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Tracking Total Water Storage over River Basins in Nigeria Using Grace Satellite

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Abstract

Regional monitoring of available water resources across Nigeria for effective management is becoming very important with the encroaching desertification in the northern part of the country. Deploying a ground-based monitoring network across the country is not feasible due to the huge financial cost. GRACE satellite provides cost-effective means of regional-scale monitoring of water resources. This study analyzed the GRACE gravity data and observed the pattern of GRACE-derived Terrestrial Water Storage (TWS) and Ground Water Storage (GWS) anomalies across the five river basin divisions of Nigeria using data from 2006 to 2012. The data were interpolated using the moving average function to generate raster images of TWS for individual months. The plot of the seasonal TWS and GWS anomalies reveals seasonal variation patterns corresponding to the region's rainfall pattern confirming the sensitivity of the satellite. The trend of the annual average TWS anomalies indicates that the TWS rose across the basins at rates between 0.19 cm/year and 1.28 cm/year. The trends of the annual average GWS plots reveal increasing GWS trends in three of the five basins. The study concludes that the increase in TWS, in most of the basins, is likely due to changes in groundwater recharge quantities and therefore suggests that increasing access to improved groundwater sources is likely to be highly successful in mitigating the adverse effect of climate change in Sub-Saharan Africa.

Keywords

GRACE, Gravity, Ground Water Storage, Terrestrial Water Storage, Satellite, River Basin

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1. Introduction

Water is an essential resource that the world cannot do without. The distribution of water on the planet earth is highly uneven. With an estimated 1.1 billion people without access to potable water, water shortage is a global issue [3, 27]. More reliable information on water resources is required for effective management to meet the increasing water demand. While monitoring facilities for precipitation and rivers operate in most regions, surveillance of subsurface water resources (soil moisture and groundwater) is insufficient [25], especially in sub-Sahara Africa.

The capacity to estimate hydrological budget parameters for several basins around the world has been enhanced by the Gravity Recovery and Climate Experiment (GRACE) satellite [2, 6, 10, 12, 17, 28, 29]. GRACE satellite measures temporal changes in gravity field which is used to compute monthly variations in Terrestrial Water Storage (TWS), ice mass variations, pressure variation at ocean depth, and sea-level changes [9, 14, 16, 20, 23]. It consists of two similar satellites that orbit at 220 km apart and 485 km above the earth [9]. The distance between the satellites varies when the

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satellites are affected by perturbations in the Earth's gravity field [7]. Such disruptions can be due to massive mass features, like mountains and seas, which have various gravitational pulls, forcing satellite orbits to speed up or slow down as they pass overhead [7, 18]. The rates at which inter-satellite spacing varies over time offer extremely detailed global gravity field solutions [18]. Each solution is in the form of a series of coefficients for a spherical harmonic expansion, which is used to define the shape of Earth's global gravity field [18]. These can track subsurface mass changes, so much that GRACE data is more precise in tracking TWS variations than data obtained using the traditional field instruments [19].

TWS variation is an essential part of understanding the hydrologic cycle. It is the aggregate sum of all surface water, soil moisture, snow water, vegetation water, and groundwater [4, 22], and is essential for water resources and agricultural management. The possibility of estimating TWS changes is important for understanding the broad variety of hydrological, climatic, and ecological processes as well as their effect on the occurrence of droughts, heatwaves, and floods [1, 8]. Despite the importance of providing accurate TWS estimates, information on the spatial and temporal changes of TWS and its parameters is in short supply, especially on a regional scale, because of the lack of global monitoring infrastructure. Ground-based observations, though accurate, only provide point-based measurements [5, 13], which are difficult to regionalize. Similarly, groundwater storage changes (GWC) are difficult to quantify considering the geographical and temporal constraints of collecting complete and reliable measurements of groundwater levels over broad geographic regions [11, 21]. This difficulty in GWC estimation hinders the development and application of an effective water management system. It is therefore important to establish large-scale monitoring systems that provide reliable and timely information on the condition of the water reservoir using the GRACE satellite.

2. Study Area Description

The study area covers the five different River basins in Nigeria [15]. Figure 1 shows the river basins of Nigeria, namely, the Hadejia-Jama'are, Sokoto-Rima River Basin (Area 1), the Upper/Lower Benue River and Lake Chad Basin (Area 2), the Upper and Lower Niger River Basin (Area 3), the Osun-Ogun, Owena River Basin (Area 4), and the Anambra-Imo, Niger Delta and Cross River Basin (Area 5).

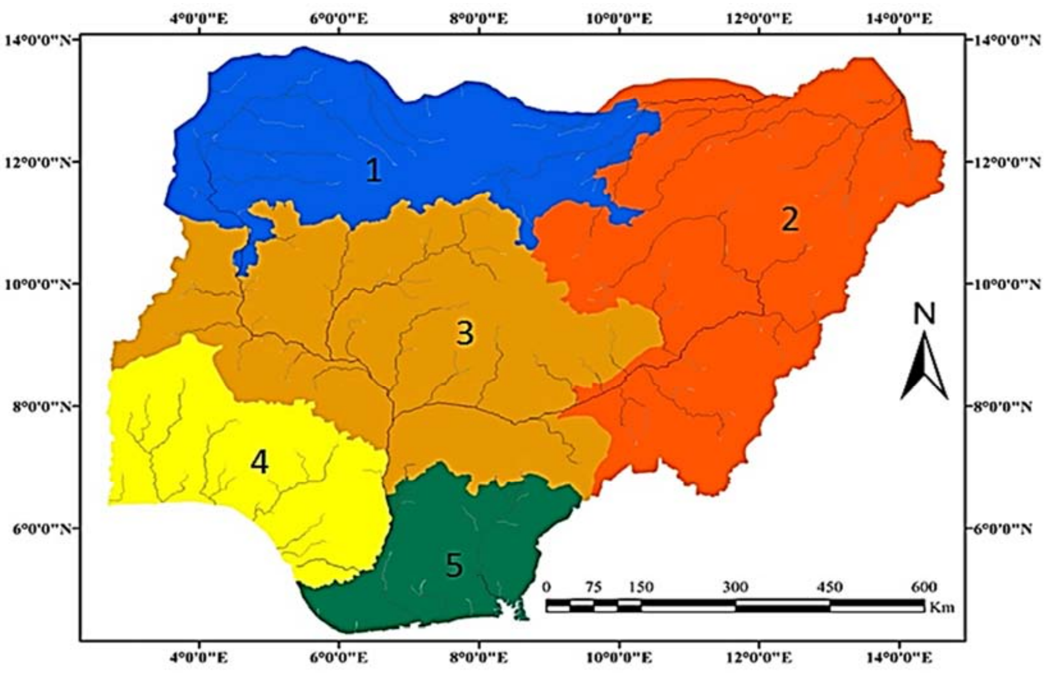

Figure 1. Map of Nigeria Showing Five Different River Basins in Nigeria (adapted from NIFFR, 2002).

3. Data and Method

GRACE level 3 (equivalent water height) 1^0 x 1^0 data (Figure 3) of the TWS estimate from April 2002 to March 2016 were used. The data contains monthly TWS anomalies in centimeters (cm), which are computed as variations from the average value of the period from 2004 to 2009. The data is derived from spherical harmonic data with order and degree up to 60. Spherical harmonics are two-dimensional basis functions represented by Legendre polynomials and cosine and sine functions of order times the longitude [23]. These are smoothened by half-width equivalent to 300 km of

Gaussian smoothing radius. The data for this study was obtained in text format and then interpolated using the moving average function to generate raster data showing the spatial distribution of TWS levels for each month.

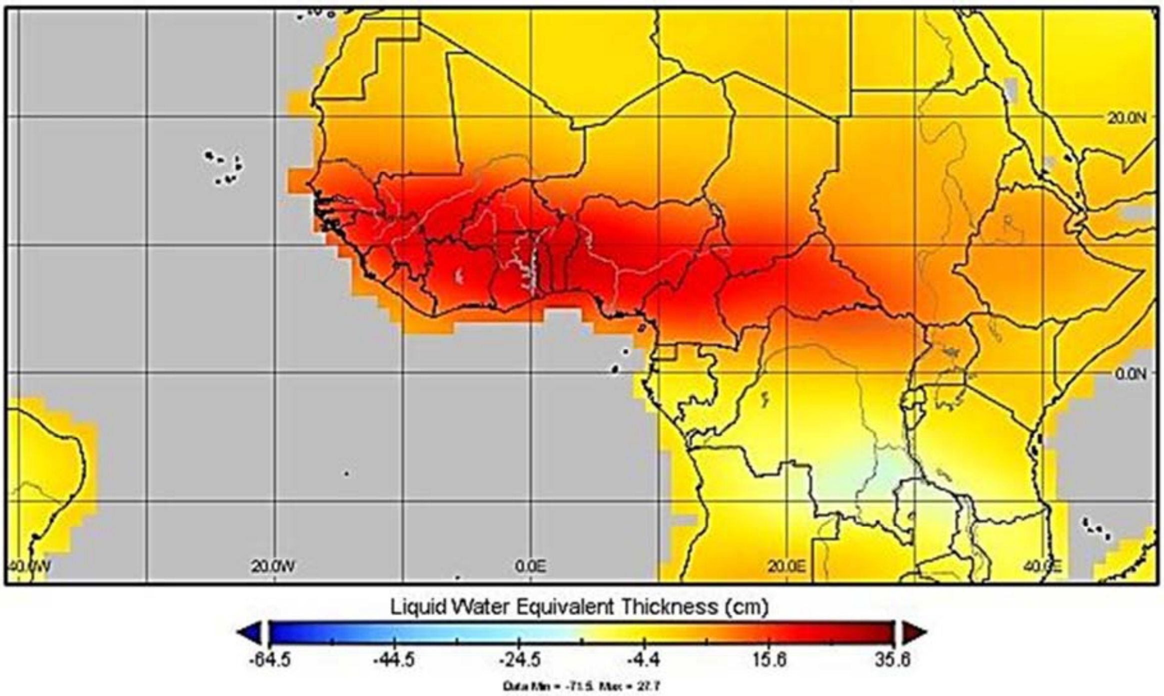

Figure 2. Interpolated Map of GRACE gravity Data over Sub-Sahara Africa.

Global Land Data Assimilation System (GLDAS) makes available optimal estimates of land surface fluxes and storages of water and energy using satellite and ground-based data. The GLDAS 0.25^0 x 0.25^0, monthly NOAH land surface model from 2006 to 2012 was acquired in the netCDF format from the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC). The GLDAS data contains Soil Moisture Content (SMC) and Canopy Water Storage (CWS) variables over the study area. As a land surface part of the hydrological cycle, soil moisture is the most critical factor that links the atmospheric and climate processes to the terrestrial water processes. The data were interpolated using the moving average function to obtain raster data for each month and each variable. The units of the SMC and CWS data were converted from millimeter to centimeter. All the GLDAS variables were resampled from $0.25^\circ \times 0.25^\circ$ to the resolution of GRACE data ($1^\circ \times 1^\circ$). The time series mean value averaged over the study period will be computed and anomalies of the GLDAS-derived maps will be generated.

The groundwater water anomaly/change (GWC) was computed using the equation below.

$$GWC(t) = TWSC(t) - (SMC(t) + CWS(t))$$

Where TWSC is the TWS anomalies derived from GRACE gravity data and GLDAS flux data respectively, SMC is the soil moisture anomalies taken from the GLDAS output field, CWS is the canopy water storage and t is time.

Rainfall data were collected from the World Bank Climate Change Portal and were plotted.

4. Discussion

4.1. Seasonal GRACE Gravity Trend

Figure 3 is the graph showing seasonal rainfall pattern, GRACE derived seasonal TWS anomalies and the GRACE derived seasonal GWS anomalies. The graph of the rainfall pattern (Figure 3a) shows a slowly rising curve between January and April; then a sharp rise from May to July and flattening to September before a rapid fall towards December. This indicates the seasonal pattern over Nigeria with the dry season commencing from November through to April and the rainy season from May to October. The graph of the GRACE derived seasonal TWS anomalies (Figure 3b) shows a common trend for the five river basins in Nigeria. It reveals a falling curve and negative TWS value anomalies from January to April corresponding to the dry season in Nigeria. Going further it shows a rising curve from negative to positive TWS anomalies value beginning from May to September, a period covering the rainy season. From October to December the curve begins to fall with positive TWS values indicating the commencement of dry season with a decreasing amount of rainfall. This pattern is also replicated by the GWS anomalies (Figure 3c). TWS and GWS anomalies patterns show the sensitivity of the GRACE satellite to land water content. The GWS anomalies pattern also indicates that precipitation is a major factor in the groundwater recharge across the country.

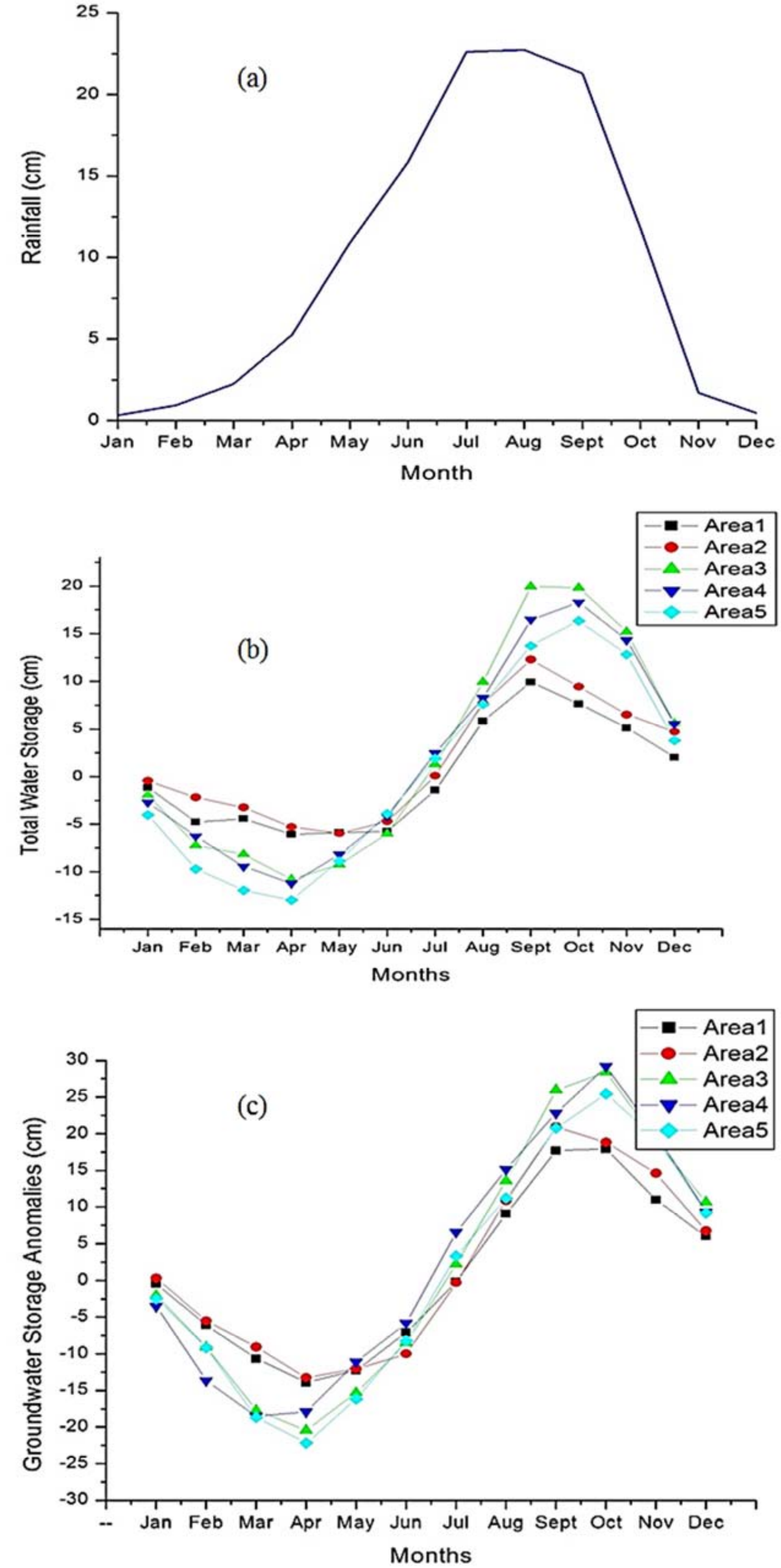

Figure 3. Graph of Seasonal Trend of Rainfall, TWS anomalies, and GWS anomaly.

4.2. Annual TWS Anomalies Trend

Generally, the trends of TWS anomalies across the five basins from 2002 to 2016 (Figure 4) showed a positive trend of rising TWS except for the Osun, Ogun, and Owena river basin (Area 4). Considering the annual variation of the TWS anomalies (Figure 3) from one basin to another, it can be observed that in the Hadeja Jama'are and Sokoto Rima river basin (Area 1) the TWS was increasing at an average rate of 0.9cm per year while at Upper/ Lower Benue and Chad basin (Area 2) the rise was at 0.44cm per year. Similar trends were also observed at the Upper and Lower Niger basin (Area 3) and the Anambra, Imo, Niger-Delta, and Cross river basin (Area 5) as the TWS increased by 1.28 cm/year and 0.59 cm/year respectively. In contrast, it is observed that the Osun, Ogun, and Owena river basin (Area 4) indicated a decline in TWS at a rate of 0.19 cm/year. In the analysis of the temporal trend of TWS anomalies across Nigeria (Figure 4), the TWS is observed to have increased at a rate of 0.69 cm per year. This result does not however correlate with the annual rainfall data over the study period. The annual average rainfall trend over the same period is a negative slope [26]. Another factor that could cause a rising trend in TWS is the decreasing rate of evapotranspiration due to a decrease in surface temperature. However, the surface temperature trend covering the same period indicates a slow temperature rise [26], i.e. more evapotranspiration. Consequently, increases in TWS must have been due to changes in the storage mechanisms in the basins and not necessarily climatic conditions over this period.

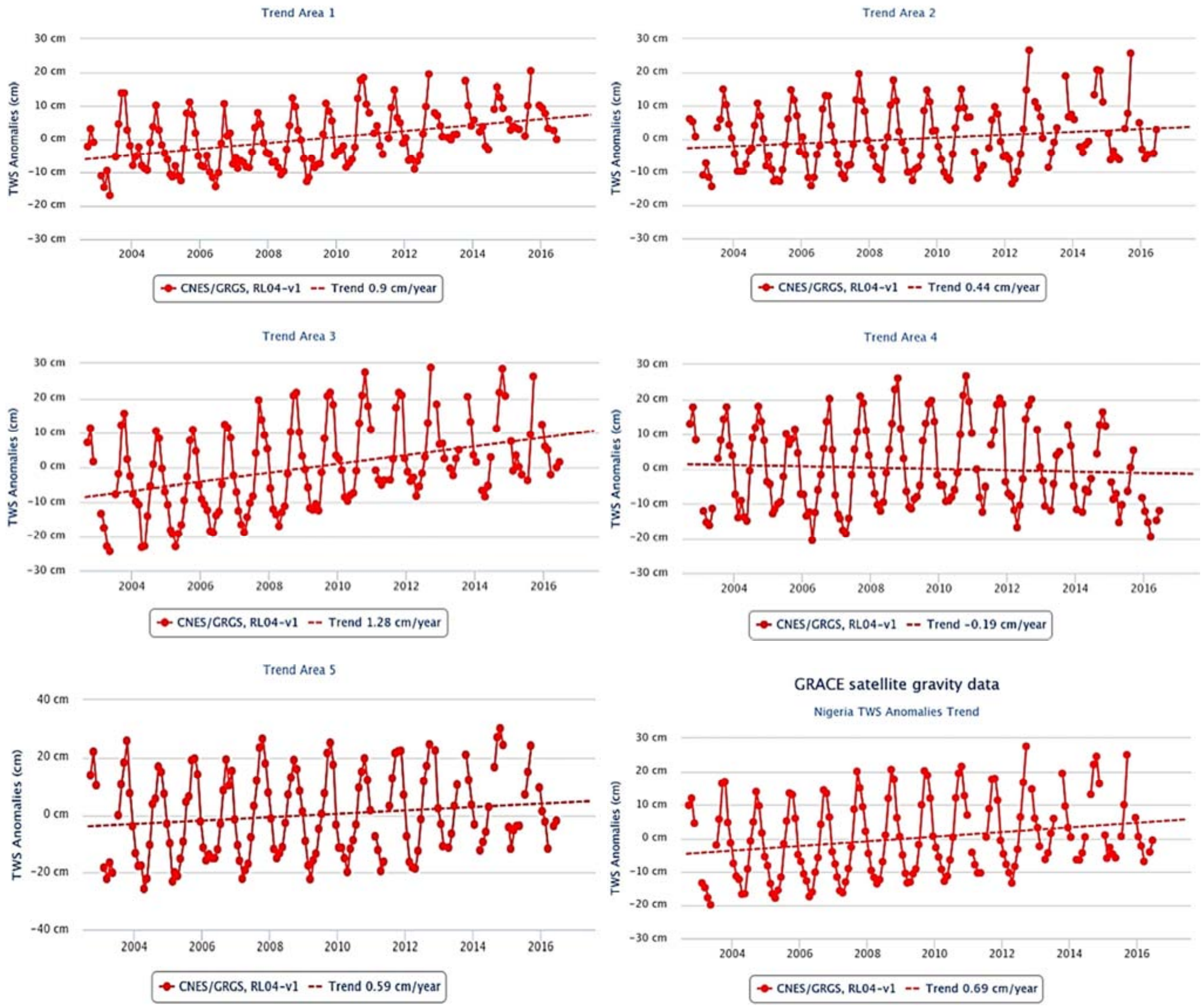

Figure 4. Annual TWS Anomalies Trend across River Basins in Nigeria.

4.3. Annual Average GWS Anomalies Trend

Figure 5 shows the GWS anomalies trend derived from the removal of soil moisture and canopy values from the TWS. It is observed that Area 1 and Area 5 experienced a decline in GWS anomalies while Area 2, Area 3, and Area 4 had increasing GWS trend. The Hadeja Jama'are and Sokoto

Rima river basin (Area 1) showed a declining GWS at a rate of 0.5449 cm/year while the Upper/ Lower Benue and Chad basin (Area 2) had a positive trend of 0.76866 cm/year. Positive trends were observed over the Upper and Lower Niger basin (Area 3) and the Osun, Ogun, and Owena river basin (Area 4) at the rate of 0.62296 cm/year and 0.40139 cm/year respectively. The Anambra, Imo, Niger-Delta, and Cross river basin (Area 5) showed a decline in GWS at a rate of 0.57828. The result for Area 5 might have been as a result of the high soil moisture value of the riverine areas.

5. Conclusion

Terrestrial water storage (TWS) is rising significantly in the river basins of Nigeria. The growing water storage in these basins cannot be attributed to precipitation or evaporation, as there was no marked increase in rainfall quantity or decrease in the surface temperature during the same period. This makes climate change an unlikely cause for increasing water storage on the large scale. The increase in TWS in most of the basins is likely due to changes in groundwater recharge quantities. It is clear from this work that groundwater storage possesses a high resilience to climate change in three of the five river basins of Nigeria and should be vital in adaptation strategies. Increasing access to improved groundwater sources is likely to be highly successful in mitigating the adverse effects of climate change.

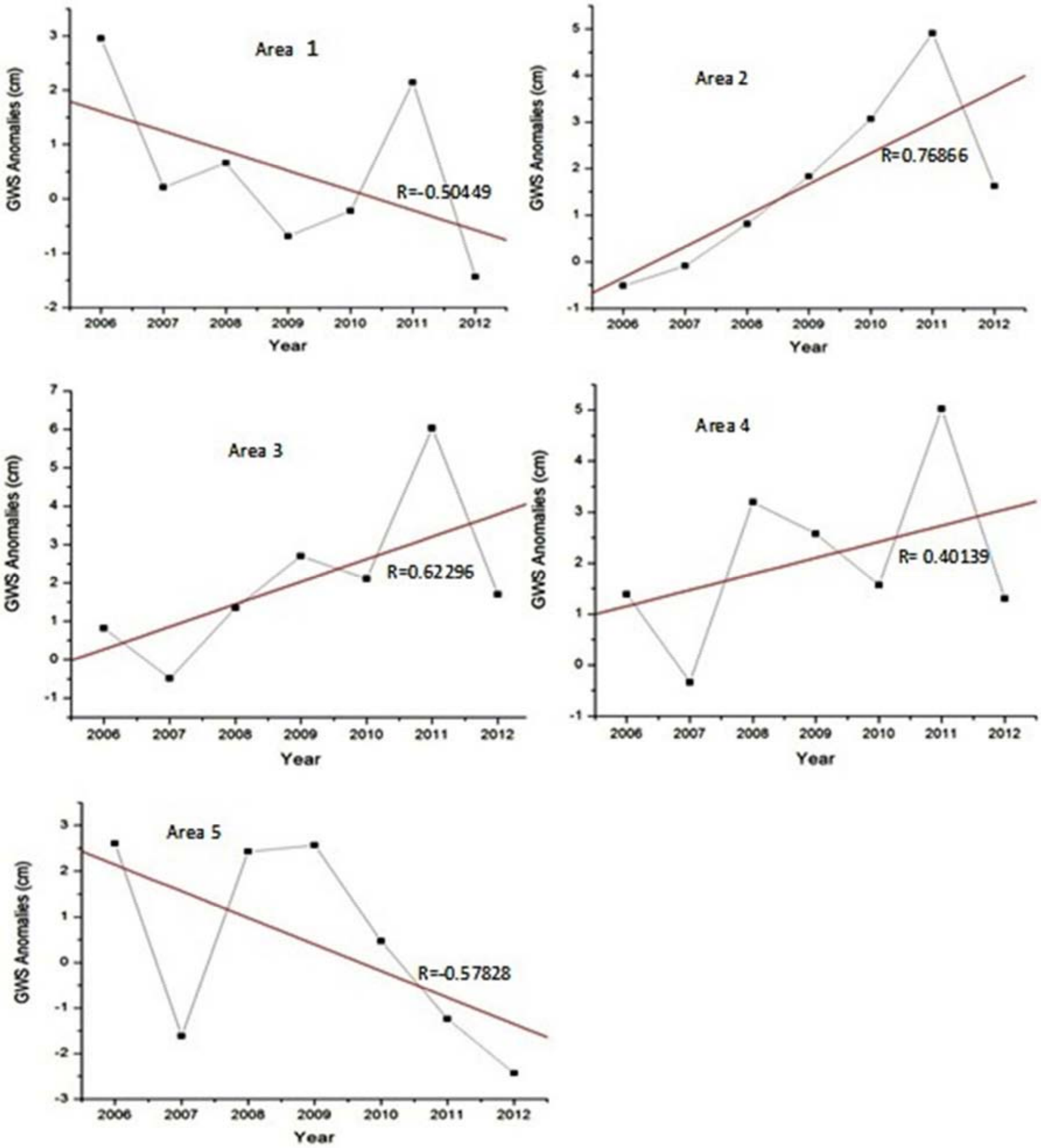

Figure 5. Annual Average GWS Anomalies Trend across River Basins in Nigeria.

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