundwater depletion (e.g. Rodell, Velicogna, and Famiglietti 2009; Gleeson et al. 2012). In a number of cases, GRACE data have also been used to assess the relationships between water storage changes and climate change (e.g. Swenson and Wahr 2006; Forootan et al. 2012).

Most of these studies characterized the first-order effects such as depletion rates, but they did not incorporate the second-order effect which is the variability of groundwater storage. This implies that when it comes to the understanding of inter-annual and decadal groundwater variations, little has been done to investigate the utility of GRACE and related water balance models, more so for small basins like the Nzoia River Basin. In such hydrological units, the variability of groundwater storage translates into supply unpredictability, which should be accounted for water security purposes (Reig, Shiao, and Gassert 2013). In addition to studying inter-annual groundwater variability in the Nzoia Basin, this study illustrates the potential use of GRACE data in regard to small-scale basins. This is because GRACE-derived groundwater storage solutions have been validated in very large basins with surface area of more than 200,000 km^2 (e.g. the Mississippi River Basin (Rodell et al. 2007), Yemen (Moore and Fisher 2012), and Bangladesh (Shamsudduha et al., 2012)).

Longuevergne, Scanlon, and Wilson (2010) argue that it is possible to derive accurate and reliable estimates of total terrestrial water storage (TWS) variations in small basins using GRACE data. In this study, the rationale for applying GRACE data for small-basin groundwater studies is based on two factors: (i) GRACE is sensitive to total mass changes concentrated within a smaller area if the magnitude is sufficient (Longuevergne et al. 2013; Scanlon et al. 2012a, 2012b). Small area refers to a hydrologic unit such as a sub-basin or reservoir. In this study, the sensitivity is determined by comparing the variations of GRACE results with the ancillary data, which are related to groundwater as Global Land Data Assimilation System (GLDAS) land surface models (LSM), lake altimetry, stream flow, and precipitation. (ii) As further presented in Longuevergne et al. (2013), virtually all independent hydrologic units like small basins and/or reservoirs are point masses at the spatial resolution of GRACE. In illustrating this fact, a small reservoir or sub-basin with a typical surface area of ~1000 km^2 is about two orders of magnitude less than that of the smallest basin (~200,000 km^2) that can be typically resolved by GRACE observations. The precision of GRACE observations allows detection of 1 cm TWS change within a 200,000 km^2 basin, which is equivalent to 2 km^3 TWS change. This is comparable in mass and hence detectability to a water level change of 2 m within a 1000 km^2 reservoir. Similar arguments can be extended for sub-basins of area less than ~200,000 km^2, as in this study. Smaller studies related either to reservoirs or basins can be found in the following references: Wang et al. (2011); Swenson and Wahr (2009); Becker et al. (2010); Singh, Seitz, and Schwatke (2012), which are lower than the nominal GRACE resolution. Further detailed summary on some of the application studies using GRACE gravimetric data can be found in a recent study by Xiao et al. (2015).

Inter-annual variation in groundwater storage measures the variability of groundwater levels at multitemporal scales of one year or longer. A decadal extent of analysis is important since it is likely to give significant and characteristic changes between 5–10 years, as opposed to shorter time intervals. Fluctuations in groundwater are driven by both natural (climate vegetation, soil) and anthropogenic processes like land-use activities. These processes are complex and exhibit non-linear interactions amongst them. As such within a single year, it is possible to observe a wide range of variability in the groundwater storage characterized by, for example, flooding, drought, and depletions. This means that inter-annual groundwater storage analysis is significant in gauging the non-linear phenomenon, while decadal analysis is significant in long-term linear and non-linear change patterns. According to Rieg et al. (2013), areas that experience high inter-annual groundwater variability tend to face a higher risk of water supply shortages, even if there is little or no net loss of groundwater.

This research aims at identifying and characterizing the inter-annual variability of groundwater storage in the Nzoia River Basin over the decadal period 2003–2013. The approach is to integrate gravimetric and land surface models from the Global Land Data Assimilation System, to quantitatively understand groundwater variations in terms of the water balance equation. In order to validate the reliability of the results, satellite radar altimetry data for Lake Victoria water level changes and *in situ* precipitation and streamflow hydrologic measurements are cross-correlated with the water balance equation results from GRACE and GLDAS-LSM.

Because groundwater recharge sustains the groundwater resources on which there is already global demand and overdependence, this study tests the applicability and reliability of gravimetric GRACE and GLDAS-LSM in understanding groundwater storage changes (GWSC) in the Nzoia River Basin. The major contribution of this study is in regard to the exploitation of the advantage that GRACE gravimetric variations can detect or sense water stored at all levels, including groundwater variations, with an accuracy of better than 1 cm of equivalent water thickness (EWT), for applications on small but very significant hydrological units. This is in contrast to other imaging systems such as radiometry and radar, which are limited to the measurement of atmospheric and near-surface phenomena. Section 2 presents brief details on the Nzoia River Basin study area. Section 3 discusses data sets and methodology and Section 4 presents the study results and discussion. The study summary, conclusions, and recommendations are presented in Section 5.

2. Study area

The Nzoia River Basin is located in the western part of Kenya and lies between latitudes 0ºN–1.5ºN and longitudes 34º E–36º E. The basin covers a geographical area of approximately 12 709 km^2 with a topographical elevation ranging between 1100 and 4200 m above mean sea level (Figure 1, adapted from Khan et al. 2011 and Ouma et al., 2012). The basin is traversed by the River Nzoia and its tributaries, which drains into Lake Victoria and the Nile River Basin. The River Nzoia has a long-term average discharge of 115.3 m^{3}s^{-1}, contributing 14.8% of the total input into Lake Victoria, only second after River Kagera at 33.5%.

The mean annual rainfall varies from a maximum of 1100–2700 mm to a minimum of 600–1100 mm. There are two rainy seasons and two dry seasons, with the short rains running from October to December and the long rains running from March to May. The dry seasons occur in the months of January–February and June–September. Due to the variable local relief and proximity to Lake Victoria, the climatic patterns within the basin are not usually regular. The low-altitude areas of the basin are prone to flooding. The Nzoia River Basin is densely populated and agriculturally productive, with rapidly expanding commercial and industrial activities in Eldoret, Kitale, Bungoma, Kakamega, Mumias, and Nzoia towns.

3. Data sets and methods

3.1. *Remote-sensing data and land-surface-based models*

3.1.1. *Gravity recovery and climate experiment*

The GRACE satellite mission, initiated by the United Sates National Aeronautics and Space Administration (NASA) and the German Deutsche Zentrum für Luft- und

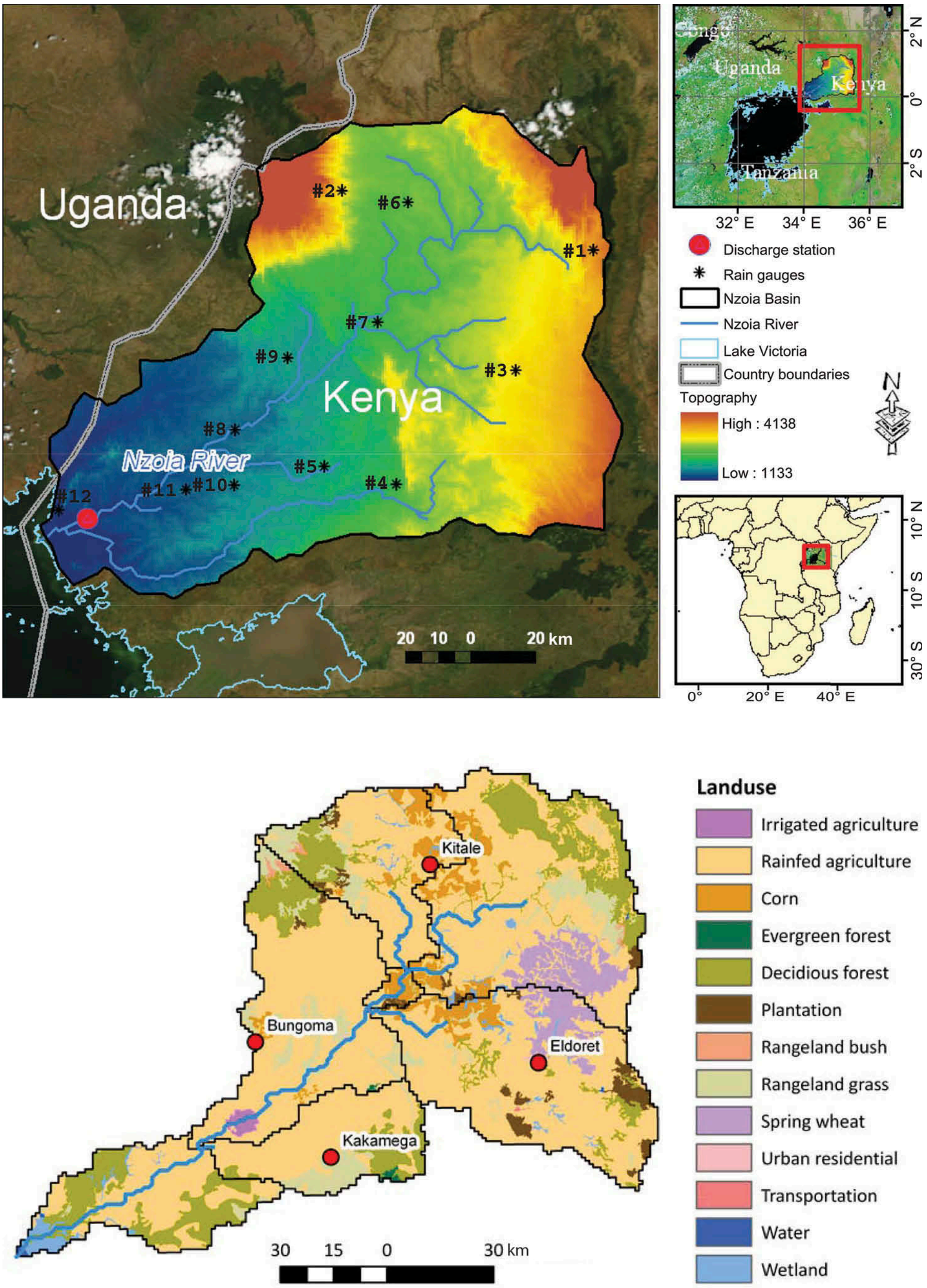


Figure 1. Nzoia River Basin in the Lake Victoria basin (above) (Khan et al. 2011) and location of the major towns and the main land uses within the basin (below).

Raumfahrt (DLR), employs two low-earth orbit (LEO) satellites in the same orbital plane at an altitude of approximately 400 km with an inclination of 89.5º. The separation between the two satellites is affected by the differences in gravity and is measured by a

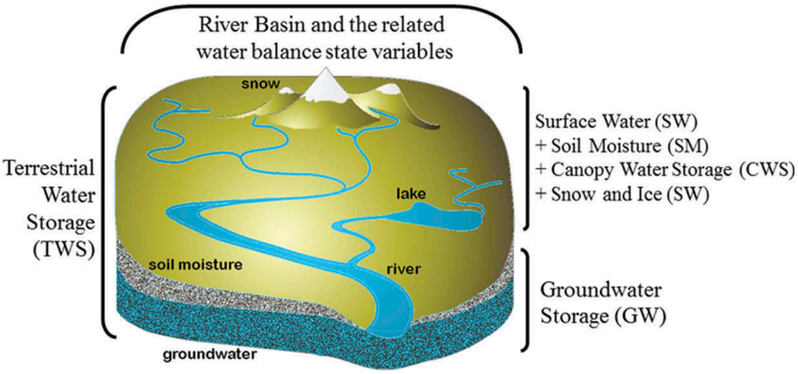


Figure 2. Components of total vertically integrated water storage and visualization of the terrestrial water storage (TWS) determination concept.

K-band range rate system with respect to the locations of the satellites, which are determined by Global Positioning System (GPS) receivers. The radar data are converted to gravitational field information in the form of spherical harmonic coefficients (Rodell et al. 2007; Wahr et al. 2004). The mission has been collecting gravimetric observations and variations since mid-2002 and the data products represent the monthly Earth gravity field variations (Tapley et al. 2004).

The advantage of GRACE data is in its ability to acquire large-scale and spatio-temporal comprehensive data. These can be used to derive annual and decadal estimates of total vertically integrated water storage variations (Figure 2), with higher accuracy at larger spatial scales (Wahr et al. 2004). From Figure 2, the mean total terrestrial water storage and its change (TWSC) as measured in EWT can be derived (Strassberg, Scanlon, and Rodell 2007). Although GRACE has relatively low spatial and temporal resolution, it has the advantage of sensing the changes in total water storage in all TWS levels or components (Rodell, Velicogna, and Famiglietti 2009).

For this study, Release-5 of GRACE (GRACE-RL05) was used to derive the TWSC from 2003–2013. The monthly mean variations from the GRACE data products as processed by the University of Texas Center for Space Research (CSR), the GeoForschungsZentrum (GFZ) Potsdam, and the Jet Propulsion Laboratory (JPL), were used in order to reduce the noise in the gravity field resolutions within the available scatter of the solutions and to derive a reliable GRACE data product (Sakumura, Bettadpur, and Bruinsma 2014). According to Bettadpur (2012), GRACE-RL05 is more accurate than previously released products. This is because the de-striping procedure applied requires less spatial smoothing as compared with the earlier versions of GRACE. For filling of missing data, linear interpolation was used according to Landerer and Swenson (2012).

The concept of basin terrestrial derivations from GRACE data is illustrated in Figure 2. In Figure 2, the total mass that determines the gravimetric changes between the GRACE satellites is determined by the combination of atmospheric and terrestrial mass. The total TWS comprises the combined contribution from groundwater storage and equivalent thickness (GWS), soil moisture (SM), snow water equivalent (SWE), surface water (SW), and water stored in biomass (BM), which can also be quantified in terms of canopy water storage (CWS) (Figure 2). Through the water balance equation, which is based on the principle that the flow into and outside of a system must equalize or balance (Rodell et al. 2007), the components of the water balance equation are aggregated in Equation (1). In Equation (1), ΔGWS is equivalent to the desired groundwater storage change:

$$\Delta \mathrm{TWS}_{\overline{\mathrm{GRACE}}} = \Delta \mathrm{GWS} + \Delta \mathrm{SM} + \Delta \mathrm{SWE} + \Delta \mathrm{SW} + \Delta \mathrm{CWS} \tag{1}$$

$$\Delta \mathrm{GWS} = \Delta \mathrm{TWS}_{\overline{\mathrm{GRACE}}} - (\Delta \mathrm{SM} + \Delta \mathrm{SW} + \Delta \mathrm{CWS}) \tag{2}$$

where Δ denotes change in the respective quantity and $\Delta \mathrm{TWS}_{\overline{\mathrm{GRACE}}}$ is change in total water storage from the averaged GRACE observation from JPL, CSR, and GFZ.

If there are significant changes in any of water balance parameters then the TWS will also change, and hence TWSC is obtained. From Equation (1), GRACE time-variable observations determine the mean monthly gravity changes, which are detected as changes in the TWS, resulting from the total mass changes. However, the changes in the determining parameters for TWS can be estimated through modelling or measurements (Strassberg, Scanlon, and Rodell 2007). By rearranging Equations (1)–(2), the changes in groundwater storage can be derived. Given the high temperatures in the study area and the absence of snow and ice components, hence the expression in Equation (2).

The standard steps in the processing of the GRACE data (Landerer and Swenson 2012) were used. These included the filtering of the monthly data products, computation of the residual gravity field solutions with respect to the temporal average over the study period, and the transformation of the residual coefficients into monthly TWS values. The GRACE data were scaled using the scaling factors provided in order to restore the energy lost through processing. These scaling factors were derived using GLDAS-NOAH LSM, which does not include the SW component of the TWS.

3.1.2. Global land data assimilation system models

GLDAS is a robust simulation system that incorporates *in situ* ground measurements and satellite-based observational data products, using advanced land-surface modelling and data assimilation techniques, with the objective of generating optimal fields of land-surface state for SM, snow and surface temperature, and flux for evapotranspiration and sensible heat flux products, at global scales and high spatial resolution (0.25–1°) in near-real time (Rodell et al. 2004). GLDAS drives four land-surface models, namely NOAH (Ek et al. 2003), Community Land Model (CLM) (Dai et al. 2003), MOSAIC (Koster and Suarez 1992), and Variable Infiltration Capacity (VIC) (Liang et al. 1994).

The GLDAS land surface model derives the TWSC from changes in the SM, SWE, and BM as depicted in Equation (3). In order to minimize any biases or errors inherent in any model, an average of four LSM hydrological outputs from NOAH, CLM, MOSAIC, and VIC was adopted for the 10-year study period. Applying the same principles as in Equation (2), the final averaged *ΔGWS* is determined according to Equation (4). According to GLDAS-LSM, the SW component is considered as an intersection of the water table and the land surface (Winter 1999). As such, given that groundwater tends to be continuous across the area of interest, SW can be considered an extension of groundwater and can be omitted from the water balance equation, except for extreme flooding scenarios:

$$\Delta \mathrm{TWS}_{\overline{\mathrm{GLDAS}}} = \Delta \mathrm{SM} + \Delta \mathrm{SWE} + \Delta \mathrm{CWS} \tag{3}$$

$$\Delta \mathrm{GWS} = \Delta \mathrm{TWS}_{\overline{\mathrm{GRACE}}} - \Delta \mathrm{TWS}_{\overline{\mathrm{GLDAS}}} \tag{4}$$

where $\Delta \mathrm{TWS}_{\overline{\mathrm{GLDAS}}}$ is change in total water storage from the four averaged GLDAS-LS models.

3.1.3. *Altimetry for variation in lake water levels*

Originally intended for mapping oceanic sea surface heights, satellite radar altimetry has also become significant in the measurement of water level variation in large lakes, flood plains, and wetlands and inland seas, with an accuracy ranging from a few to tens of centimetres (Papa et al., 2015). Through USDA and NASA, water level variation in up to 75 large lakes with surface area greater than 100 km^2 worldwide is routinely monitored through the USDA Global Reservoir and Lake Monitor project. The time series of altimetric water level variation data for large lakes and reservoirs can be found on the USDA reservoir database, at http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir.

Total lake water volume is dependent on the balance between water input and output. The former is characterized by the sum of direct precipitation over the lake, the surface runoff from the drainage basin area, and underground seepage (Hassan and Jin, 2014). The Nzoia River Basin, which is formed by the Nzoia River and its tributaries, forms part of the larger Lake Victoria basin as shown in Figure 1, and thus any hydrological variation in the basin will also impact on Lake Victoria water level in terms of groundwater and SW storage and transfer.

According to validation studies by Crétaux (2011), satellite altimetric lake levels in comparison with *in situ* stage measurements of the Ugandan section of Lake Victoria, during the period 2000–2004, showed excellent agreement with a root mean square (RMS) of 3–4 cm. For this study the altimetry data from Jason-1 and ENVISAT were averaged to obtain the monthly lake level changes from 2003–2013 and to validate and cross-correlate the study results. Merging by averaging the altimetry data sets is important, since despite the fact that Jason-1 has slightly higher accuracy than ENVISAT, it also tends to be noisier. Thus a simple average of the altimetry observations from ENVISAT and Jason-1 was used in order to derive the most accurate lake altimetry data (Durrant, Greenslade, and Simmonds 2009).

3.2. In situ *hydrological parameter measurements*

3.2.1. *Precipitation*

An understanding of lake water storage variations in the spatio-temporal domain is not only fundamental to understanding the impact of climate change, but also the impact of human activity on terrestrial water resources. Variations in precipitation have an impact on the water balance of a lake, and thus the relationship between the lake water level and precipitation are significant in understanding groundwater variation (Crétaux, 2011). In this study, the daily precipitation records from 18 meteorological stations were collected for the study period 2003–2013. The monthly precipitation data for each station were obtained by averaging the daily recorded precipitation values. The rainfall deviation was obtained by subtracting the monthly from the mean rainfall values.

3.2.2. Streamflow discharge observations

Daily streamflow discharge data from the last gauging station on the Nzoia River were obtained for the complete 10-year duration of the case study. To enable meaningful comparisons with the other data sets, the streamflow data were collected in terms of gauge height and averaged to mean monthly observations.

3.3. Detrending and deseasonalization of GRACE data

Groundwater changes and variability studies are often confounded by the presence of seasonal and trend components. These factors often exaggerate or dampen the actual variability of the time series and should be removed to properly isolate the variability of groundwater levels (Zhang and Qi 2005). The raw groundwater storage change time series should be deseasonalized and detrended in order to isolate the groundwater storage variation, and the computed groundwater changes time series need to be seasonally adjusted before inter-annual fluctuation analysis. The decomposition technique developed by Brockwell and Davis (2002) was adopted for this study.

For determination of long-term trend analysis, the classical decomposition model using the integrative time series modelling (ITSM 2000) software by Brockwell and Davis (2002) was used. The model removes seasonality using a standard d-component moving average function, and the residuals from the deseasonalized data are examined with linear regression in order to infer and demonstrate the significant trends in each data time series. The decomposition model is a stable seasonal filter that is useful in deseasonalizing time series data through additive decomposition.

3.4. Quantification of inter-annual standard deviation

To quantify the level of year-to-year volatility in groundwater change levels, the inter-annual standard deviation is computed. The inter-annual standard deviation is determined as proposed by Wilcox and Gueymard (2010), in order to retrieve the mean annual groundwater changes over the study period 2003–2013.

Figure 3 presents the schematic flow of data processing, methodology, and results validation as adopted in this study.

4. Results and discussion

4.1. GRACE terrestrial water storage: preprocessing and TWSC derivation

4.1.1. Harmonization and scaling of GRACE-TWS dataset estimates

The processed GRACE-TWS change data source from GFZ, CSR, and JPL data was compared in this study to infer any anomalies in the derived TWS estimations. Scatterplot analysis was used to compare differences among the three data sets and the results presented in Figure 4(a). The three data sources correlated well as depicted in Figure 4 (a), with the coefficient of determination (R^2) greater than 0.80 and correlation above 90%. In Figure 4(b), the similarity in the time series plots of the TWSC data from the three GRACE data sources also shows a near-similar trend, as seen by the frequency and location of the peaks and troughs from 2003 to 2013. The linear fits also indicate the close correlations between the data sets, with minor differences.

The observed differences in Figure 4 are attributed to the fact that the models and processing strategies adopted are inherently different. To minimize any inherent errors in

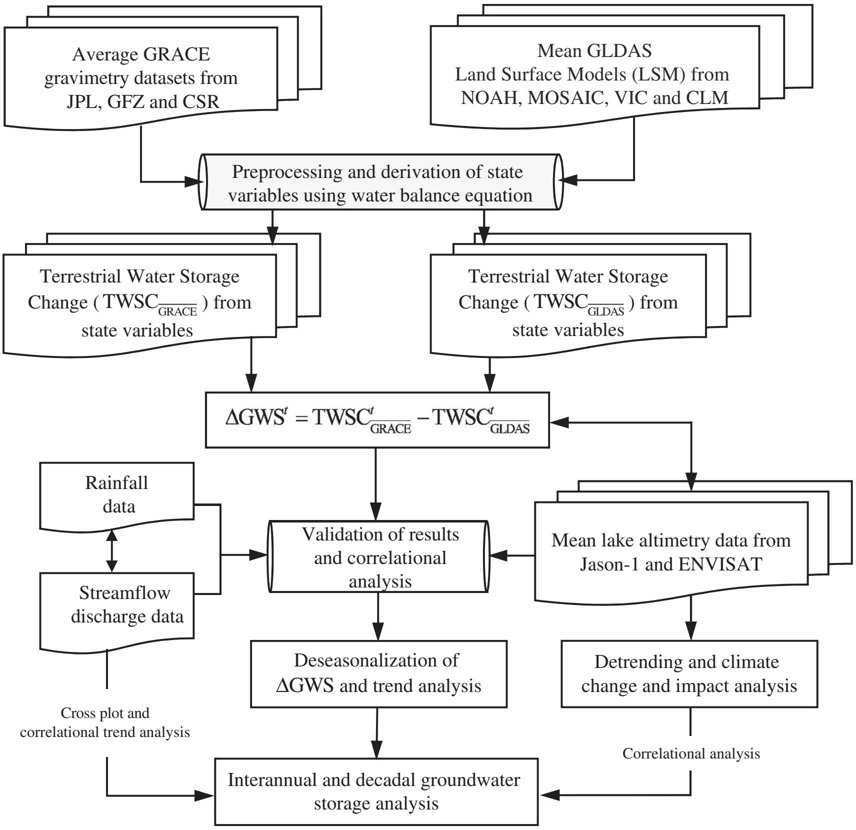
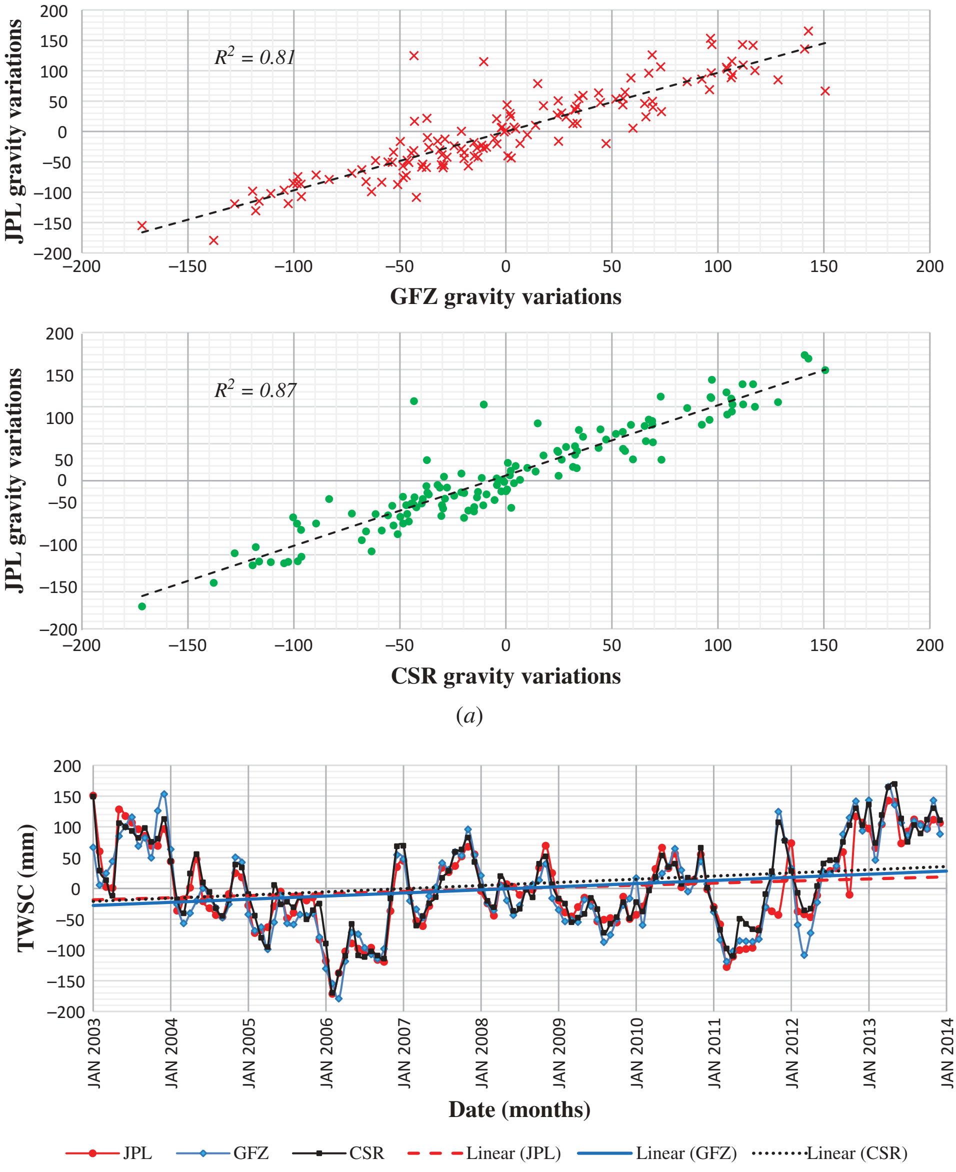


Figure 3. Schematic flowchart of the methodological approach. t denotes the specific and corresponding time of spatial comparison.

GRACE-TWSC data sources, a simple arithmetic averaging is adopted as an effective way of harmonizing and reducing the noise in the gravity field observations (Xiao et al. 2015). GRACE-TWSC data harmonization is also significant in this study given that the size of the study areas is less than the 200,000 km^2 recommended for GRACE data applications.

GRACE-TWSC estimates suffer from signal degradation due to measurement errors and noise, which are manifested as both random errors that increase as a function of spherical harmonic spectral degree (Wahr et al. 2004), and systematic errors that are correlated within a particular spectral order (Swenson and Wahr 2006). Through filtering and scaling, spatial resolution discrepancies are reconciled. According to Swenson and Wahr (2007), Rodell et al. (2004), and Landerer and Swenson (2012), if the GRACE signal attenuations are not scaled, they tend to reduce the ability and accuracy of closing the regional water balance, and also if unscaled the signal attenuation becomes an error in the residual water budget modelling.

Figure 5 shows the comparative results for the averaged unscaled and the averaged scaled (filtered) GRACE-TWSC. The scaling is achieved by multiplying the monthly TWSC grid values by their respective grid scaling factors, which are provided. In Figure 5 it is observed that the amplitude of the scaled TWSC is higher than the unscaled TWSC, but their seasonal and annual variations are the same. From Figure 5, a maximum positive



(*a*)

(*b*)

Figure 4. Comparison of gravity variation solutions from JPL, GFZ, and CSR in terms of (a) data scatterplot and correlation and (b) total water storage change and variation comparison for the 10-year study period.

Note: The units in the *x* and *y* axes in Figure 4(*a*) are in milligals (mgal), and 1 gal = 0.01m/s^2 as expressed in terms of gravity variation measurements.

TWSC value of 118.9 and 157.5 mm is respectively observed for the unscaled and scaled TWSC values. The highest negative TWSC values are respectively −128.9 and −165.5 mm. The results in Figure 5 show that preprocessing increases the amplitude and scale for further analysis.

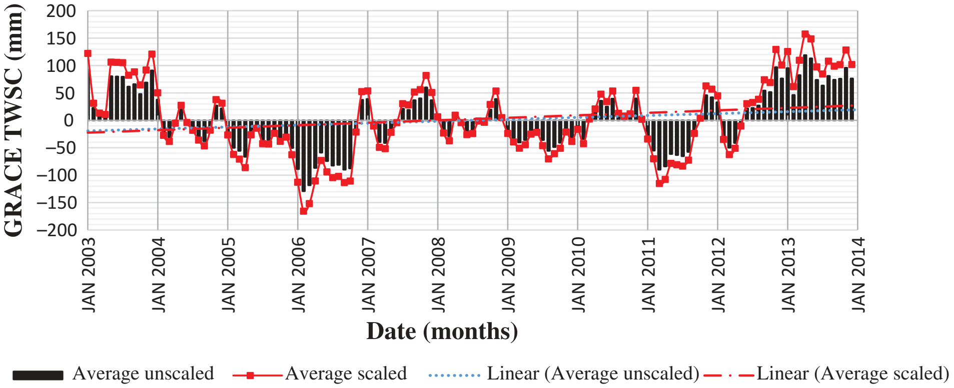


Figure 5. Time series comparison of unscaled and scaled GRACE-TWSC from 2003–2013 showing the increased magnitude and amplitude of TWSC after filtering and scaling.

4.1.2. *TWSC derivation: monthly, annual, and decadal variations*

The results for the area-averaged and scaled monthly mean GRACE-TWSC from 2003 to 2013 for the NRB is presented in Figure 6. A linear trend line fitted to the time series by least squares estimate indicates that in the basin there was an overall gain in groundwater storage at the rate of +4.536 mm year^{-1} from 2003–2013. This is equivalent to an increase of groundwater depth of 212 million cubic metres (mcm) year^{-1}. In order to better understand the variations in TWSC, a polynomial trend line shows a gradual decrease in TWS from May 2003 to December 2005, followed by an increase in TWS to January 2010, which is succeeded by another decline to January 2012 and an increase to the end of 2013. The observed trend depicts a

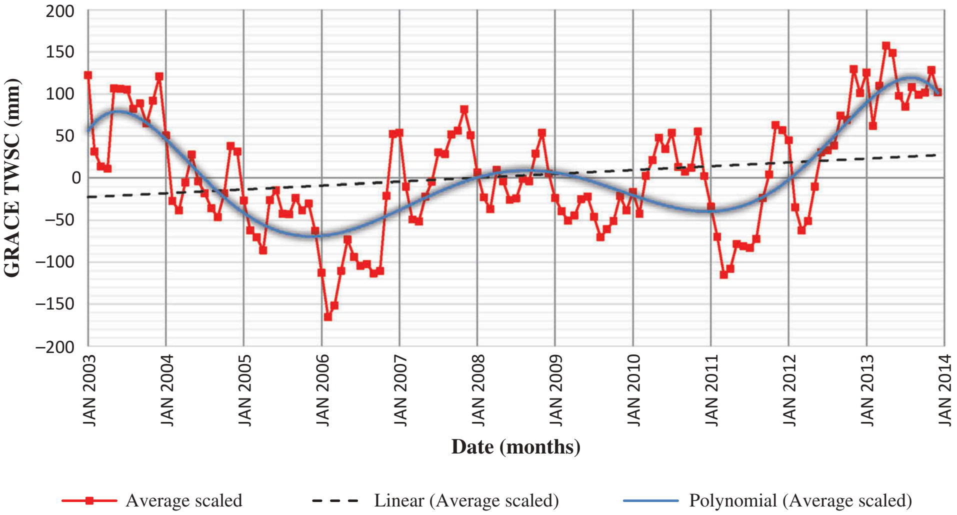


Figure 6. Monthly GRACE-TWSC for the Nzoia River Basin showing an overall linear increase in groundwater with a periodic polynomial trend showing a periodic variation in groundwater variation.

sinusoidal variation, which characterizes the climatic regimes in this region over time – for example, the effect of the Indian Ocean dipole (IOD) or Indian Niño on rainfall in 2006 (Becker et al., 2010).

In order to understand the average TWSC variations as determined from GRACE data, Table 1 shows the 10-year monthly and annual averages for the TWSC in the basin. In the basin area, the long rains are between April and July and the short rains last from October to December, while the dry seasons occur in the months of January–March and August–September. The monthly average results in Table 1 show that TWSC is positive during the rainy seasons and negative during the dry seasons, or at least for a short while after the onset of the rainy seasons. This translates into an increase in TWS mostly during the rainy seasons and a drop below the mean value during the dry seasons. The yearly negative trends in storage change are therefore a more reliable reflection of storage dynamics in the study area.

As shown in Table 1, the highest reduction in TWS is experienced during the dry months of February and March. This extreme reduction causes dry conditions; at the onset of the long rains in April, the environment (soil and biomass) is generally dry and thus much water is needed to bring TWS up to the expected mean value. This is why the overall effect of the long rains is not immediately registered by GRACE as per the mean monthly observations. On the other hand, the dry spell experienced from August to September is not so severe as in January–March. Thus, following the onset of the short rains in October, the soil is not as dry as observed in March. From the above scenario, the prevailing conditions therefore allow the short rains to cause greater changes in TWS as compared with the long rains. The recorded net average monthly change in TWS in the basin was found to increase by 5.126 mm year^{-1}, while the annual average change increased by 4.068 mm year^{-1}. This translates into a total monthly basin water storage increase of 239 mcm year^{-1} and a net annual increase of 190 mcm year^{-1}.

Climate variations, which are triggered by both natural and anthropogenic causes, force changes in the SW balance, which can increase or decrease water storage. Cool and wet climatic conditions tend to drive storage upwards, and warm and dry conditions tend to drive it downwards (Milly et al. 2010). These conditions and phenomena contribute to the observed TWSC variations as detected by the GRACE data analysis. In relation to the results shown in Figure 6, the drop between 2003 and 2006 is attributed to the drought experienced during that period, while the rising limb from then up to 2010 is attributed to the occurrence of the El Niño Southern Oscillation (ENSO) in 2006, which stabilized TWS in the basin.

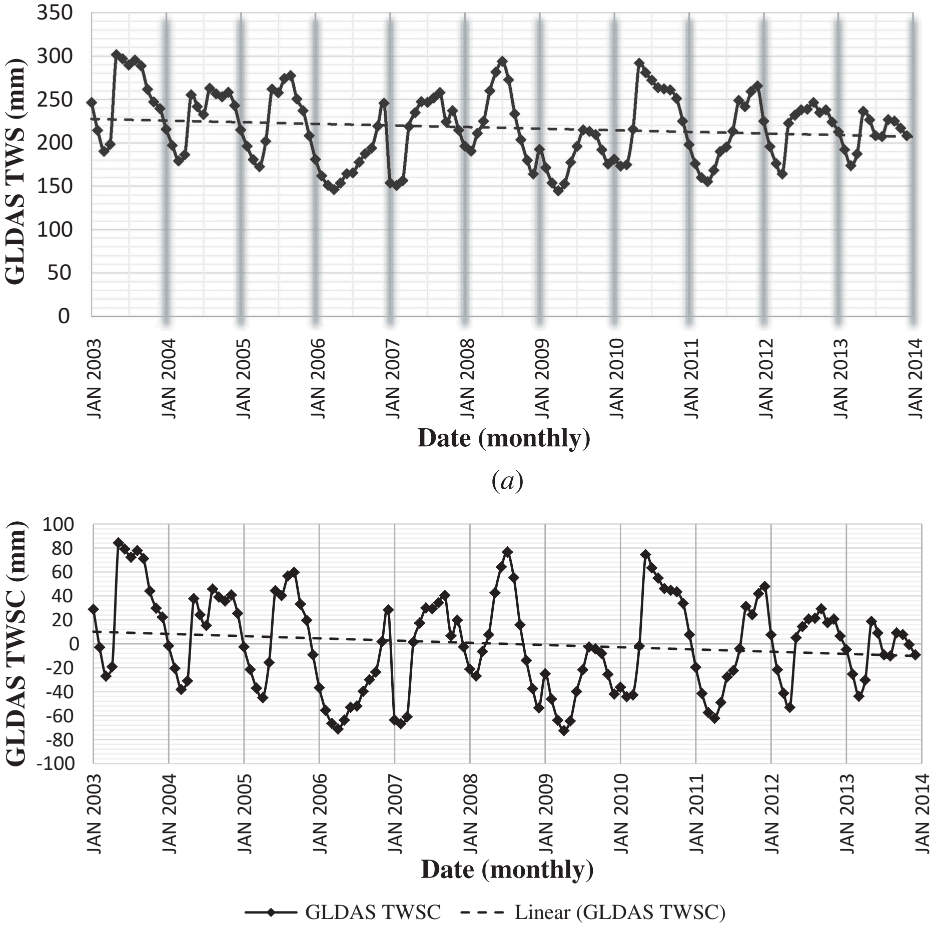
4.2. TWSC from GLDAS land-surface models

The monthly TWS changes from GLDAS were obtained by averaging the daily SM and CWS state variable values from the four GLDAS land-surface models from January 2003 to December 2013. The results in Figure 7(a) show a general decline at the rate of 1.852 mm year^{-1} in TWS in the basin, as shown by the fitted linear trend line. This decreasing trend is attributed to land-use changes, especially the reduction of forest cover for fuel and transformion into other land-use activities like subsistence agriculture. When the canopy cover is reduced, transpiration is reduced such that runoff is favoured more in the hydrologic cycle and there is little canopy water content. Depending on local climate and topography, this could lead to either more or less water being stored in the soil, hence an increase in the SM content (Milly et al. 2010).

Table 1. Monthly and annual average TWSC from GRACE data.

	GRACE terrestrial water storage change (TWSC)											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10-year monthly average change (mm)	+17.26	−34.64	−40.85	−23.38	+8.33	+2.14	−1.04	−4.98	+4.45	+10.81	+51.65	+38.33

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Annual average change (mm)	+78.62	−3.78	−43.82	−92.23	+18.01	−1.23	−41.04	+15.81	−45.11	+30.17	+110.33



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(*b*)

Figure 7. Monthly TWS (a) and TWSC (b) from GLDAS-LSM comprising soil moisture and canopy water state variables.

To determine the monthly TWSC, the mean monthly TWS for the study area was first obtained by averaging the monthly values, and then the monthly values were subtracted from the mean monthly TWS to derive the TWSC, as shown in in Figure 7(b). From a least squares trend fit there is a decline in TWSC at a rate of approximately 0.154 mm year^{-1}. This contradicts the observed incremental trend observed from GRACE-TWSC of 4.540 mm year^{-1}, which is explained by the fact GLDAS land surface models do not take into account groundwater variation, which is the main storage for total terrestrial water.

In terms of the monthly averages, Table 2 shows that the average monthly TWSC is +4.887 mm year^{-1}, which is slightly comparable to the monthly average from GRACE shown in Table 1. The results in Table 1 show that water storage is generally higher after the onset of long rains, implying a direct influence of rainfall on TWSC as contained in the SM and CWS. The decline from October onwards is translated to the removal of water from storage through streamflow discharge, evaporation, and infiltration into groundwater reserves. This is because GLDAS land surface models go to a depth of 200 cm, which can

Table 2. Monthly and annual average TWSC from the GLDAS-LS models.

	GLDAS-LSM terrestrial water storage change (TWSC)											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
10-year monthly average change (mm)	−15.98	−33.97	−44.17	−34.36	+7.86	+18.86	+18.47	+25.44	+27.79	+15.13	+13.05	+1.88

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Annual average change (mm)	+38.31	+14.30	+10.17	−38.53	−1.30	+8.49	−34.73	+20.21	−11.60	+2.18	−7.49

be affected by plant roots through evapotranspiration and infiltration depending on the geophysical characteristics of the soil.

From the cumulative annual average TWSC in Table 2, it is observed that there is a general decline in the variability of TWS in the region at the rate of 2.352 mm year^{-1} as determined from the LSM state variables. This contradicts the positive annual gain determined in Table 1. The steep decline noted between 2003 and 2006 is attributable to the drought experienced in the region during the same period, while the drastic incline in 2006 is a result of the ENSO effect during the same period. The same phenomenon is observed in the GRACE-TWSC results presented in Table 1.

The results in Tables 1 and 2 imply that the overall trend of TWSC from GRACE and GLDAS analysis may not necessarily provide the correct trend in TWSC within a given region. Thus annual and decadal groundwater variability analysis is considered for an accurate and conclusive analysis of results.

4.3. Comparison of TWSC from GRACE and GLDAS-LSM

A plot of the TWSC as derived from the state variables in GRACE and GLDAS is presented in Figure 8(a) and 8(b). From the mean monthly variation trends in Figure 8(a), it is observed that the TWSC estimates from GRACE and GLDAS-LSM agree quite well for the period 2003–2013, despite the difference in amplitude, which can be explained by the components in the water balance equations. Furthermore, the variation in monthly GRACE-TWSC is generally higher than that in the monthly GLDAS-LSM-derived TWSC, because of the seasonal effects of groundwater storage detected by GRACE and not by the canopy water- and SM-based GLDAS models (Ferreira et al. 2014). Furthermore, the loss of forest cover can cause an increase in the the water table as a result of decreased evapotranspiration while the removal of vegetation also reduces evaporative loss, and water-delivery infrastructure can enhance recharge, leading to increase in groundwater storage. A regression analysis on the two data sets (Figure 8(b)) produces $R^2 = 0.24$, which is within the acceptable range of 0.2–0.5 as predicted by Rowlands et al. (2010).

In order to further explain the differences observed for TWSC between GRACE and GLDAS-LSM, a comparison with the state variables is carried out. This is because the determination of groundwater changes is a function of the TWSC and the state variables from GLDAS. Thus the correlation and accuracy of the GLDAS state variables with the GRACE-TWSC is important as an accuracy measure. A monthly comparative evaluation for TWSC from GRACE and GLDAS-LSM state variables is presented in Figure 9. The results in Figure 9 show that TWSC obtained from GRACE and SM and CWS in GLDAS-LSM have the same trend. Additionally, seasonal cycles from the two models show similar patterns as seen by the peaks and depressions. The observed lag in the comparative analysis is normal since the state variables must first change in order to impact on the TWSC. This implies that the determined groundwater changes are reliable.

From the comparative results it can be deduced that the storage changes in the SM are less as compared with TWSC from GRACE. This means that there is less storage loss in unsaturated storage, i.e. SM. The storage change in the canopy storage is high due to exposure to the environmental effects of temperature, and human interference with vegetation for land use. While the annual variability trends

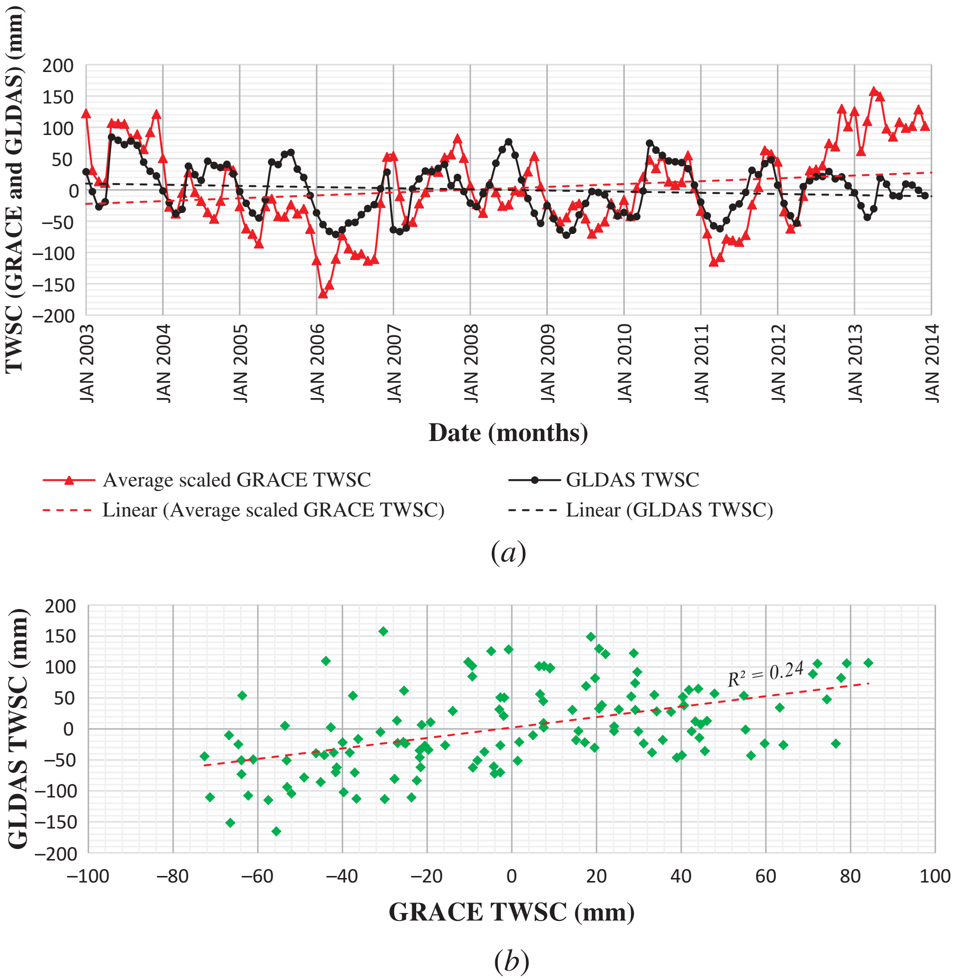


Figure 8. Comparison of TWSC from GRACE and GLDAS: (a) monthly variations and (b) regression correlation analysis for the study duration.

in SM and CWS changes are negative, the GRACE-TWSC is positive. This finding confirms that an overall storage loss exists in the study area for the period 2003–2013. To quantify the stored water resources of a region, SM and groundwater have been documented to play a significant role (Voss et al. 2013).

The average monthly–seasonal analysis indicates that both changes in SM and TWSC are generally higher in the dry seasons and lowest in the wet seasons. However, the overall storage change is positive for the wet seasons and negative for the dry seasons. These trends largely reflect the prevailing agro-climatic conditions, which are critical for sustainable water management and preservation of fragile but valuable wetland ecosystems in the region (Moiwo, Lu, and Tao 2012). The peaks and troughs appear more prominently on a seasonal basis than on the monthly intervals and the oscillations between peaks and troughs correspond to the different seasons and climatic variations in the basin.

Characteristically, the low storage values correspond to dry periods. On the other hand, the long rains periods show high peaks. The observed increase in TWSC and the

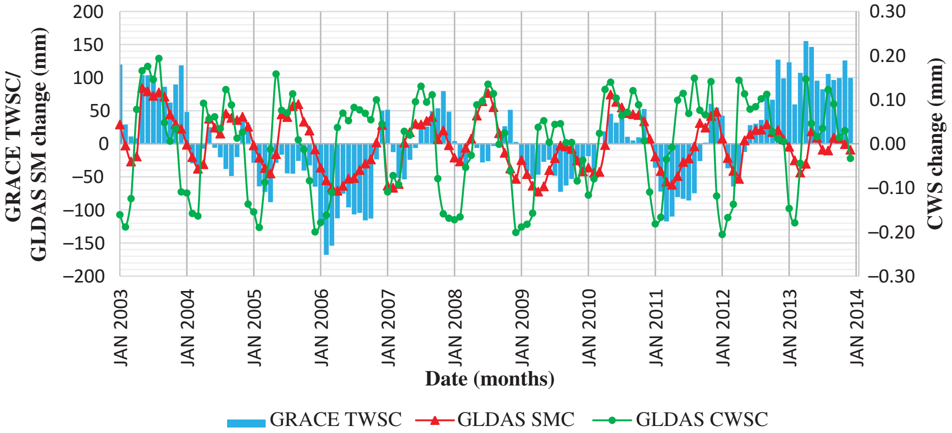


Figure 9. Average monthly comparison of GRACE-TWSC and changes in GLDAS-LSM soil moisture and canopy water storage state variables.

corresponding decrease in the same period from GLDAS-LSM can be linked to an increase in evapotranspiration, as temperatures rise during the dry months. The increase in TWSC can be attributed to a decrease in the runoff volumes from the area.

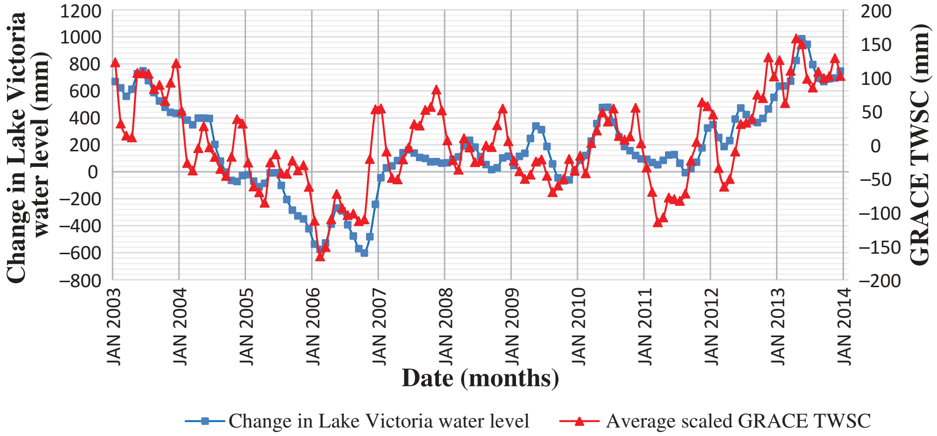
4.4. TWS variation comparison with Lake Victoria *altimetric height variations*

Within the basin's hydrological system, the groundwater interacts with the SW. As such, variations in Lake Victoria water levels will also be manifested in the basin groundwater water storage change. Figure 10(a) shows the monthly plots of GRACE-based terrestrial water storage changes (TWSC) in the Nzoia Basin and the Lake Victoria altimetric water level changes from 2003 to 2013. The results show a patterned agreement between the TWSC and variations in the Lake Victoria altimetric water level variations. There is a general agreement in the peaks and troughs of both sets of data with a notable phase lag of approximately two months. This lag difference is a cause–effect phenomenon. The results show established correlation between the hydrological components and systems as captured by gravimeteric and altimentric measurements.

Similarly, the results for the monthly plots of GLDAS-TWSC and the changes in altimetry lake levels for the period 2003–2013 are presented in Figure 10(b). The peaks and troughs of the two data sets agree in seasonality, both representing the 2003–2006 drought with an observed decline in TWS and lake levels. In addition, the seasonal cycle of TWSC shows a good agreement in terms of amplitude and phase with the Lake Victoria altimetry heights. The lag in the altimetry series and the GLDAS-TWSC clearly shows that the volume of water in the basin area is contributed to by the SW of the lake.

4.5. GWSC determination and comparison with altimetric and insitu *measurements*

Variation of water levels in natural water bodies such as lakes indicates changes in the hydrological budget of the lake catchments such as basins. Such changes are caused not only by climatic variations such as precipitation, evapotranspiration, and other



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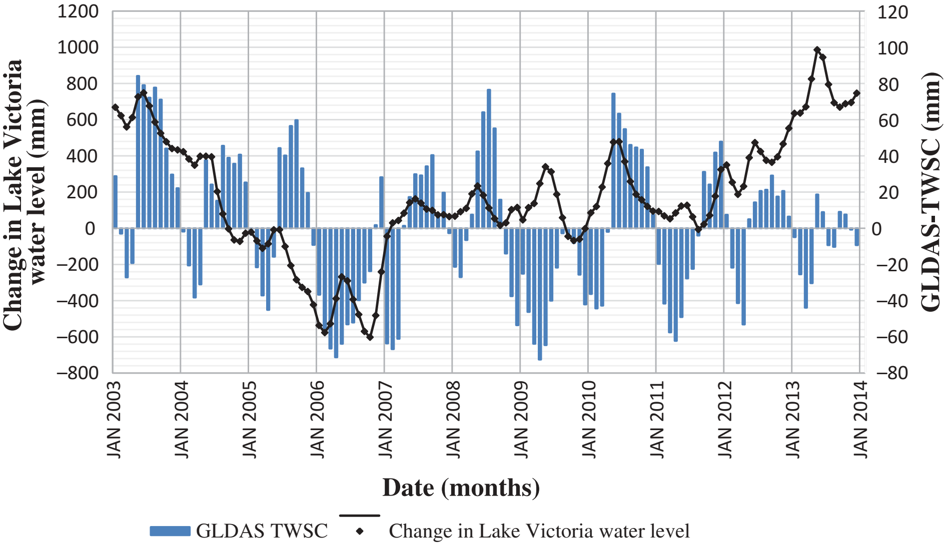

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Figure 10. Time series comparison of TWSC and Lake Victoria altimetric water level variations from 2003 to 2013 from (a) GRACE and (b) GLDAS- LSM.

meteorological components, but also by changes in the runoff characteristics in the catchment or basin and are dependent on the size of catchment per lake surface area (Vuglinskiy et al. 2009).

4.5.1. *GWSC and Lake Victoria altimetry height variations*

According to the water balance equation (Equation 4), the net groundwater change is determined from the difference in the mean TWSCs as determined from GRACE and GLDAS-LSM. Figure 11 shows the basin groundwater change and variations in the Nzoia River Basin, and the trend comparison to the Lake Victoria altimetry data. The results for

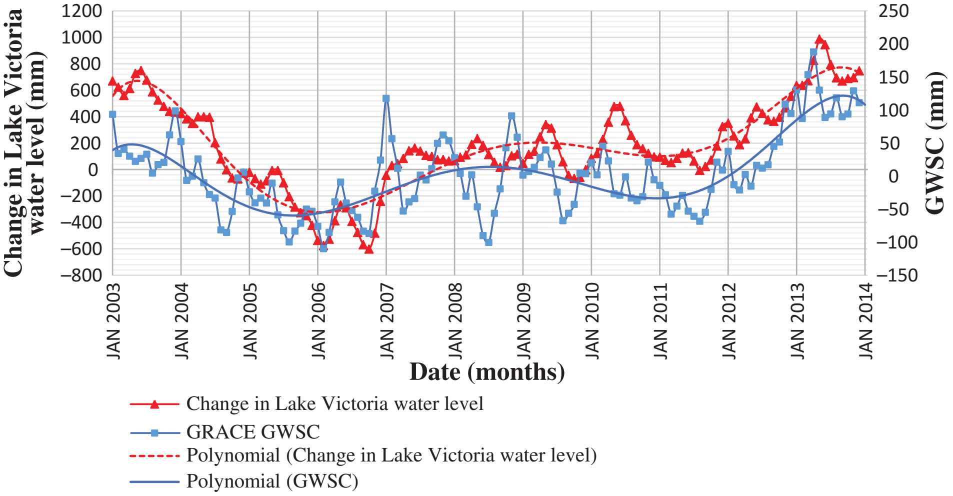


Figure 11. Time series comparison of determined groundwater variations from the water balance approach and Lake Victoria altimetric surface water level changes.

the groundwater variations show a steady decline in GWS in the basin from 2003 to January 2006, and because of the ENSO phenomenon of 2006, the GWS in the basin increased to stable storage with seasonal cyclic variations to the beginning of 2013. Because of water balance and saturation, the amount of groundwater change is seen to be equal to the degree of change in the lake level. The same trend is observed for lake level variations, but with obvious different amplitudes. While the fluctuations in the lake levels can be attributed to anthropogenic factors, it can also be seen that natural and climatic variations also play a significant role as verified by the corresponding sinusoidal variation patterns between the lake levels and water balance equation-based groundwater changes.

4.5.2. *River discharge comparative analysis with TWSC and GWSC results*

The results for the comparative evaluation of the Nzoia River discharge against the changes in total water storage and groundwater storage are presented in Figure 12. In Figure 12(a), the comparison between GRACE-TWSC and the monthly deviations from the mean height of the Nzioa River flows is presented. The results are seen to be similar with respect to monthly and seasonal variation, which is explained by the fact that GRACE measures the reservoir variations as part of the TWS in the basin, and therefore the observed close agreement in the trends of the river discharge deviations and TWSC.

When compared to the GLDAS-LSM-derived TWSC, the river flow trends are similar in seasonal and monthly behaviour as shown in Figure 12(b). The GLDAS-TWSC and the height variations show a negative trend in the first period up to 2006 and a positive trend towards the end of the study period. The observed minor dissimilarity between GLDAS-LSM-derived TWSC and river discharge can be attributed to the fact that wetlands only marginally affect the basin seasonal water balance. For the basin GWSC and river discharge comparison, Figure 12(c) shows that the river flow variations are dissimilar, and this could be attributed to the other contributors of flow, such as precipitation, which do not affect GWS immediately unlike river flow. The plot shows an increase in GWSC

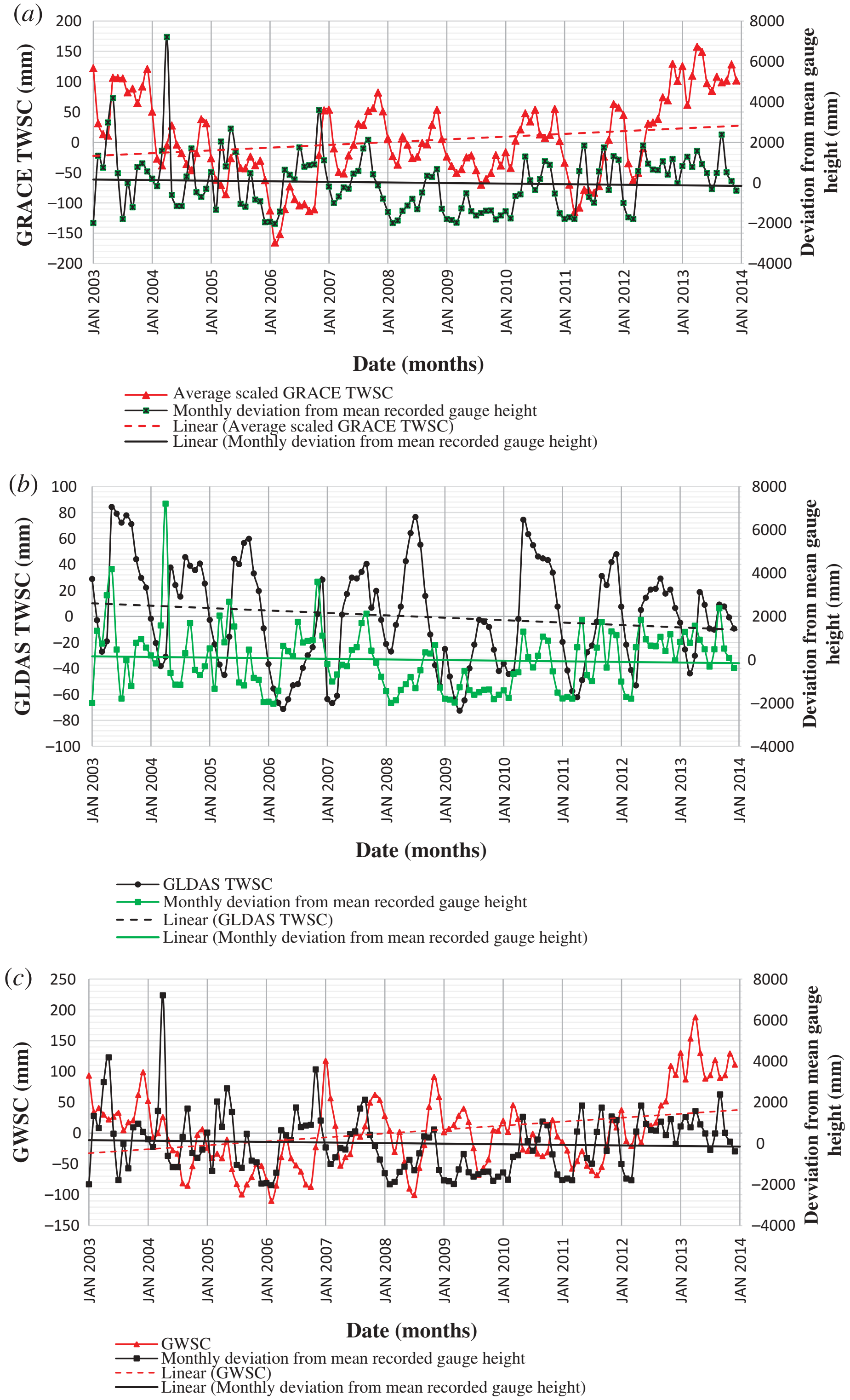


Figure 12. Monthly comparative deviations from the mean recorded river flow discharge with: (a) GRACE-TWSC, (b) GLDAS-LSM TWSC, and (c) GWSC as derived from the water balance approach for the study period.

towards the end of the study period as compared to the decrease in river discharge, which is related to the effects of negative changes in land use in the basin due to increased population and demand from agricultural and industrial land.

4.5.3. Rainfall variations with TWSC and GWSC

Rainfall is an important component of the water cycle and is the prime source of groundwater recharge. Thus to further validate the results, the average annual rainfall variations in the basin are compared with the derived TWSC from GRACE and GLDAS-LSM and the groundwater storage from the water balance equation. The cross-plot results in Figure 13(a) show that the seasonal and monthly plots of GRACE-TWSC and rainfall variations exhibit the expected seasonal amplitudes and phase changes. There is an expected lag in TWSC gain with respect to rainfall. The rainfall variations with GLDAS-TWSC also exhibit the same expected pattern as that shown in Figure 13(b). The results in Figure 13(a) and 13(b), with a cause–impact effect, show that the major hydrologic input in the basin is rainfall.

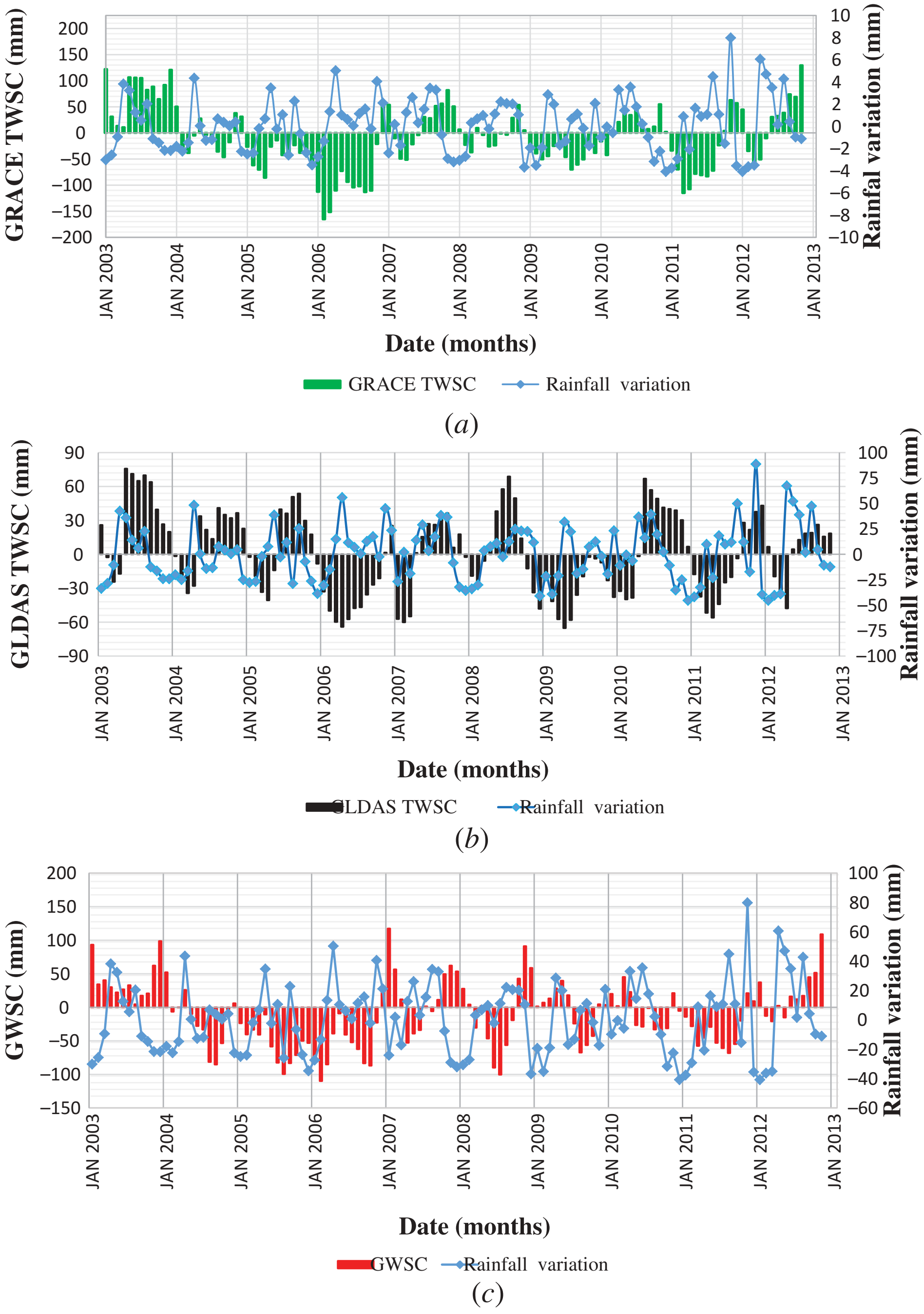
The difference in TWSC between GRACE and GLDAS, which represents the net GWSC in the basin, is presented in Figure 13(c) in comparison to the rainfall measurements and changes in the basin. The net recharge leads to a rise in groundwater levels in the wet season, and in the dry season the levels naturally fall as groundwater is either evapotranspirated or discharged into rivers and wetlands, where it either evaporates or is discharged into Lake Victoria. The seasonal fluctuations of the groundwater variations in response to rainfall depend on the type, size, and other physical properties of the aquifer as well as the amount of recharge from other sources apart from rainfall. In many areas, the aquifers essentially fill and spill in the wet and dry seasons, respectively. Notably therefore, changes in regional precipitation can lead to large variations in water storage (Milly et al. 2010).

Generally, it is observed that increased rainfall variability may decrease groundwater recharge in humid areas. More frequent heavy rainfall results in exceeding the infiltration capacity of the soil, thereby increasing surface runoff. In semi-arid and arid areas, however, increased rainfall variability may increase groundwater recharge because only high-intensity rainfall is able to infiltrate fast enough before evaporating. Considering the location of the Nzoia River Basin where both of these conditions exist due to climatic variations, agreement between GWSC and rainfall variation as observed in Figure 13(c) can be interrelated.

4.6. Climate change analysis based on seasonaltrend decomposition

In order to understand the variation between groundwater change and climate variability at the basin scale, the monthly GWSC was filtered using the seasonal trend decomposition procedure based on loses (STL) as proposed by Cleveland et al. (1990). In principle, the STL method is a filtering procedure that decomposes time series into additive components of variability trend and seasonal and residual components by application of the LOESS smoothing model (Brockwell and Davis 2002; Hassan and Jin, 2014). LOESS smoothing results in detrended and deseasonalized data sets.

Detrending is applied to the GRACE time series data to enable the general study of GWSC behaviour in the basin. This implies an equilibrium condition where the total inflow equals the total outflow. From the detrended monthly GWSC results in Figure 14 (a), linear and sinusoidal trends are observed from the time series data obtained. A decline in GWSC can be observed from the year 2003 to the year 2006 followed by a rise thereafter to 2008 and another decline to 2011, after which there is a rise until the end of

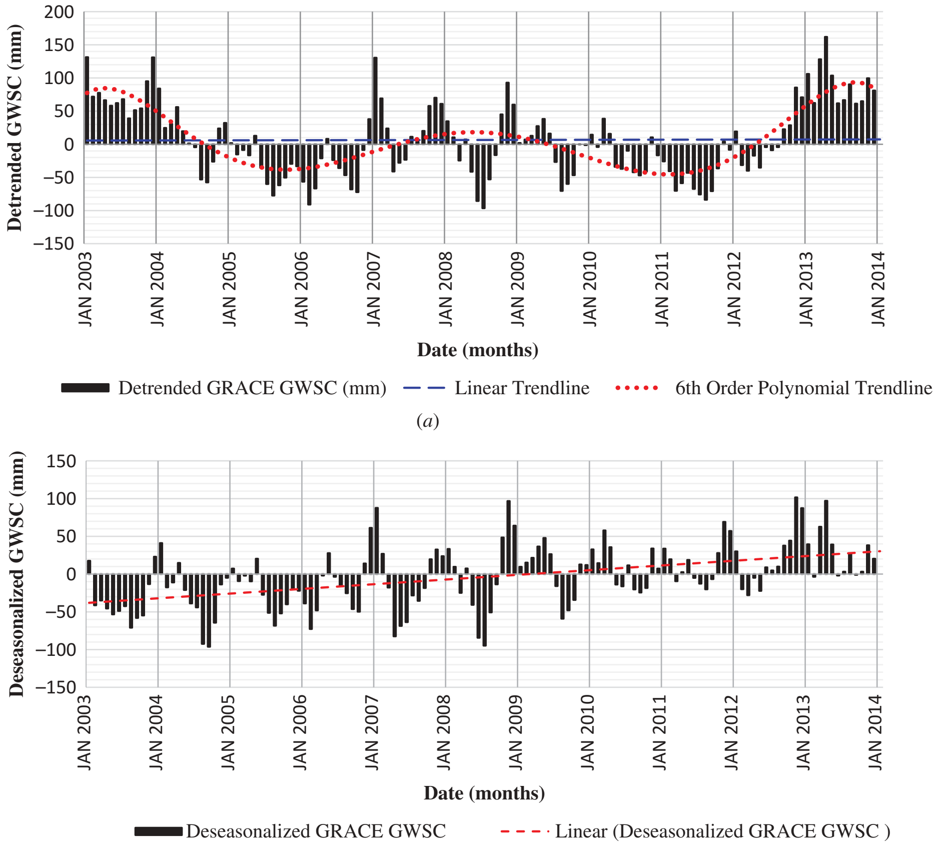


(a)

(b)

(c)

Figure 13. Comparative evaluation results between rainfall variation in the basin and those derived: (a) GRACE-TWSC, (b) GLDA-LSM-derived TWSC, and (c) groundwater storage change.



(*a*)

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Figure 14. (a) Detrended and (b) deseasonalized GWSC time series of the NRB for 2003–2013.

the study period. The decadal averaged seasonal trends show that all major hydrological components except runoff are expected to increase.

Contrary to detrending, deseasonalization is performed to remove the effect of seasons on the GWSC in order to allow the study of annual variability of the GWSC without the effect of the seasons. From the fitted linear trend a general increase in the variability of GWS is observed even after the elimination of the effect of wet and dry seasons on the time series, as depicted in Figure 14(b). The most significant increase in the variability of GWS is observed between 2012 and 2013. This may be explained by the predicted impacts of climate warming on groundwater including changes in the magnitude and timing of recharge (Kløve et al., 2014). The climate change phenomenon can also be observed in Figure 14(b) for November 2012 and March 2013, where the timing of recharge is much closer as compared with the other periods. This can be validated by the previous flood scenario experience in the basin for 2002, 2003, and 2008. The increasing GWS observed towards the end of the study period from Figure 14(b) supports previous findings that there will be increased annual rainfall with the highest amounts expected in western parts of Kenya around Mount Elgon, Elgeyo Escarpment, and the Cherangani Hills, which is the catchment of River Nzoia that drains through Budalangi District and is likely to result in flooding within the basin

In general, climate change and variability have directly and indirectly affected, and will continue to affect, groundwater quantity in complex and unprecedented ways. It is projected that future climate change will affect recharge rates and, in turn, the depth of groundwater levels and the amount of available groundwater (Kløve et al. 2014).

4.7. *Inter-annual groundwater variability analysis from deseasonalized climate data*

Table 3 shows the results of the deseasonalized GWSC in the basin during the study period. The results provide an inter-annual analysis scenario of the groundwater storage dynamics for the study area. The results indicate the maximum positive and negative deviations from the mean GWSC. The maximum positive deviation is observed to occur towards the end of the study period, and can be related to climate change phenomenon as already discussed in Section 4.6. The years 2004, 2005, 2006, and 2011 are observed to have the least positive deviation, which can be attributed to the droughts that occurred during these periods. It is observed that the drought years have the maximum reduction while the years succeeding the El Niño of 2006 have a low maximum reduction in GWS. The average recharge time is observed to be seven months, with unique values being observed towards the end of the study period.

5. Summary and conclusions

This study adopted the water balance equation in order to help understand the inter-annual and decadal groundwater variations in the Nazoia River Basin from 2003 to 2013, by using the gravimetric variation measurements from GRACE and the land surface models from GLDAS. Given the size of the Nzoia River Basin, in comparison to the recommend minimum application area-size for GRACE and GLDAS data, the data-averaging approach was adopted in order to minimize any bias in the analysis. This was coupled with an area-based weighting to the averaged data sets. The results of the study were validated using satellite-based lake altimetry data and *in situ* measurements from rainfall and streamflow, which are principal groundwater water change indicators.

The average results for the 10-year period showed that the TWSC in the basin as determined from GRACE gravity water balance components recorded an increase of 4.54 mm year^{-1} in terms of EWT, which is equivalent to a gain in terrestrial or total water storage gain of 212 mcm year^{-1}. From the average GLDAS-LSM, the TWSC was recorded at an average rate of loss of 5.18 mm year^{-1}, which is a water loss of 242 mcm year^{-1} for the study period. This difference reflects the fact that GLDAS-LSM does not account for groundwater, which is the main contributor to the total TWS.

From the water balance approach, the net groundwater depth increased by 6.38 mm year^{-1}, which is equivalent to aquifer recharge of 298 mcm year^{-1}. Similarly, the deseasonalized trend confirmed an average gain of 6.21 mm year^{-1} in groundwater depth. Both results are comparable to the national estimated natural groundwater safe yield of 330 mcm year^{-1} from aquifer recharge by the Kenyan Water Resources Management Authority (WRMA).

In the absence of long-term well-based groundwater *in situ* measurements, the results of the study showed close similarity and correlation for streamflow discharge, rainfall, and altimetry water levels with the total storage water change and groundwater storage changes. Such an analysis and validation approach is suitable in areas where there is lack of reliable spatial and temporal *in situ* data. Furthermore, indicative climate change analysis shows the effect of climate change on the groundwater storage regime in the

Table 3. Inter-annual analysis of the groundwater storage dynamics in the Nzoia River Basin from 2003 to 2013 ($\text{GWSC}_i$and $\overline{\text{GWSC}}$ are respectively the mean and observed groundwater changes).

Year	Maximum increase (mm)	Maximum decrease (mm)	Difference between max and min (mm)	Time for recharge/ depletion (months)	Mean rate of recharge/depletion (mm)	Annual standard deviation (mm/year) $\left[\sigma = \left(\frac{1}{n}\sum_{i=1}^{n}\left(\overline{\text{GWSC}} - \text{GWSC}_i\right)^2\right)^{\frac{1}{2}}\right]$	Annual average GWSC (mm year^{-1})
2003	98.70	4.56	94.14	4	40.31	28.3	+0.2184
2004	52.18	−85.35	137.53	8	−18.01	39.1	−5.6755
2005	−23.80	−99.55	75.75	3	−53.99	25.3	−4.1212
2006	−9.24	−109.92	100.68	10	−53.69	36.6	+5.178
2007	117.45	−52.87	170.32	3	19.30	47.9	+0.2312
2008	91.17	−100.43	191.60	5	−9.72	56.3	+5.2151
2009	39.57	−67.53	107.10	3	−6.31	32.5	−4.1112
2010	45.19	−37.32	82.51	9	−4.40	26.2	−3.2648
2011	21.09	−68.36	89.45	3	−33.51	27.3	+2.7702
2012	108.90	−20.93	129.83	9	27.99	39.8	+8.8824
2013	187.83	87.14	100.69	3	117.82	29.4	−2.6970

basin. For example the drought of 2003 and ENSO phenomenon in 2006 can be linked directly to the changes in total and groundwater water storage variations in the Nzoia River Basin. Thus the results of this study can be related to climatic phenomena in the region for future adaptations in response to climate change and rapid population growth, as overdependence on groundwater intensifies.

From the results of this study, it is concluded that even in small basins, GRACE gravity-variable solutions and GLDAS-LSM provide reliable data sets suitable for the study of small-area groundwater storage variations and are significant in data-scarce regions in helping to understand the spatio-temporal variations in groundwater quantity and recharge. Further studies on the impacts of climate change are recommended and ongoing, together with the influence of anthropogenic change phenomena on groundwater variations.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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