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Decadal Trends and Periodicity of Terrestrial Water Storage in Nigeria-GRACE Satellite Observations

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Abstract

This study investigates spatiotemporal variations in Terrestrial Water Storage (TWS) over Nigeria during the period 2002-2024 using Gravity Recovery and Climate Experiment (GRACE) satellite data. We employed Google Earth Engine (GEE) and analytical framework including trend analysis, change point detection, anomaly detection, frequency, and rate of change analyses to characterize hydrological dynamics. Results show a statistically significant increasing trend in water storage (Mann-Kendall test: p-value < 0.001, Tau = 0.43), with a higher magnitude after 2018 (from 0.68 cm/year prior to 2018 to 2.87 cm/year post-2018). Change point analysis identified July 2019 as a critical transition date, dividing the time series into two regimes with very distinct characteristics (mean TWS: 2.52 cm vs. 23.13 cm). Frequency analysis revealed multi-scale cyclical behavior, such as annual seasonality (11.1 - 12.3 months), semi-annual, and long-term hydrological variations that may correspond to multi-year climate oscillations. Wavelet analysis demonstrated the non-stationary properties of these cycles, with the annual pattern exhibiting varied intensity over the study interval (strong in 2002-2009, attenuated in 2010-2015, and re-strengthened in 2018-2024) along with the recent development of a 60-month periodicity. Spatial analysis indicated strong regional heterogeneity with stronger positive trends in northern regions than in central and southern regions. The analysis of climate records revealed no corresponding increasing trend, suggesting that water storage changes may be driven by other factors like human activities instead of natural climatic conditions. Such anthropogenic influences may include expanded water infrastructure, improved water management practice, and land use modifications. These findings provide critical information for strategic water management interventions in the creation of water security, as well as the need for adaptive management techniques for both water availability and flood risk in different regions of Nigeria.

Keywords

Spatio-Temporal Variation, Total Water Storage, Grace Satellite, Nigeria

1. Introduction

The most populated African country with over 200 million people, Nigeria particularly faces water resource challenges. Although Nigeria holds vast water resources, it is plagued by water access and quality challenges driven by climatic volatility, high population growth rates, urbanization, and inadequate infrastructure [1]-[3].

Information on spatiotemporal changes in Total Water Storage (TWS) is required for effective water resource management for sustainability, agricultural planning, and hazard management in Nigeria. The classical ground-based observation networks have been generally sparse in space and lacking in temporal continuity, particularly in developing nations [4] [5].

The introduction of the Gravity Recovery and Climate Experiment (GRACE) satellite mission in 2002 and GRACE Follow-On (GRACE-FO) in 2018 revolutionized the ability to measure large-scale water storage changes from space [6] [7]. The missions measure temporal changes in the Earth's gravity field that can be converted to estimates of changes in terrestrial water storage at regional to continental scales [8]. GRACE measures total water stored in all reservoirs in the water cycle ranging from surface water, soil moisture, and groundwater to snow/ice and gives combined insights into water resource dynamics [9] [10].

Earlier studies have made use of GRACE data to study the water storage dynamics of various countries in Africa. [11] examined seasonally varying TWS changes over Africa during 2003-2013 and documented significant regional variations in water storage trends. [12] explored groundwater storage anomalies over Africa using GRACE data integrated with machine learning approaches and documented complex spatiotemporal features induced by anthropogenic and natural forcing. Specifically for Nigeria, [13] contrasted GRACE-based terrestrial water storage and groundwater storage anomalies within its five major river basins and identified water storage trends ranging from 0.19 - 1.28 cm/year throughout 2006-2012. [14] examined spatiotemporal properties of drought and land water storage over Lake Chad Basin, northeastern Nigeria using GRACE data. [15] used GRACE data within a multi-methodology framework that assessed water mass variations over parts of Nigeria.

Despite these contributions, detailed analysis over the entire region remains limited. The majority of analyses have been on some aspects of Nigeria [16] [17], or have addressed Nigeria as part of regional broader-scale studies on Niger River Basin and West Africa hydrology [18]-[20]. This work aims to fill this gap through an extensive assessment of TWS changes over Nigeria during 2002-2024 using GRACE data.

The primary objectives in this research include: 1) to identify and quantify hydrologic dynamics in TWS over Nigeria; 2) to identify and characterize anomalies in the record of TWS.

This work integrates Google Earth Engine analysis and multiple analytical techniques to provide a holistic understanding of water storage dynamics in Nigeria, offering valuable insights for water resource planning, agricultural management, and climate adaptation strategies in the region.

2. Materials and Method of Study

2.1. Data Sources

In this study, we utilized the GRACE Monthly Mass Grids Release 6.3 Version 4—Global Mascons dataset [21] to investigate Total Water Storage (TWS) variations across Nigeria between 2002 and 2024. The dataset is made up of monthly gridded global water storage anomalies with respect to a temporal mean, processed by the Jet Propulsion Laboratory (JPL). The datasets are in netCDF format and represent water storage anomaly equivalents in terms of centimeters of water thickness. The Mascon (mass concentration) solution used is derived from the inversion of monthly changes in the gravitational field using geolocated spherical cap mass concentration functions instead of conventional global spherical harmonic coefficients. The sensing technique, as explained by [22], effectively eliminates correlated errors by introducing realistic geophysical information into the inversion scheme. As a result, these Mascon grids eliminate the need for decorrelation or smoothing usually demanded by conventional spherical harmonic gravity solutions, hence making them especially useful for regional studies. The global-scale Mascon solution includes 4551 relatively independent estimates of mass change on the Earth's surface, which are obtained from an equal-area grid with each mascon having a resolution of 3 degrees. To explore the possible climatic factors that control water storage variability, we analyze precipitation and evapotranspiration data that come with GRACE data.

Several corrections are typically required for GRACE data analysis, majority of which were already implemented in the Release 6.3 Version 4 Mascon solutions. The JPL RL06.3Mv04 solutions are already corrected for Glacial Isostatic Adjustment (GIA) effects using the ICE-6G-D model [23], which accounts for the ongoing response of the solid Earth to the melting of late-Pleistocene ice sheets. The dataset is also corrected for atmospheric and oceanic mass variations using the AOD1B RL06 de-aliasing model [24]. Unlike spherical harmonic solutions, no scaling factors were applied to the Mascon solutions as they are not required for the JPL Mascon products.

Several limitations of the dataset are to be acknowledged when interpreting results. The JPL Mascon solution does not correct for leakage errors across coastlines, which may affect the accuracy of TWS estimates in coastal regions of southern Nigeria. Additionally, the spatial resolution of GRACE data (approximately 3 degrees or ~300 km) means that smaller-scale hydrological features cannot be resolved in this analysis. Finally, the GRACE measurement error increases at lower latitudes, which may affect the signal-to-noise ratio in the Nigerian study area [6]. Despite these limitations, the GRACE Mascon solution represents the most comprehensive dataset available for analyzing large-scale water storage changes in Nigeria over the study period.

2.2. Methodology

The initial processing of data was done using Google Earth Engine (GEE), a cloud-based computing platform that is well suited for performing geospatial computations on large datasets [25]. GRACE datasets were uploaded into GEE, from which spatial subsets were extracted corresponding to Nigeria's boundaries. The mean total water storage (TWS) values were computed using the ee.Reducer.mean() function in Google Earth Engine (GEE). The analysis was conducted over the boundary of Nigeria and time period between 2002 and 2023. Every image within the dataset is a grid-based representation of water storage changes. The spatial analysis was performed by selecting monthly time steps, and using visualization parameters such as color scales and thresholds, and filtering out invalid or extraneous pixels. Final maps provide a wide spatial coverage of TWS distribution.

For each image in the dataset, the reducer summed pixel values over the given area to calculate the mean by adding all relevant pixel values and then dividing by the number of pixels included. This process yielded an ordered list of mean TWS values for the given region. The resulting dataset was then exported for further analysis with Python.

The GRACE measurements were examined with different Python packages in order to define the spatiotemporal dynamics of terrestrial water storage (TWS) in Nigeria. The analysis of trends in TWS over various temporal periods was carried out using the Mann-Kendall statistical test. The trends' statistical significance was determined with a confidence of 95% ($p < 0.05$). Detection of significant changes in the TWS time series was achieved by employing the ruptures library [26]. Temporal relationships within the TWS measurements were examined with autocorrelation and partial autocorrelation functions in the stats models library, allowing us to identify periodic and seasonal patterns in the measurements.

Terrestrial water storage (TWS) extremes were determined by a threshold, in which measurements greater than two standard deviations from the mean were classified as extreme anomalies. Principal periodic patterns in the TWS time series were determined using the Fast Fourier Transform (FFT) in combination with wavelet analysis with PyWavelet, allowing short-term seasonal cycles and long-term oscillatory trends in the dataset to be identified.

Regime Analysis was carried out having identified a clear indication of a change point in 2019, TWS time series was broken down into two independent regimes for independent examination. The mean water storage, rate of trend and its statistical significance, duration in months, variability measured in terms of the standard deviation, and frequency and amplitude of the extreme events in both regimes were calculated. This enabled the hydrological conditions of pre- and post-detected change point periods to be described and compared, therefore understanding changes in dynamic water storage in Nigeria. Identification of changes in TWS patterns by regime analysis was necessary in determining whether changes represented a temporary anomaly or a potential flip to a new hydrological regime, an event of significant implications to climate adaptation and water resources in Nigeria.

To examine the relationship between TWS changes and climate variability, we also analyzed precipitation and evapotranspiration during the same period. The TWS-climate comparison enabled the quantification of how much of the changes in water storage were due to climate processes versus other drivers such as land use change or water management.

3. Results and Discussion

3.1. Result

Descriptive statistics of the data showed a mean of 7.91 cm and standard deviation of 14.40 cm (**Table 1**). Long-term TWS trend analysis in Nigeria revealed significant changes over the study period (2002-2024). This change was further confirmed statistically using Mann-Kendall test and showed a significant growing trend (p-value: 0.0, z-value: 9.82, Tau: 0.43) in water storage across the time series. Trend analysis identified different rates before and after 2018 (**Figure 1**). Pre-2018 years showed a rate of change of 0.68 cm/yr (p-value: 0.001316) and spans 175 months, while post-2018 years showed a faster growth with 2.87 cm/yr (p-value: 0.000311) for 62 months.

Table 1. Basic statistics for TWS data.

Statistical measures	Water storage (cm)
Mean	8.29
Standard deviation	14.3871
Minimum	−17.3800
25%	−3.2270
50%	7.3310
75%	16.9690
Maximum	49.3790

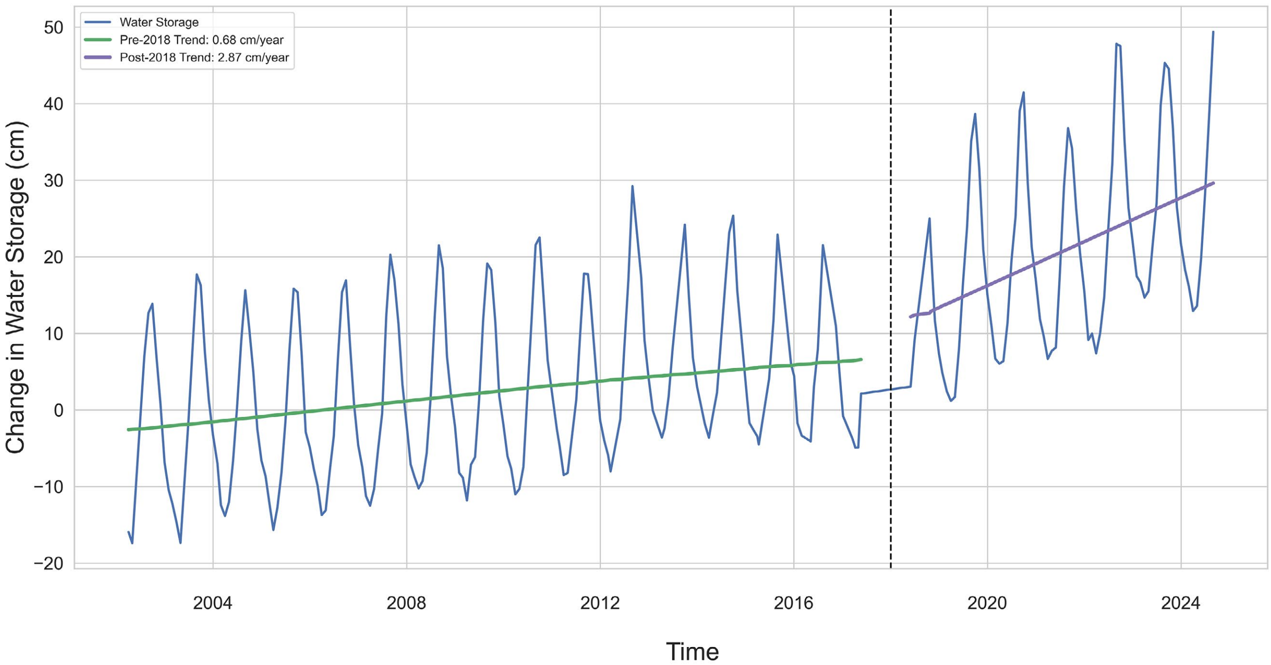
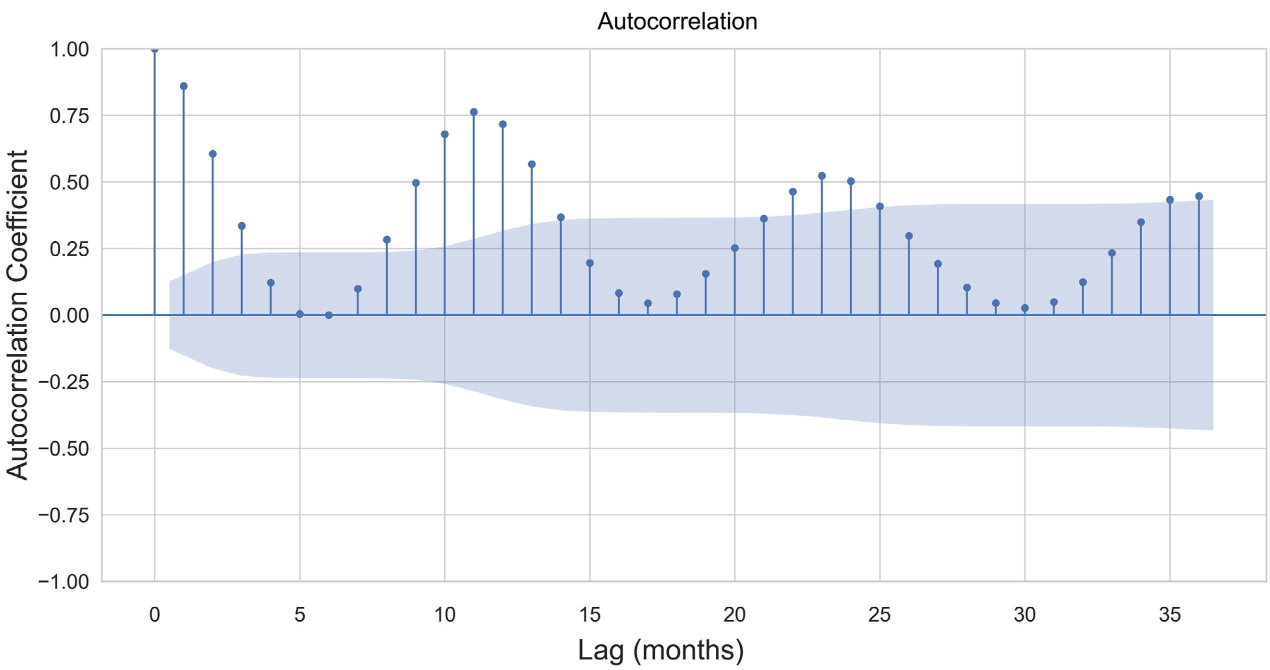
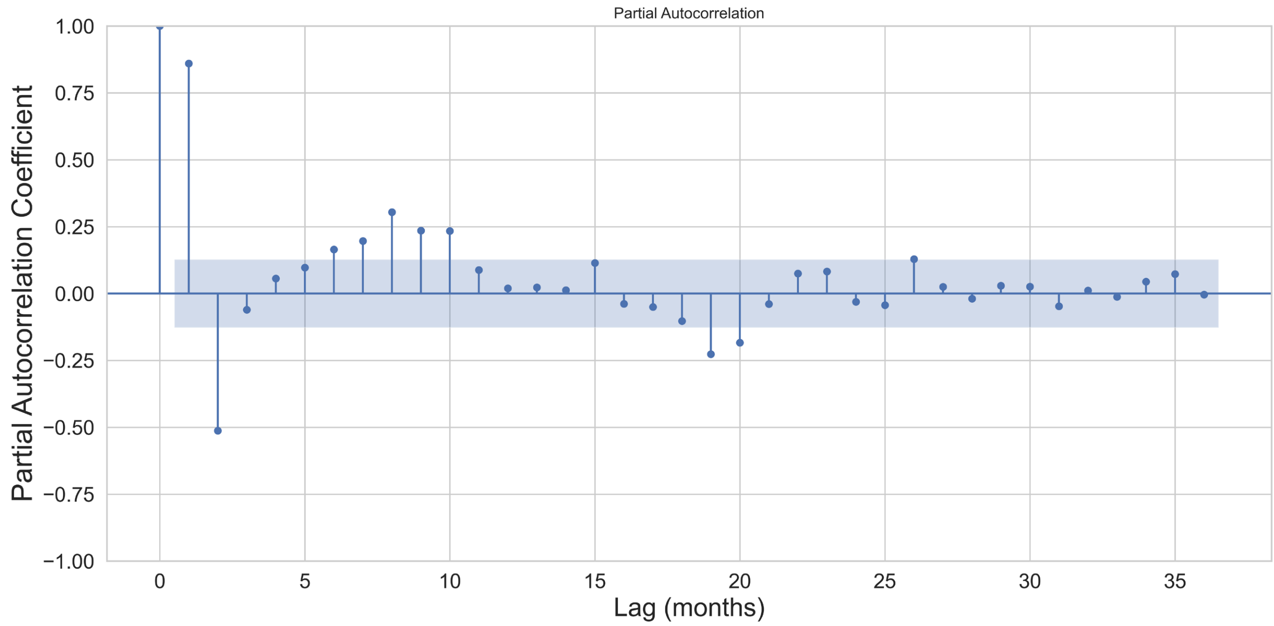


Figure 1. Time series plot of TWS in Nigeria from 2002-2024, showing the overall increasing trend with different rates before and after 2018.

The autocorrelation analysis (**Figure 2(a)**) detected temporal dependency in the TWS data, with different autocorrelation values determined at multiple lag periods. The partial-autocorrelation function (**Figure 2(b)**) indicated that there were correlation values for lag periods of approximately 10 - 12 months after the effects of shorter lags are removed.



(a)



(b)

Figure 2. Correlogram of the time series (a) Autocorrelation function of TWS data, showing temporal dependencies at various lag intervals, (b) Partial-autocorrelation function of TWS data, highlighting the strongest direct correlations at specific lag periods.

Figure 3 shows the decomposition of the time series data into trend, seasonal and residual components. Using the residuals (lower panel) and threshold of 2 standard deviation, extreme anomalies were computed and identified at above 21.28 cm in the TWS data. 5 of the 237 months (2.1%) were found to be extreme anomalies. The anomalously high instances were mostly in the later part of the time series.

The spectral analysis of Total Water Storage (TWS) data shows a number of prominent frequency components which identify the variability of the water cycle. **Figure 4(a)** shows a clear cluster of peaks at 0.08 - 0.09 cycles/month, which corresponds to the 11 - 12-month annual cycle marked by the red dashed line; this is the expected seasonal pattern of wet and dry periods affecting water storage. There is also a secondary but significant peak near 0.17 cycles/month (close to the green dashed line), which points to a semi-annual component most probably depicting transition periods between seasons. Most striking is the extremely high amplitude at low frequencies on the left of the plot (0.01 - 0.03 cycles/month), which signifies longer-term hydrological variations that may correspond to multi-year climate oscillations. Wavelet power spectrum (**Figure 4(b)**) showed the time variability of the periodicities. The 12-month (annual) spectrum showed modulating power during the study period with clear-cut periods of high power (2002-2009), reducing power (2010-2015) and return of intensity (2018-2024). The analysis also showed the emergence of power in the 60-month (5-year) band in recent years (2020-2024). Other factors such as edge effect were not considered and this may slightly or significantly affect the estimates.

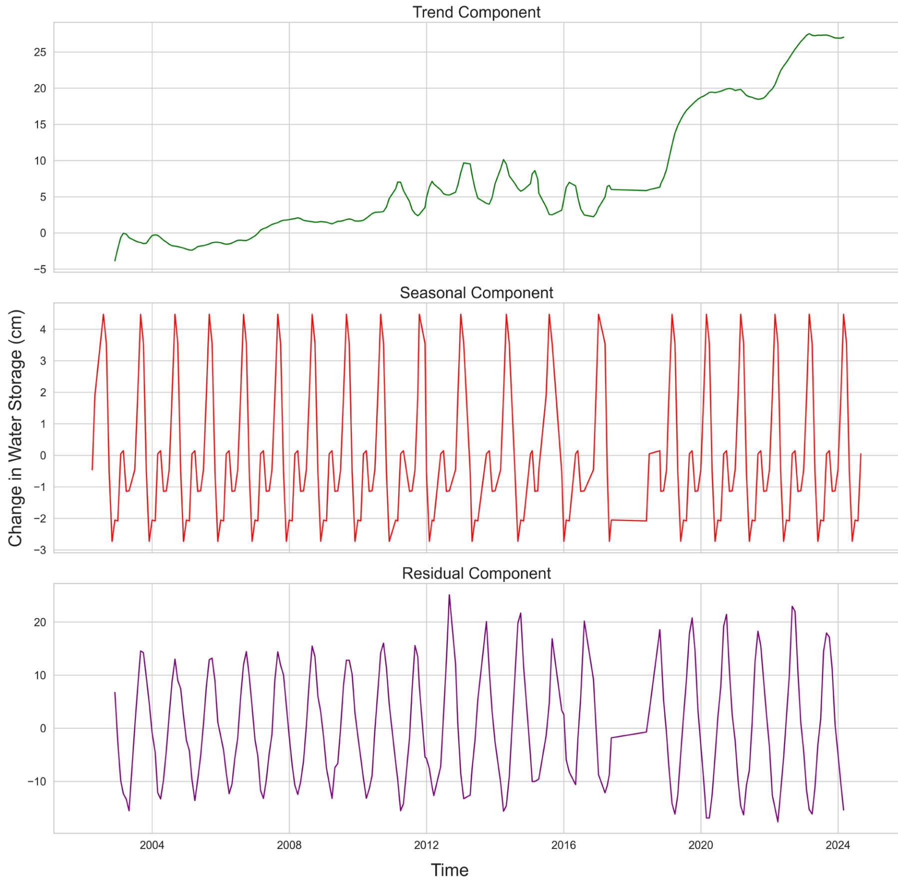
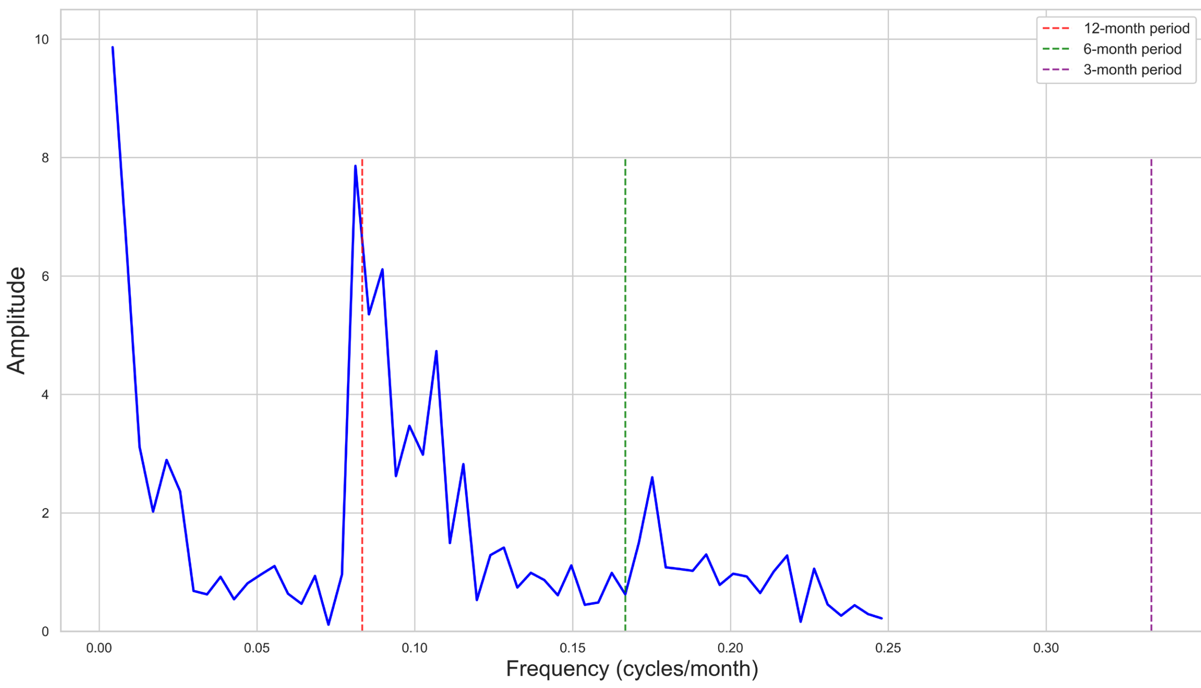
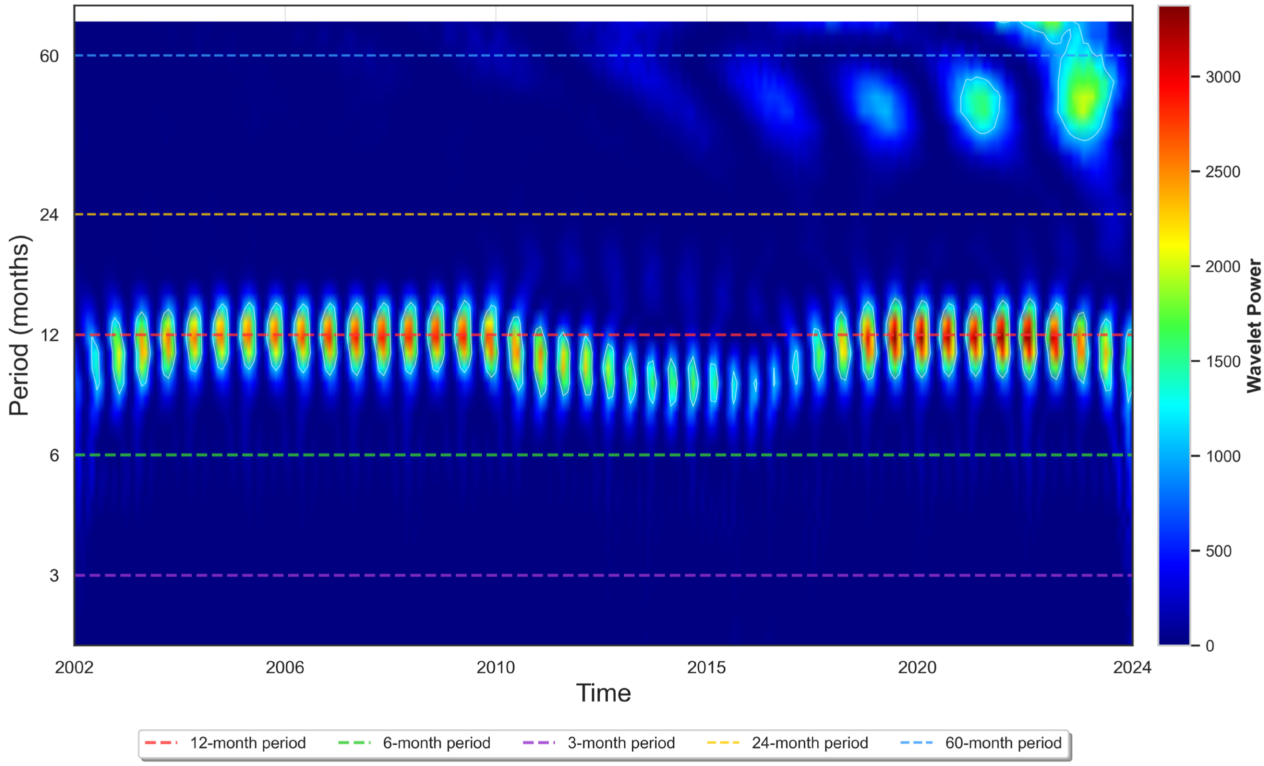


Figure 3. Anomaly detection in TWS data, identifying extreme events exceeding two standard deviations from the mean.



(a)



(b)

Figure 4. Spectral analysis of the time series data of Nigeria from 2002-2024 (a) Frequency analysis showing the dominant cyclical patterns in the TWS data (b) Wavelet power spectrum of terrestrial water storage (TWS).

Rate of change analysis computed showed the monthly rate of change as 0.28 cm/month with the standard deviation of 6.92 cm/month. The yearly rate of change was 1.69 cm/year with the standard deviation of 8.74 cm/year. The spatial analysis of the TWS variability in Nigeria shows considerable regional differences (see Figure 5). More pronounced positive trends were observed in the northern areas compared to the southern and central regions. Precisely, northern areas, particularly in the northeast and northwest, have the most pronounced positive anomalies, with localized areas of terrestrial water storage increase exceeding 2.5 cm/year. On the other hand, most of the central and southern areas were characterized by weak changes, where some of them showed marginal (of 1.0 - 1.5 cm/year in the southern coastal regions or even slightly negative trends. Such spatial variation in terrestrial water storage changes may reflect spatially varying climatic zones of Nigeria, ranging from northern regions where it is generally semi-arid to southern regions of more humid tropical climate of the country. Interestingly, our analysis of climate variables, precipitation and evapotranspiration, revealed no corresponding increasing trend over the same period, despite water storage showing a consistent upward trajectory. Temporal precipitation and evapotranspiration trends throughout Nigeria between 2006 and 2023 depict pronounced climatic patterns and changing hydrological dynamics (Figure 6 and Figure 7). As indicated in Figure 6, precipitation is characterized by a strong north-south gradient, with the humid south receiving much higher rates of precipitation than the arid north. However, interannual variability is apparent, as indicated by the relatively wet years of 2006 and 2018, juxtaposed with the extremely dry year of 2015 over much of the country. In contrast, **Figure 7** depicts a steady and increasing trend in evapotranspiration, most starkly expressed in the north of Nigeria, where water resources are already limited. Whereas the southern parts of the country consistently record high rates of evapotranspiration due to plentiful moisture and widespread vegetative cover, the strong increase in evapotranspiration in the north implies increasing land surface temperatures combined with vegetation stress. This disconnect between climate data and TWS trends suggests that other factors may be driving the observed increases in water storage. Several non-climatic factors may explain this phenomenon: 1) expansion of irrigation infrastructure and water management projects, particularly in northern regions; 2) construction of dams and reservoirs that enhance water storage capacity; 3) implementation of water conservation measures and reduced groundwater extraction rates due to policy changes; 4) land use modifications including agricultural practice changes that improve soil water retention; and 5) potential reforestation efforts in previously degraded areas. The more pronounced TWS increases in northern Nigeria, despite no corresponding precipitation increases, strongly suggest that human interventions in water resources management have played a significant role in the observed water storage trends across the country.

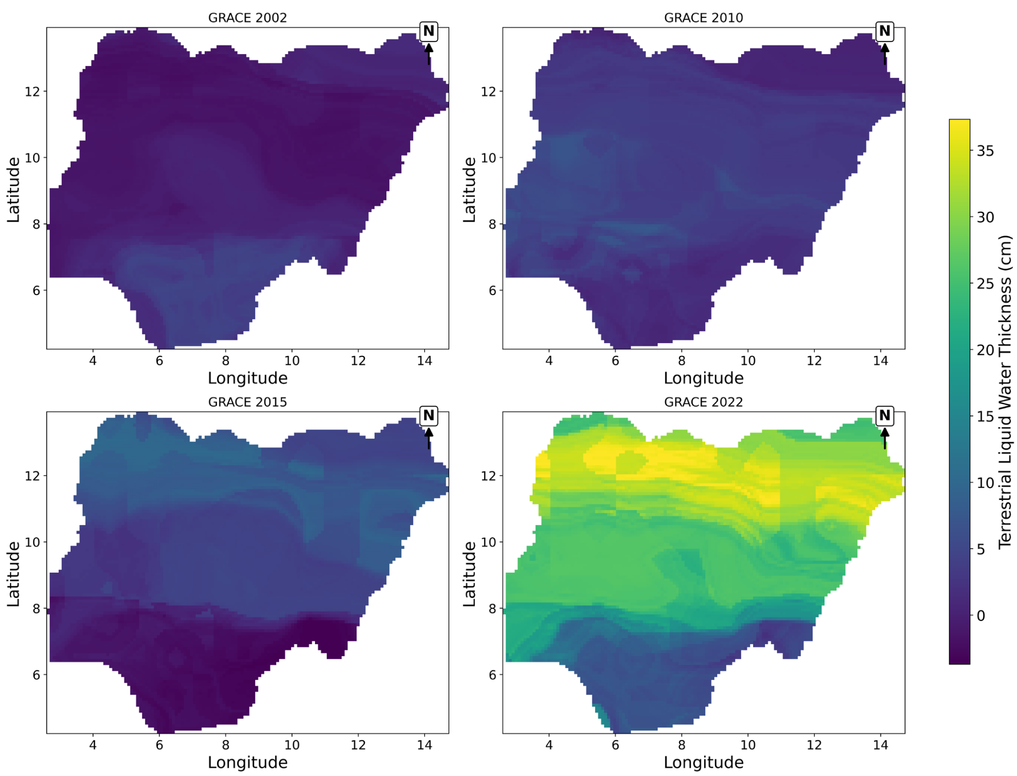


Figure 5. Spatial distribution of TWS changes across Nigeria, showing regional patterns of water storage dynamics.

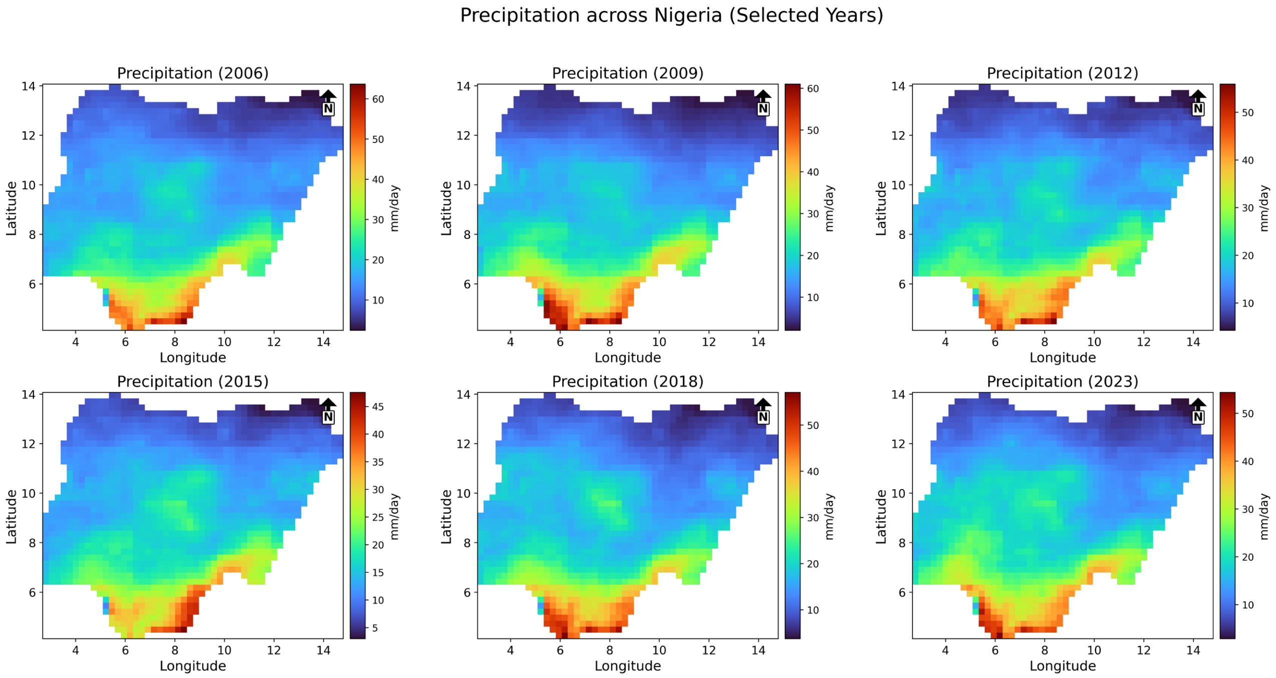


Figure 6. Spatial and temporal variation of precipitation in Nigeria from 2006-2023.

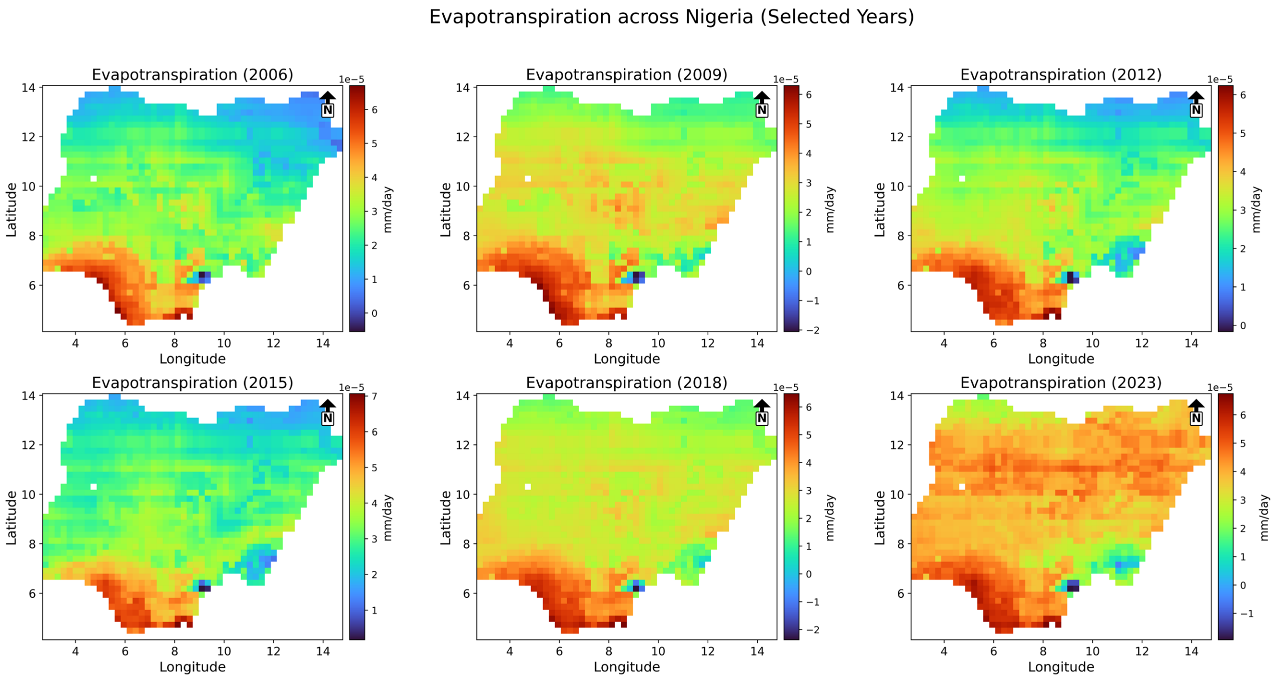


Figure 7. Spatial and temporal variation of evapotranspiration across Nigeria from 2006-2023.

3.2. Discussion

Nigeria has experienced a sudden increase in terrestrial water storage (TWS) since 2018. This sudden change, as detected by the presence of a change point in July 2019, may suggest the arrival of a new hydrologic regime under which the country has experienced significantly improved water holding. By detailed examination through wavelet time-frequency decomposition, we reveal the multifaceted nature of the hydrologic change. The wavelet power spectrum provides useful information on the time evolution of water storage patterns. The annual cycle had definite phases-maximal in 2002-2009, decreasing in 2010-2015, and then again established in 2018-2024. Periodic decreasing and reinforcing of the yearly cycle suggest more complicated underlying processes than changes in trends. The heightened vigor in the yearly cycle during the years post-2018 coincides in time with TWS rate of change and can be attributed to a reflection of improved management practices optimizing the seasonality of storage. The establishment of a 60-month (5-year) periodicity suggests the development of an oscillating process on a longer time scale with the power to significantly influence future water storage dynamics.

The dramatic rise in mean TWS from 2.52 cm to 23.13 cm in the new regime suggests an enormous augmentation in national reserves of water with some implications. Although rises of such magnitude can enhance agricultural productivity and water security in the parched regions, they could also enhance the risk of floods when catastrophic rainfall follows as revealed in the anomaly analysis which testifies to the creation of positive TWS anomalies in the following years with implications of heightened susceptibility to floods.

Increased TWS rises in Northern Nigeria in the absence of comparable rises in climate data like precipitation and evapotranspiration may suggest that human operations in the management of water resources have been primarily responsible for the storage of water in the country as seen in the record. This interpretation requires further investigation through ground-based hydrological and infrastructure datasets.

The overall outcome indicates that management of the water resources in terms of infrastructure in the northern part of Nigeria has been successful in augmenting water storage despite the lack of positive precipitation patterns. This has implications for other regions of the world with scarcity of water as it indicates the possible contribution of focused human intervention in strengthening water security.

4. Conclusions

This work investigated the changes in Total Water Storage in Nigeria from 2002 to 2024 using GRACE satellite data. The water resource management of Nigeria is faced with significant threats from climatic variability, population increase, and land use change and it is hence essential to monitor and understand TWS dynamics for sustainable development. The work integrated analysis framework encompassing trend analysis, change point analysis, correlation analysis, anomaly analysis, frequency analysis, and the rate of change to present multi-faceted information on Nigeria's water storage dynamics.

Our findings reveal a complex hydrological system undergoing significant transformation, particularly since 2019. The increasing trend of water storage (0.68 cm/year until 2018 and 2.87 cm/year post-2018) indicates an underlying shift in

Nigeria's availability of water resources, and the Mann-Kendall test verifies the increasing trend to be statistically significant. The indication of July 2019 as a change point dividing the time series into two regimes further indicates the magnitude of hydrologic change in which mean storage of the water has grown from 2.52 cm in Regime 1 to 23.13 cm in Regime 2.

Surprisingly, we observed a decoupling of strong TWS trends from climate data, which suggests that the observed storage gains are largely caused by forces other than natural climatic tendencies. The recovery of storage is found to be less attributable to favorable climatic conditions and may be more due to human intervention in the management of water resources. The fact that the TWS gain is higher in the north, where the corresponding rise in precipitation and evapotranspiration was minimal, may confirm the success of targeted infrastructure development initiatives, water-saving policies, and land use regulation measures.

The prevalence of multiple cyclical modes at multiple timescales (annual to decadal and multi-decadal) indicates both natural climatic and potentially anthropogenic control of the dynamic system. The strong temporal persistence observed in the autocorrelation results indicates that wet or dry conditions tend to continue over consecutive months, which has important implications for hydrological forecasting capabilities.

Spatial analysis indicates the hydrologic shift is not homogeneous and the northern part of the nation has experienced the most significant gains in water storage (usually >2.5 cm/year), in comparison to less significant rises (1.0 - 1.5 cm/year) from the southern coast.

These findings have significant implications for agricultural policy, the nation disaster management, and water resources planning. The proven record of successful human action for augmenting storage in difficult regions of the north has significant implications for other regions of the world where water is stressed.

Future research should merge GRACE observations with other remote sensing datasets and in-situ measurements in order to support a better overall assessment of Nigeria's hydrologic resources, major drivers and examine the sustainability of current management practices.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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