DIAGNOSING THE TERRESTRIAL WATER STORAGE VARIATION OVER THE NIGERIAN SPACE: THE GRACE PERSPECTIVE

Ikenna D. Arungwa[1], Francis I. Okeke[2], Elochukwu C. Moka[2], Ikechukwu Kalu[3], Chukwuma J. Okolie[4]

[1] Federal University of Technology, Owerri, Imo State, Nigeria, (arungwaikenna@gmail.com)
[2] University of Nigeria, Enugu Campus, (francis.okeke,elochukwu.moka)@unn.edu.ng
[3] University of Uyo, Nigeria, (kaluikechukwu360@gmail.com)
[4] University of Lagos, Nigeria, (cokolie@unilag.edu.ng)

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ABSTRACT:

Besides its paramount role to life and human survival on the earth, water also plays a crucial role in understanding certain earth processes. Water can be quite hazardous, whether in a surplus state or in a deficit state. The former presents as flood, while the latter presents as drought. Nigeria, unfortunately, over the years has been shown not to be immune to both extreme states of water. It is, therefore, crucial to continually monitor the state of water in order to mitigate whatever danger both states may present to the nation. One key index for measuring the quantity of water on land is the Terrestrial Water Storage (TWS), which incidentally is obtainable from gravity data of the Gravity Recovery and Climate Experiment (GRACE) satellite mission. This study leverages on the availability of GRACE mascon data to give insight into the dynamics of TWS within Nigeria. The study observed an increasing trend of TWS in all hydrological areas and basins within Nigeria. Trends of up 10mm/year were observed in the Sokoto-Rima basin. The flash and fluvial flooding events of 2012 and 2015, were captured by GRACE satellites. In terms of its seasonal fluctuations, TWS values are relatively minimal in the first 6 months of the year and maximal in the remaining 6 months. Its peak value is usually observed around October of each year. A clear inter-annual pattern is also observed in peak values of TWS within the period of study (2002-2017).

1. INTRODUCTION

Issues related to water predates human existence, and will certainly remain with human race. Hence, issues related to water – be it deficit or surplus- will remain an evergreen and continuous discourse. Little wonder, issues related to water resource management are always trending, particularly when one considers the fact that natural storages are consistently under pressure of excessive exploitation - due to its relatively finite nature, population growth, economic development, rapid industrialization, ever increasing use of water for agricultural purposes etc. The result of these anthropogenic activities and the combined effects of climate change and variation, causes either scarcity or life threatening, unmanageable surplus (that presents as flooding), and variation of freshwater resources in both space and time domain. The frequency of hydrological extremes (floods and droughts) which have direct correlation with freshwater availability, and which is also a direct reflection of our varying climate, is on the rise (Abelen, et al 2015, Long, 2014, Thomas, et al 2014, Yi, 2016, Yirdaw, 2008, Xuhui et al 2018). Beside all these, the knowledge of Terrestrial Water Storage (TWS), or some of its components (Surface Water -SWS, Soil Moisture Storage -SMS or Ground Water Storage -GWS) is critical for prevention and control of geological/geophysical hazards & disasters (subsidence), for design of engineering works (dams, dykes, tunnels, slopes etc.) and geothermal exploitation (Xiang et al, 2016, Soni & Syed, 2015).

Therefore, a fairly accurate, comprehensive and continuous knowledge of the TWS across a region is essential to properly understand the water cycle dynamics, to predict & manage hydrological extremes and its related impact, to assess the availability. It is also critical in improving on the overall freshwater resources situation in any region, and ultimately make informed, sustainable and effective decision regarding water resources and its management (Forootan et al, 2014; Soyoum & Milewski, 2016). While it is clear that the Nigerian clime is not immune to drought-particularly in the northern region of the country, flooding is also another hydrological hazard that threatens life and livelihood in Nigeria. The 2012 and 2015 major flooding events, that affected many States, are example of the devastation flooding could cause Preparation in electronic form in Nigeria (Federal Government of Nigeria, 2013; Premium Times September 20, 2015).

In the works of Dacho et al (2021), the spatiotemporal distribution and trend of TWS and Groundwater Storage (GWS) were studied in Nigeria using Gravity Recovery and Climate Experiment (GRACE) data for a 6-year period between 2006 – 2012. The seasonal pattern of TWS was observed to correspond to rainfall pattern of Nigeria. An overall increase in the trend of TWS was also observed for the study period. The study made use of Spherical Harmonics (SH) data which has been shown to be less optimal to mascon GRACE solutions (Awange et al, 2011). Besides, the study did not explain how errors in GRACE SH was handled. While findings of the study are useful for the period of the study, it did not offer insight into the nature of the TWS before 2006 and after 2012.

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In Shiru et al (2021), a projection of water availability and sustainability in Nigeria was conducted. TWS of the region was simulated using GRACE TWS of 2002 – 2016. Thereafter, a projection of water availability based on simulated TWS was conducted. The experiment revealed that water storage decreases during wet seasons and increases during dry seasons. It projected a decrease in water availability in the range of 0 – 12mm from 2010 – 2099. In its projection, annual changes in water storage are expected to increase in the southern part of the country, particularly in the south eastern part. One drawback of this study is the use of a model that is based of SH solution which obviously has its own inherent setbacks.

Consequent upon the foregoing, this study is aimed at leveraging on the availability of a more optimal GRACE mascon data to give insight into the dynamics of TWS.

2. DATA AND METHOD

2.1 Area of Study

Located within Longitude 2˚15'E & 14˚45'E, Latitude 4˚10'N and 13˚50'N, with a land area of approximately 924,000 km^2; a population of over 200 million; Humid South & Dry North ecological zones; Mean Annual Rainfall: above 3000mm (in SE at the coast) & less than 250mm (at the extreme NE part of the country) and an average annual Temperatures: 230C –320C, Nigeria has been identified to have 8 major regional aquifer systems (Maduabuchi, 2014). It is also identified as having 8 hydrological areas (Figure 1 and Table 1), and extensively drained by River Niger and its tributaries, with a spatial variation of groundwater resource. The eight (8) different hydrological areas (River basins) in Nigeria are covered by the study. Figure 1 shows the river basins of Nigeria, namely, the Niger North, Niger Central, Upper Benue, Lower Benue, Niger South, Western Litoral, Eastern Litoral, and Lake Chad.

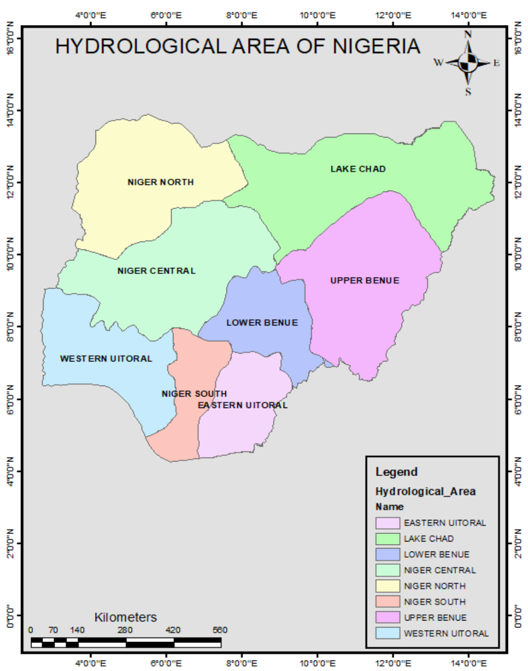

Figure 1. Hydrological Divisions of Nigeria (modified after Iguniwari and George, 2018)

S/NO	River Basin	Hydrological Area
1	Sokoto-Rima River Basin	Niger North
2	Kaduna River Basin	Niger Central
3	Gongola River Basin	Upper Benue
4	Benue River Basin	Lower Benue
5	Anambra River Basin	Niger South
6	Osun River Basin	Western Litoral
7	Cross River Basin	Eastern Litoral
8	Hadejia River Basin	Lake Chad

Table 1. River basins and hydrological areas of Nigeria

2.2 Gravity Recovery and Climate Experiment (GRACE) Data

The GRACE satellite mission was launched in March 2002. Since then, it has continued to observe the gravity field of the earth. Its data have granted scientists the lee way into understanding certain earth processes that are correlated with the gravity field of the earth. In the field of hydrology and hydrogeodesy for instance, there have been a plethora of studies aimed at understanding, modelling and predicting the dynamics of water resources of the earth (Abelen et al 2015, Awange et al 2016, Agboma et al 2009, Long et al 2014, Thomas et al 2014, Yirdaw et al 2008, Yi et al, 2016, Xuhui et al, 2018, Ndehedehe, et al, 2015). The initial dataset from the mission were in the form of solutions of Spherical Harmonics (SH), which if converted to Equivalent Water Height (E.W.H) (using equations 1 - 3), gives an estimate of available water in the respective natural water storages

The SH had some challenges that limited it usage. Some of the issues that affected the optimal use of GRACE SH solutions ranged from high frequency noise, limited spatial resolution, leakage of signal, to signal attenuation as a result filtering and smoothening. In view of the above, the GRACE Mass Concentration (mascon) was introduced as an optimal alternative to SHs, hence increasing the effectiveness of GRACE data (Awange et al, 2011). Mass Concentrations blocks (mascons) is simply an alternative form of representing the gravity field basis functions. Mascons offers the advantage of implementing geophysical constraints in a relatively easier manner, when compared to its SH equivalent. These constraints are key to removal of noise from GRACE observations at 2nd level stage of processing.

2.3 Processing of Gravity Recovery and Climate Experiment (GRACE) Data

The appropriate processes have been applied to mascon solutions before using them for the study. They include, but not limited to, replacement of degree 2 order 0 (C20), with its equivalents from Satellite Laser Ranging; estimation of Geocenter Coefficients using standard methods; applications of Glacial Isostatic Adjustment (GIA) corrections. Details of corrections are exhaustively described by the following Swenson et al (2008), Sun et al (2016), Cheng et al (2011) http://www2.csr.utexas.edu/grace/RL06_details.html and https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/

For this study, the TWS was derived from GRACE-mascon data. The data is obtainable from the Centre for Space Research, University of Texas, Austin (http://www2.csr.utexas.edu/grace/RL06_mascons.html).

Total Water Storage variation can be defined mathematically defined in the spectral domain as:

$$\Delta T^{TWS}(\theta,\lambda) = \sum_{l=0}^{\infty}\sum_{m=0}^{l}\left\{\Delta C_{lm}^{TWS}\cos m\lambda + \Delta S_{lm}^{TWS}\sin m\lambda\right\} \times \tilde{P}_{lm}(\cos\theta) \quad (1)$$

$$= \sum_{l=0}^{60}\sum_{m=0}^{l}\left\{\Delta C_{lm}^{TWS}\cos m\lambda + \Delta S_{lm}^{TWS}\sin m\lambda\right\} \times \tilde{P}_{lm}(\cos\theta) \quad (2)$$

The method proposed by Wahr et al (1998) can be used to convert the TWS variation expressed in Spherical Harmonics to TWS variation in equivalent water thickness/Height (EWT/EWH).

$$\Delta T^{TWS}(\theta,\lambda) = \Delta h^{TWS}(\theta,\lambda) = \frac{\gamma\rho_{ave}}{3\rho_{water}}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}\left\{\Delta C_{lm}^{TWS}\cos m\lambda + \Delta S_{lm}^{TWS}\sin m\lambda\right\} \times \tilde{P}_{lm}(\cos\theta) \quad (3)$$

Where the maximum degree (l) and order (m) is 60. θ, λ are respectively the co-latitude and longitude of the point of interest. $\tilde{P}_{lm}$ is the fully normalized associated Legendre functions. ΔC_{lm}^{TWS} and ΔS_{lm}^{TWS} are changes in the Stoke's Spherical Harmonics coefficients from the GRACE solution for the period under review. γ is the radius of the earth (6378136.300m), ρ_{ave} is the average density of the earth (5517kg/m^3) ρ_{water} is the density of water (assumed ρ_{water} to be 1000kg/m^3); k, is the satellite load love number of degree l.

In this study, we leveraged on specialized MATLAB functions to realize the following:

i. Extract and overlay TWS data over the study area.
ii. Perform temporal interpolations to estimate TWS for the missing months in GRACE solutions.
iii. Compute and plot the temporal and Spatial mean distribution of TWS over study are (Figures 2&3).
iv. Compute and plot the seasonal spatial and temporal distribution of TWS (Figures 4&5).
v. Compute and plot trends in spatial distribution of TWS (Figure 6)

3. RESULTS AND DISCUSIONS

This section briefly describes result and the attendant implication of the result over the Nigerian space within the period of 2002-2017

Figure 2 shows a mean spatial distribution TWS over Nigeria within a period of 2002-2017. TWS over Nigeria generally varies from 10-35mm with maximum value observed around Ogun and the Hadejia river basins. Relatively minimal values are observed around cross river and Anambra basin. Generally, within Nigeria there seem to be a North-South spatial variation of TWS, which tends to correspond with the region's climatic settings and the spatial rainfall patterns within the study period. This pattern is somewhat consistent with the findings of Dasho et al (2021) and Shiru et al (2021).

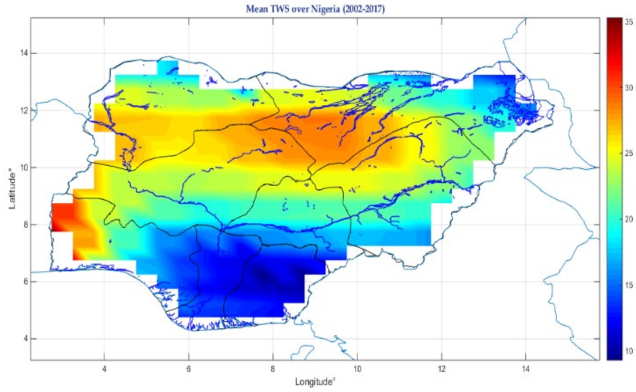

Figure 2. Mean Spatial Distribution of TWS over Nigeria (2002-2017)

Figure 3 shows the temporal distribution of TWS over the study period. TWS is observed to have an increasing trend from the 2012. Maximum amplitude of the TWS is observed in October 2012. This is can be attributed to be the resultant effect of the 2012 rainfall that culminated into a devastating flood which led to loss of lives and properties. The maximum increase in TWS in the month of October was a direct response to the increase in rainfall that started in July of 2012 (Federal Government of Nigeria, 2013). Besides rainfall, other factors may also have been responsible for this variation. Further research is certainly needed to unravel these factors. Apart from the exceptional case of 2012, there also exist a steady rise in the peak values of TWS from 2013 – 2016. Another exceptional peak value is observed around October of 2015. Again, there are reports of flooding events in Nigeria, affecting 11 out of the 36 States in the year 2015 (https://reliefweb.int/disaster/fl-2015-000155-nga), Premium Times September 20, 2015). From the foregoing, it is safe to assert that TWS is connected to flash and fluvial flooding within Nigeria. Groundwater flooding (which is another type of flooding) may also be connected to TWS. However, research into the spatial and temporal behaviour of the groundwater within the study area and period is needed to confirm this conjecture.

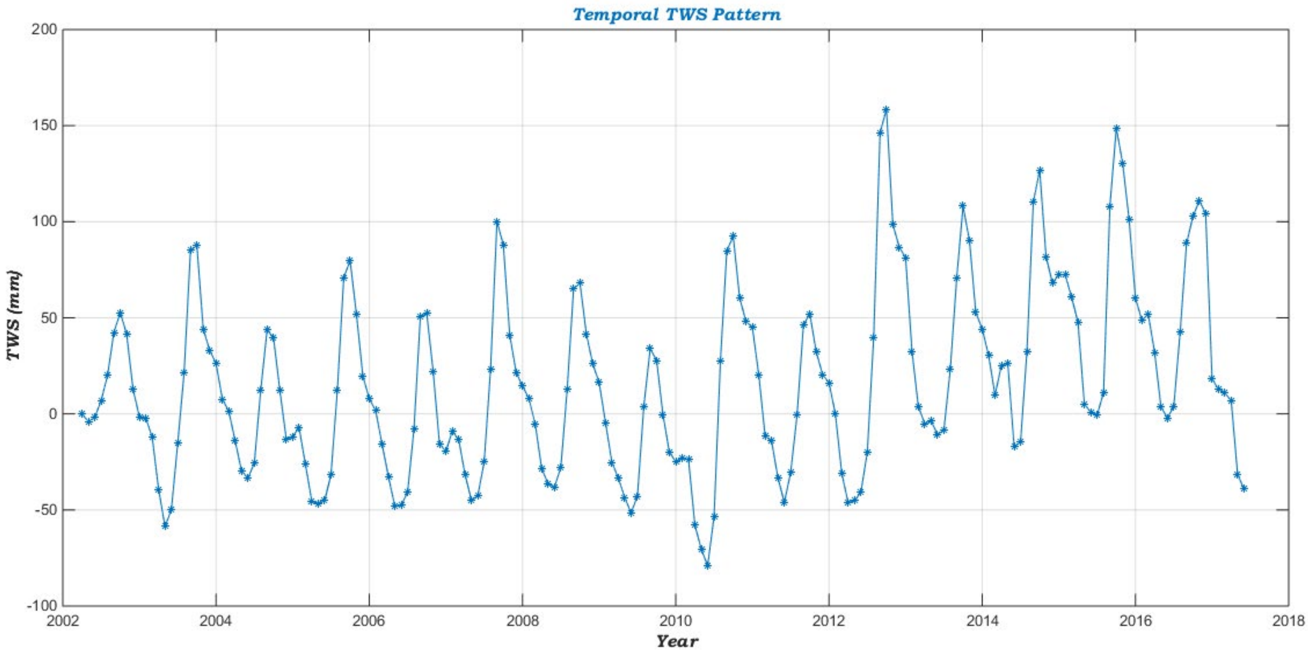

Figure 3. Temporal Pattern of TWS over Nigeria (2002-2017)

Another visible pattern in the time series that calls for extra attention, is the inter-annual pattern inherent in the peak values.

TWS has been identified as an indicator for regional climate. Egbuawa et al (2017) confirm that trends in El Nino Southern Oscillation (ENSO) originating from Indian and Pacific Ocean affect regional climates in Nigeria. They further linked coastal flooding of 2012 and the intensive dust haze of 2015 in southern Nigeria to the 2012 and 2015 strong El Nino events respectively.

Incidentally, the two periods where TWS showed significant peaks coincides with these years of strong El Nino events. With this in mind, it may be necessary to conduct a research to investigate the correlation between significant changes of TWS (in 2012 and 2015) and the El Nino events of these years.

The seasonal spatial variation of TWS is shown in Figure 4. It is closely structured to mimic the seasonal patterns in Nigeria (2 wet and 2 dry seasons).

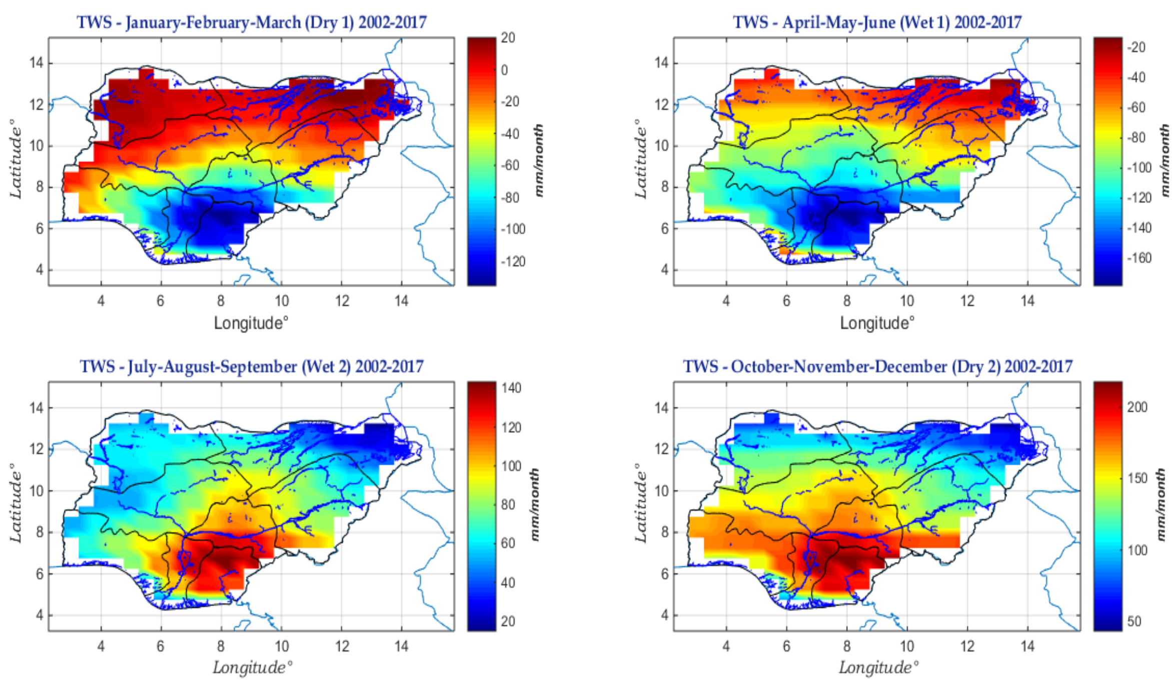

Figure 4. Spatial Seasonal Patterns of TWS over Nigeria (2002-2017)

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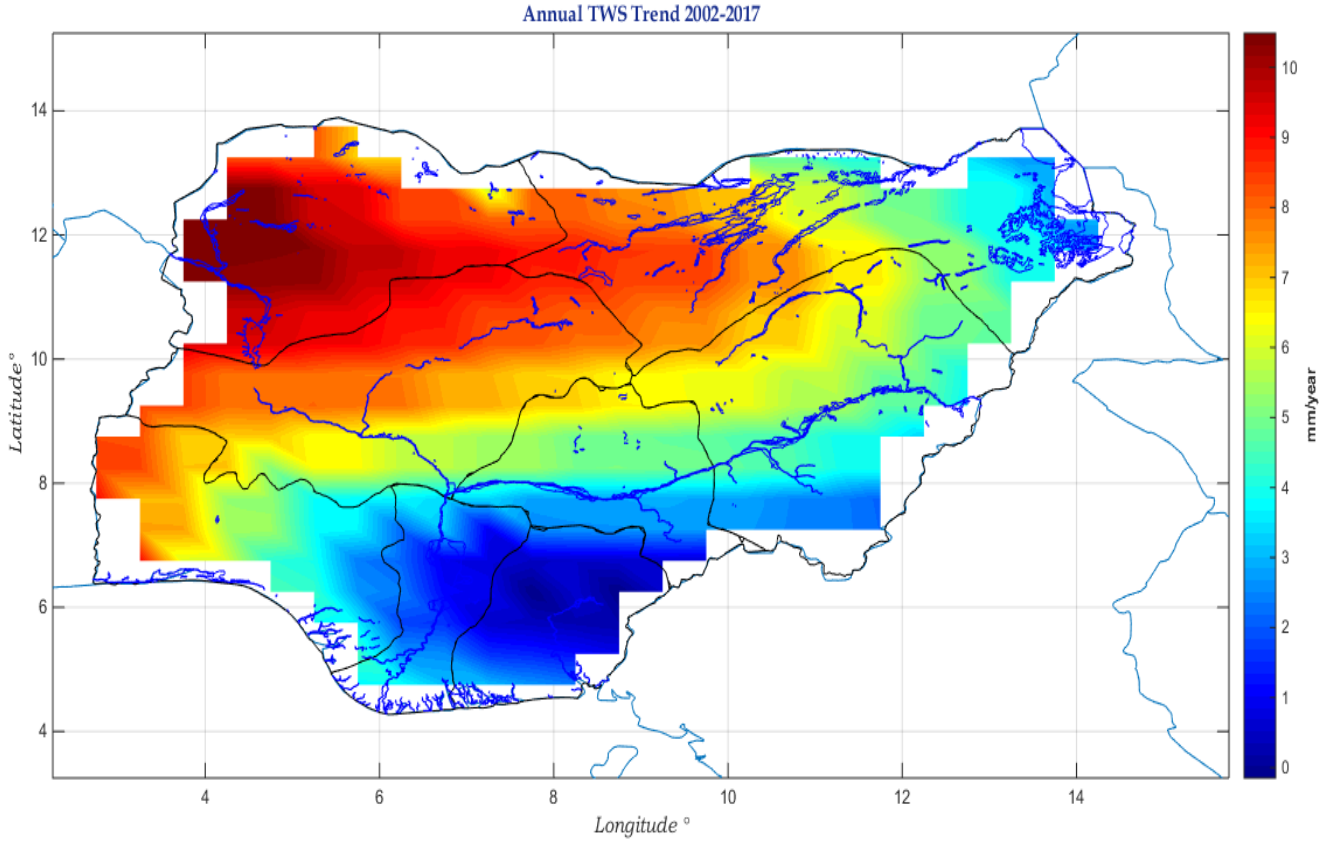

Figure 5. Mean Temporal Seasonal Fluctuations of TWS

The minimal values of TWS are observed within the first dry and wet seasons (i.e., January – March; and April – June). This is seen as deficit around Cross River and Anambra Basins. Maximum values are observed around the 2 wet and dry periods (i.e., July-September and October – December) around same river Basin. One clear distinguishable attribute of TWS within Nigeria is the opposite phase phenomenon it displays between the Southern and Northern part of Nigeria in the first dry period. To some extent, this pattern agrees with the projections of Shiru et al (2021) which was explained previously. This stark temporal pattern may be attributed to the lag in the response time between rainfall and TWS. Again, extra research with rainfall data is needed to fully comprehend this pattern in space and time.

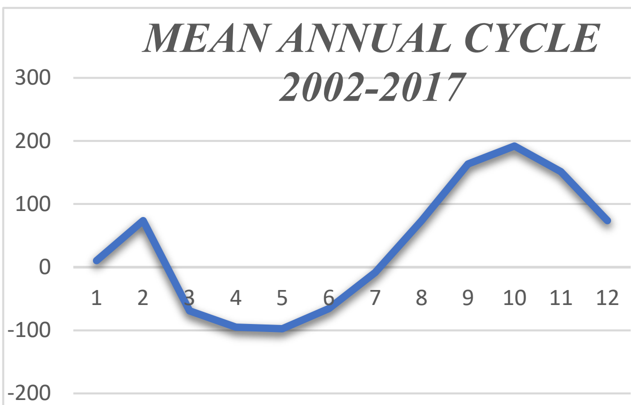

Figure 6. Spatial Trend of TWS (2002-2017)

This pattern agrees with Figure 5 which shows the mean temporal seasonal fluctuations of TWS. Maximum amplitude (peak) is observed in the month of October while a trough is noticed around May. Figure 6 shows the spatial trend of TWS in Nigeria. Generally, there is an existence of increasing trend of TWS within Nigeria with maximum value of about 10mm /year observed around the Sokoto – Rima Basin. Minimal values are observed around Anambra-Imo, Niger- Delta, and Cross River Basins. In terms of spatial trends of TWS, similar patterns are observed in Ogun – Osun, lower Niger, upper Niger, Sokoto_ Rima, and Hadejia- Jama'are River Basins. This general increase in TWS trend is in agreement with the results of Shiru et al (2021), which projects an increase in the spatial changes of water storage in both the Northern and Southern parts of the country.

4. CONCLUSION

This study presents the first analysis of Space-Time variation of TWS storage derived from GRACE-mascon satellite data over major hydrological areas and basins within Nigeria. Generally speaking, there exist a positive (increasing) trend of TWS in almost all basins within Nigeria. In addition, the flash and fluvial flooding events of 2012 and 2015, appear to be related to the increase in TWS within the country. The spatial distribution of TWS appears to be in tandem with the climatic settings of the country. Minimal values of TWS are also observed between the first 6 months of the year (January – June), while the maximum values are observed within the last six months (July – December). The Time series of TWS within the country is characterized by inter annual patterns. The causes and drivers of these spatial and temporal patterns are issues further research will unravel.

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