



Spatiotemporal Analysis of Groundwater Storage Dynamics across the Major Aquifer Systems in Nigeria Using GLDAS Data

Peter Adetokunbo¹, Ayodeji Adekunle Eluyemi^{2*}, Michael Ayuk Ayuk³,
Rasheed Babatunde Adesina⁴, Segun Aguda⁵, Olayiwola Grace Olaseeni⁶, Joel Olayide Amosun⁶

¹Boone Pickens School of Geology, Oklahoma State University, Stillwater, USA

²Centre for Energy Research and Development (CERD), Obafemi Awolowo University (OAU), Ile-Ife, Nigeria

³Department of Applied Geophysics, Federal University of Technology, Akure, Nigeria

⁴Department of Marine Science and Technology, Federal University of Technology, Akure, Nigeria

⁵Department of Project Management, Missouri State University, Springfield, Missouri State, USA

⁶Department of Geophysics, Federal University Oye-Ekiti, Oye-Ekiti, Nigeria

Email: *ay_dot2006@yahoo.com

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Abstract

The spatial variability of groundwater storage in Nigeria was investigated using Global Land Data Assimilation System (GLDAS) data over 21 years (2003 and 2023). The spatial and temporal analyses of the data were conducted in Google Earth Engine (GEE) and Python to assess regional and national aquifer responses to environmental change. The time analysis of the data revealed high groundwater recharge rates from 1.2 mm/year (2003-2013) to 14.5 mm/year (2013-2023). Three hydrogeological regions were identified that closely match the major aquifer systems in Nigeria: the extremely high groundwater storage (2500 - 3400 mm) of the Niger Delta Basin, the intermediate values (2000 - 2500 mm) of the Middle Belt region (Middle Niger Basin/Benue Trough), and low values (300 - 1500 mm) in Northern Nigeria (principally Basement Complex/Chad Basin). One major transition zone occurred in southwest Nigeria where the groundwater storage indicated a well-defined gradient of the transition from unconsolidated coastal aquifers at Lagos/Ogun to basement complex rocks at Ondo. The time lapse difference map revealed major regional contrast with a sharp increase (80% - 100%) in northeast Nigeria (Chad Basin) and moderate decrease (1% - 20%) in southern regions. The findings show the differential behavior of aquifer systems in Nigeria and their response to the diverse climatic changes and anthropogenic stresses which have implications for regional water resource planning.

Subject Areas

Environmental Sciences

Keywords

GLDAS, Groundwater, Nigeria, Hydrogeology

1. Introduction

Groundwater represents the most valuable and readily accessible freshwater resource in Nigeria, serving as the primary water supply for over 70% of the population. This reliance is especially pronounced in rural and peri-urban areas, where surface water infrastructure remains limited or underdeveloped [1] [2]. As the most populous country in Africa, Nigeria faces increasing stress on its groundwater resources due to rapid population growth, accelerating urbanization. Intensified agricultural activities and expanding industrialization are all occurring within the broader context of climate change and increasing rainfall variability [3] [4]. It is therefore critical to understand the spatiotemporal variation of groundwater storage in the country's varied hydrogeological framework in order to manage the water resources sustainably and plan national development.

Groundwater resources in Nigeria are distributed across multiple major aquifer systems, each characterized by distinct hydrogeological properties that govern their storage capacity, recharge dynamics, and vulnerability to environmental stress. The southern coastal sedimentary basin, including the Niger Delta, has multi-layered thick successions of high-yielding good quality water aquifers [5] [6]. The southwest possesses an intricate area of transition in which unconsolidated coastal aquifers increasingly change into crystalline basement rocks to create variable groundwater conditions in relatively short distances [7] [8]. The Middle Belt is characterized by the Benue Trough and Middle Niger Basin aquifer systems, while the northern regions are blanketed with crystalline basement complex rocks with localized sedimentary basins, including the Chad Basin in the northeast [9] [10].

Climate change is currently a dominant driver of groundwater dynamics in West Africa [11]-[13], highlighting patterns of precipitation changes over Nigeria, noting an increase in rainfall variability with significant implications for groundwater recharge processes. [14] observed changes in recharge patterns over the semi-arid Sahel region, while [15] highlighted increased saltwater intrusion into the aquifers of the coastal areas in the southern regions. [16] reported substantial groundwater level depletion in rapidly urbanizing centers such as Lagos, Kano, and Port Harcourt attributing this trend to excessive groundwater abstraction that surpasses natural recharge rates.

Traditional groundwater monitoring in Nigeria has been significantly hindered by the fragmented nature of data collection systems. Existing studies are often limited in spatial scope, focusing primarily on local scales or short periods of time, thereby limiting the capacity for long-term assessments and comprehensive na-

tional-scale groundwater management [17]. The availability of satellite monitoring systems, particularly the Global Land Data Assimilation System (GLDAS), has enabled holistic groundwater assessment on large spatial and temporal scales. GLDAS integrates satellite measurements, surface observations, and land surface modeling in estimating hydrological parameters such as groundwater storage [18]. Although several studies have utilized GLDAS datasets for continental-scale assessments of groundwater resources across Africa [19] [20], there remains a notable scarcity of national-scale investigations for Nigeria that integrate GLDAS data with detailed characterization of local aquifer systems. This gap hinders the development of context-specific groundwater management strategies tailored to Nigeria's diverse hydrogeological settings.

This study presents a comprehensive assessment of groundwater storage dynamics in Nigeria over a 21-year period, from 2003 and 2023, using data derived from the GLDAS. The primary objectives are threefold: a) to quantify the temporal trends in groundwater storage across the country, identifying distinct phases and rates of change; b) to characterize the spatial distribution of groundwater storage across Nigeria's major aquifer systems; and c) to derive insights and implications for regional water resource management based on the observed patterns of groundwater variability.

2. Hydrogeology of Nigeria

Nigeria is situated within latitudes about 4°N and 14°N, and longitudes about 3°E and 15°E in West Africa. The country crosses climatic regimes from humid tropical in the south coastal area to semi-arid in the Sahelian area in the far northeast. The quantity of annual rainfall varies immensely in this area—over 3000 mm/year in the south to less than 500 mm/year in the north [21]. These climatic regimes and geological heterogeneity are key controlling variables behind Nigeria's hydrogeological system.

The hydrogeology of Nigeria can broadly be divided into basement aquifers, consolidated sedimentary aquifers, and unconsolidated alluvial aquifers [22]. Basement aquifers are found largely in the central and southwestern regions, where water is stored and transmitted by weathered and fractured crystalline rocks. The aquifers are mainly of limited capacity and thickness. Consolidated sedimentary aquifers are found mainly in northeast and northwest Nigeria, mainly in Chad Basin and Sokoto Basin. The units, composed mainly of sandstones and limestones, are more prolific in terms of productivity and are major sources of groundwater for domestic use and irrigation use. Unconsolidated aquifers, found mainly in river valleys and deltaic regions, are composed of sand and gravel and are typically highly permeable.

Figure 1 demonstrates the geographical distribution of the aquifer systems in Nigeria. The map indicates regional hydrogeologic systems variability, which is significant in water resource development, especially in relatively underserved rural areas.

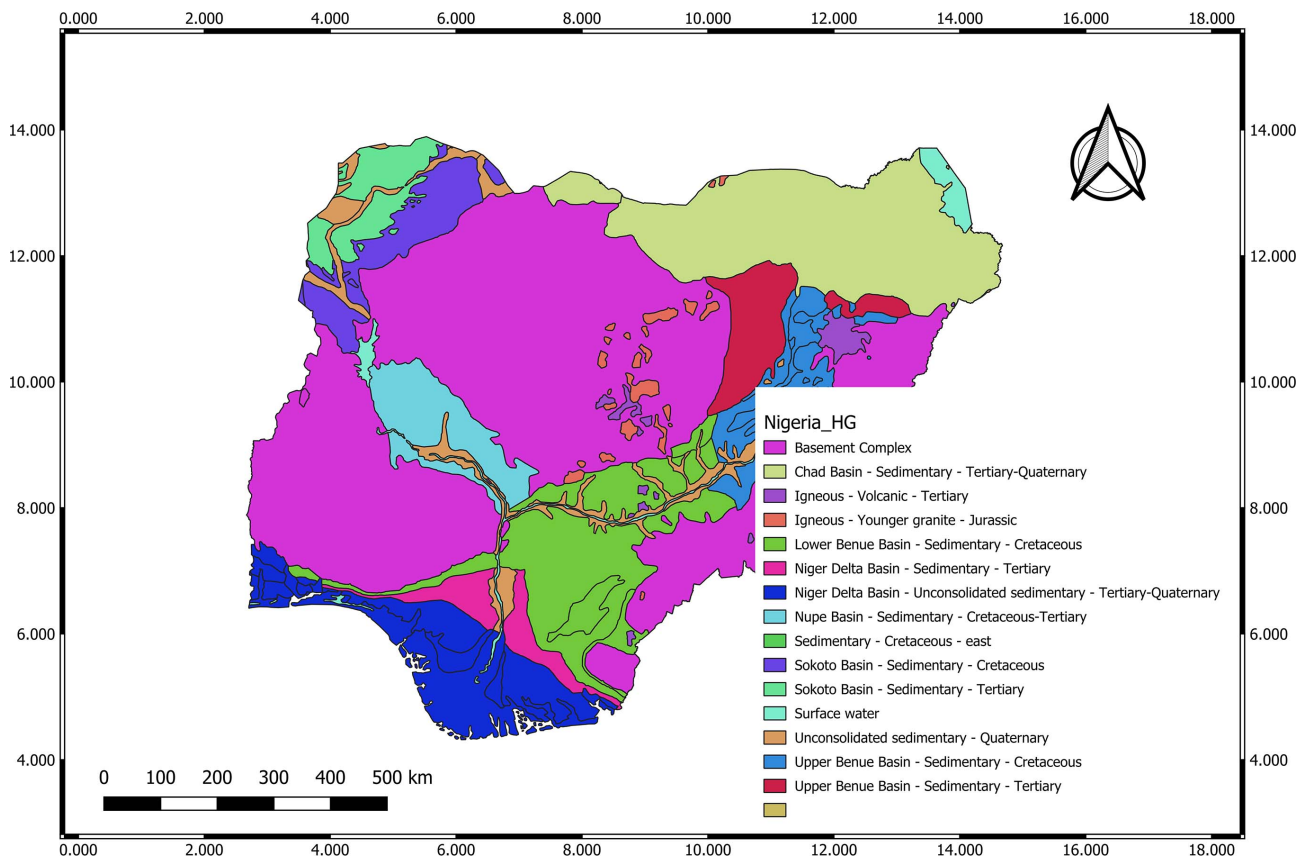


Figure 1. Hydrogeology map of Nigeria. Shapefile for this map was downloaded from Africa Groundwater Atlas, British Geological Survey.

3. Methodology

This study investigated groundwater storage variability across Nigeria using Global Land Data Assimilation System Version 2.2 (GLDAS-2.2) data spanning from February 2003 to December 2023. All data processing and preparation were done through Google Earth Engine (GEE), a cloud computing platform providing large-scale geospatial analysis [23]. Following GEE analysis, the resulting data and images were analyzed and visualized with Python. Nigeria's variable hydrogeological landscape, covering a surface area equivalent to approximately 923,768 km², hosts several major aquifer systems upon which our regional investigation focuses.

GLDAS-2.2 GRACE-DA was the primary dataset. The product incorporates data assimilation of Gravity Recovery and Climate Experiment (GRACE) satellite data, significantly improving terrestrial water storage accuracy [24].

Temporal analysis was carried out to establish trends and periods of significant change in groundwater storage across Nigeria. Monthly groundwater storage was aggregated from Google Earth Engine to create time series data for the entire country and for sample monitoring points over the major aquifer systems. The 21-year span was divided into two temporal phases (2003-2013 and 2013-2023). Linear regression was used for each phase in order to quantify rates of groundwa-

ter change. The cumulative change in groundwater over the complete time span was found by integrating each rate over each time step, seasonally adjusted with a filter length of 12 months.

Spatial analysis within the Google Earth Engine platform was conducted to map groundwater storage distribution. Mean annual value of groundwater storage was determined for each grid cell and transformed to continuous spatial distribution maps.

We assessed temporal change in spatial trend by calculating a map of percentage change in groundwater storage between 2003-2013 versus later periods (2013-2023). All spatial analysis was conducted within Nigeria's administrative boundaries and principal geographical features to provide spatial context for groundwater trends observed.

The approach facilitated regional and nation-wide groundwater resource characterization simultaneously, in a bid to quantify Nigeria's principal aquifer systems differential responses to dynamic environmental change.

4. Results

The analysis of the Global Land Data Assimilation System (GLDAS) data revealed substantial spatial and temporal variability in groundwater storage across Nigeria during the period from 2003 to 2023. The observed fluctuations indicate dynamic patterns of groundwater gain and depletion, varying significantly across different regions and timeframes. The temporal assessments conducted at selected monitoring sites—Kaduna, Ondo, and Port Harcourt—revealed distinct groundwater storage patterns unique to each region, as presented in **Figure 2**. The dataset, spanning over two decades, highlights both seasonal and interannual fluctuations in groundwater storage. All three monitoring sites have distinct annual cycles, likely corresponding to regional recharge mechanisms influenced by precipitation variability and other climatic drivers. However, significant regional differences were observed in the amplitude of these fluctuations and in the direction and magnitude of long-term trends, underscoring the heterogeneous nature of groundwater dynamics across Nigeria.

Groundwater storage trends within the boundary of Kaduna State, denoted by the blue line in **Figure 2**, display significant interannual variability and a marked increasing trend beginning after 2020. This upward shift may be indicative of increased recharge rates or a reduction in groundwater abstraction. Additionally, Kaduna displays a relatively large seasonal amplitude, suggesting a strong sensitivity to the region's distinct wet and dry climatic periods.

On the contrary, groundwater storage in Ondo State, located in the humid southwestern region and denoted by the red line in **Figure 2**, demonstrates more stable seasonal cycles with limited interannual variability. The long-term trend appears relatively steady, implying a sustained balance between recharge and discharge processes over time.

Port Harcourt, situated in the coastal Niger Delta and represented by the green

line, shows the highest overall groundwater storage among the three locations. The temporal pattern is relatively stable with minimal long-time variability, likely reflecting the consistently high precipitation in the region, which supports continuous recharge throughout the year.

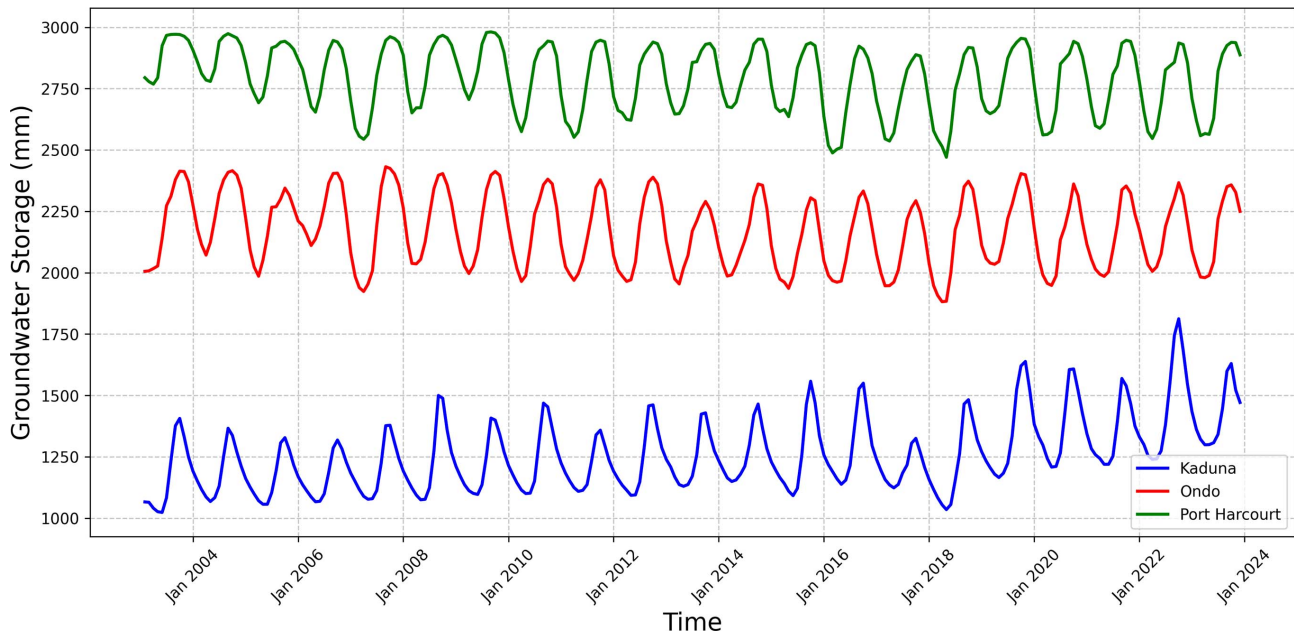


Figure 2. Groundwater levels at three monitoring stations. Monitoring stations were strategically placed in the north, southwest and the south-south regions of Nigeria.

The national-scale groundwater storage pattern reflects the aggregation of individual station trends, as illustrated in **Figure 3**. Overall, the analysis indicates a positive trend in groundwater storage across Nigeria over the 21-year observation period. However, this increasing trend exhibited notable temporal variability. During the initial decade (2003-2013), the rate of increase was relatively modest, with an average annual gain of 1.2 mm/year. In contrast, the subsequent period (2013-2023) experienced a significant acceleration in groundwater recharge, with the annual increase rising sharply to 14.5 mm/year, approximately a twelvefold increase compared to the earlier period. The cumulative change in groundwater storage over the entire study period was estimated at 126.6 mm, signifying a substantial net gain in groundwater resources at the national level, despite underlying regional differences.

The spatial distribution of groundwater storage, as presented in **Figure 4**, delineates distinct hydrogeological zones across Nigeria that align closely with the distribution of the country's major aquifer systems. The southern region, particularly between latitudes 6°N and 7°N, covering the Niger Delta to the coastal areas, exhibited the highest groundwater storage values, ranging from approximately 2500 to 3400 mm. This area corresponds to the Niger Delta Basin aquifer system, which is underlain by thick sequences of highly permeable sediments, conferring substantial groundwater storage potential.

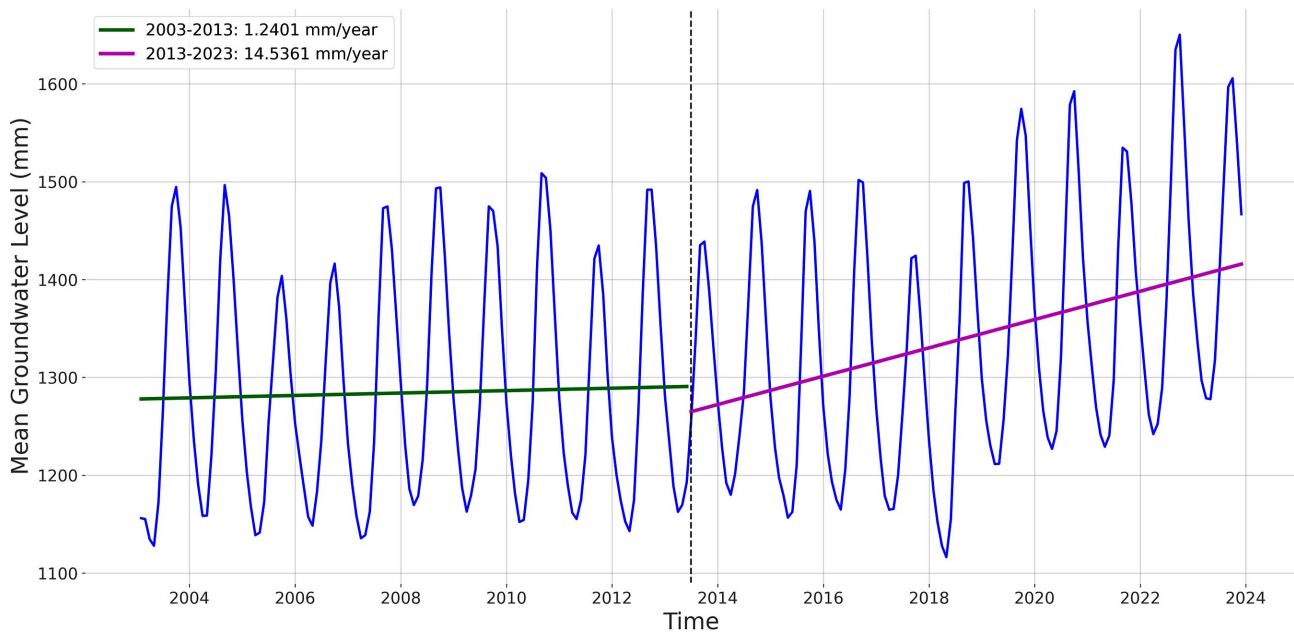


Figure 3. Mean groundwater storage for the entire country.

In the southwestern region, a clear gradient in groundwater storage was observed, reflecting a transition from the unconsolidated coastal aquifers in areas such as Lagos and Ogun States to the basement complex formations prevalent in Ondo State. Groundwater storage values in coastal Lagos and western Ogun ranged from 2200 to 2800 mm, gradually decreasing eastward and northward toward Ondo as the underlying hydrogeology shifts to less permeable crystalline rock formations.

A prominent groundwater hotspot was identified in the north-central region (Mid-Belt), between latitudes 8°N and 10°N around longitude 6°E , where storage values aggregated between 2000 and 2500 mm. This area includes portions of the Middle Niger Basin and the Benue Trough, where extensive alluvial and sedimentary deposits enhance aquifer storage capacity.

In contrast, northern Nigeria, situated north of 10°N , generally recorded much lower groundwater storage values, ranging from 300 to 1500 mm. This region, characterized by a semi-arid to arid Sahelian climate, is underlain predominantly by crystalline basement complex aquifers and segments of the Chad Basin. These geological units typically exhibit lower recharge rates and limited storage capacity relative to the more productive sedimentary aquifers of the south.

A notable anomalous feature identified in the spatial analysis is a localized groundwater hotspot centered around 10.5°N latitude and 10°E longitude, appearing as a distinct yellow zone. This anomaly likely corresponds to a localized groundwater basin situated near the southern boundary of the Chad Basin aquifer system, possibly within northern Bauchi State or the western part of Gombe State. The elevated groundwater storage in this area may be attributed to favorable hydrogeological conditions, where fracture networks within the crystalline basement complex intersect with the overlying sedimentary units of the Chad Basin. Such

structural and lithological interactions can enhance permeability and storage capacity, resulting in localized zones of elevated groundwater availability, even in regions characterized by comparatively lower rainfall than the southern coastal zones.

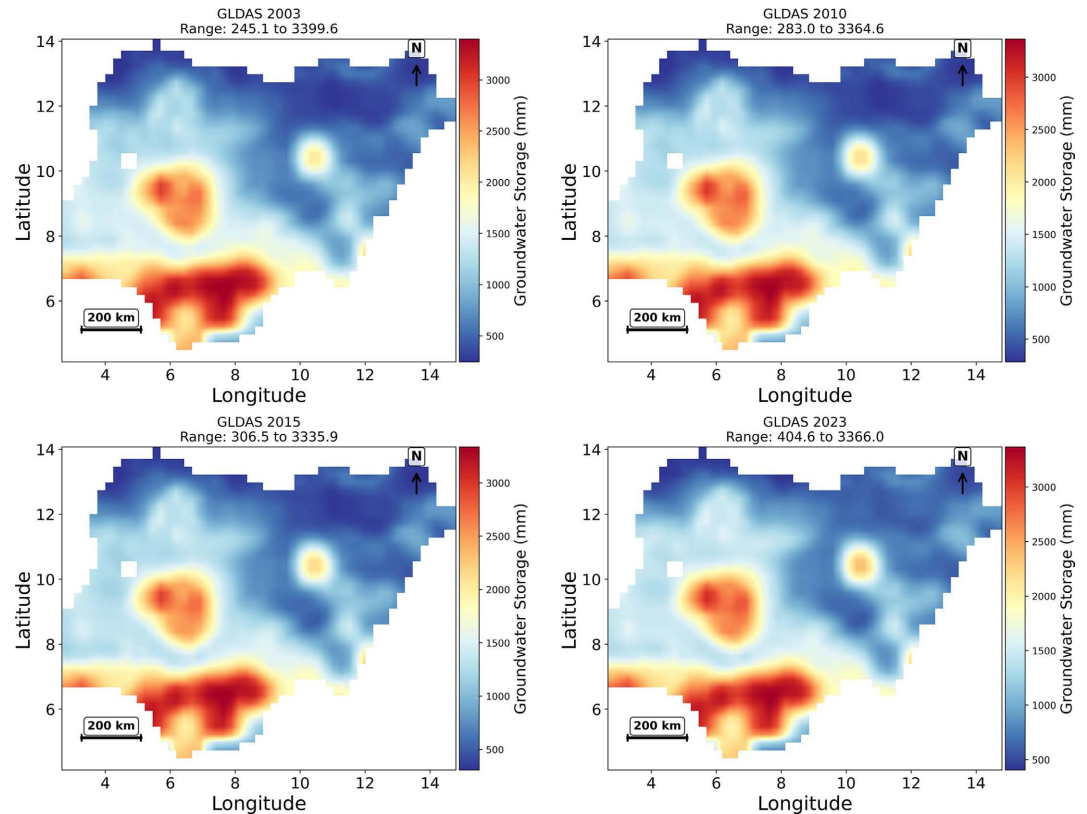


Figure 4. Spatial and temporal variability of groundwater storage in Nigeria (a) 2003 (b) 2010 (c) 2015 (d) 2023.

The groundwater storage difference map (**Figure 5**) reveals substantial regional variability in storage changes across Nigeria over the study period. Notably, the northeastern region, particularly between latitudes 12°N and 13°N and longitudes 10°E to 12°E , recorded the most pronounced increase in groundwater storage, with relative gains ranging from 80% to 100%. This area falls within the extent of the Chad Basin aquifer system, and the observed increase suggests that this large transboundary aquifer is undergoing significant recharge, potentially linked to regional hydrological or climatic shifts.

Conversely, the southern region encompassing the Niger Delta Basin, the coastal sedimentary aquifers, and the transitional aquifer systems of the southwest exhibited a consistent, albeit modest, decline in groundwater storage over the same period. This pattern may reflect persistent pressure from groundwater abstraction in densely populated areas and potential changes in recharge dynamics.

A distinct zonal boundary is evident along latitudes 10°N to 11°N , marking a transition from negative to positive groundwater storage changes. This boundary

trends east–west and corresponds spatially with Nigeria’s Middle Belt region, roughly aligning with the geological interface between the crystalline basement complex aquifers to the south and the expansive sedimentary basins to the north. The contrasting trends across this boundary highlight the influence of underlying geology and regional hydroclimatic conditions on groundwater dynamics.

GLDAS Groundwater Percent Change from 2003, 2010, and 2015 to 2023

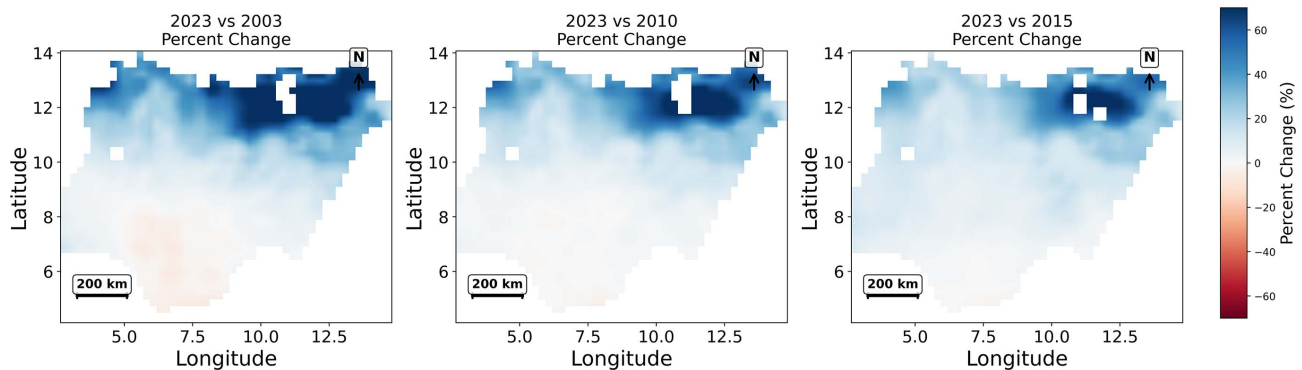


Figure 5. Difference map showing time-lapse of 2023 versus (a) 2003 (b) 2010 and (c) 2015.

5. Discussion

The spatial distribution of groundwater storage across Nigeria reveals the interplay of the geological framework of major aquifer systems and the prevailing climatic gradient. In southern Nigeria, notably within the Niger Delta Basin, high groundwater storage corresponds to the favorable hydrogeological characteristics of the basin. Here, thick sequences of poorly consolidated to unconsolidated sediments provide substantial storage capacity, further enhanced by the region’s high annual rainfall. This is supported by numerous studies which have documented the Niger Delta Basin’s favorable hydrogeological conditions, characterized by thick, poorly consolidated to unconsolidated sedimentary deposits that provide extensive groundwater storage capacity. For example, [5] and [25] highlighted that the basin’s sediment thickness and high porosity facilitate significant aquifer storage and yield. Additionally, the region’s high annual rainfall, often exceeding 2000 mm, further enhances groundwater recharge and storage potential [26]. Together, these factors establish the Niger Delta as a key groundwater reservoir in southern Nigeria.

A distinct hydrogeological transition is observed in the southwestern domain, where aquifer properties change markedly over relatively short distances. This transition zone encompasses coastal unconsolidated aquifers in Lagos and western Ogun states, characterized by high porosity and permeability typical of sedimentary systems, supporting large storage coefficients and relatively higher transmissivity [27] [28]. In contrast, the adjoining crystalline basement complex formations, such as those in Ondo State, support groundwater primarily within weathered profiles and fractured rock systems, which are generally associated with

lower storage capacity and limited yield as supported by studies by [29]. This southwest transition zone thus represents a naturally occurring gradient in groundwater availability, as corroborated by spatial variations in groundwater estimates from the Global Land Data Assimilation System (GLDAS). These observations highlight the role of underlying geology and climatic input in shaping regional groundwater dynamics and underscore the importance of localized hydrogeological assessments in water resource planning as stated by [30].

The markedly lower groundwater storage observed across northern Nigeria is primarily attributable to the hydrogeological limitations of the underlying aquifer systems, notably the crystalline Basement Complex and portions of the Chad Basin. In these regions, groundwater storage is largely restricted to secondary porosity features, such as weathered zones, fractures, and relatively thin sedimentary sequences, which inherently limit the volume and continuity of groundwater reserves [31] [32]. An exception to this general trend is the localized groundwater hotspot near Bauchi, which likely reflects a significant hydrogeological anomaly. This anomaly may be attributed to the structural intersection between fracture systems within the Basement Complex and the margin of the Chad Basin sedimentary sequence. Such a geological boundary can enhance permeability and groundwater retention capacity due to the combined effects of structural conduits and lithological variation [33] [34]. This unique setting may facilitate increased groundwater recharge and storage, distinguishing the area from the otherwise low-storage domains typical of the northern region.

The dramatic difference in groundwater accumulation rates between the early and late phases of the study period suggests a fundamental shift in the hydrological regime of Nigeria, extending beyond the bounds of typical interannual climate variability. Notably, the twelve-fold increase in the rate of groundwater storage accumulation observed after 2013 indicates the influence of significant changes, potentially involving large-scale modifications in rainfall dynamics, alterations in groundwater abstraction patterns, or a combination of both.

In the northeastern part of the country, the Chad Basin aquifer system exhibited an 80% - 100% increase in groundwater storage, marking a significant hydrological transformation. One plausible explanation is a climatic shift associated with the northward migration of the West African Monsoon, leading to increased precipitation and enhanced recharge in the region [35] [36]. Alternatively, the observed aquifer recovery may be partially attributed to a substantial decline in groundwater withdrawals, likely resulting from local security challenges and population displacement, which reduced pressure on the aquifer system [37] [38]. Under such conditions, natural recharge processes would dominate the groundwater balance, facilitating measurable increases in storage.

Moderate declines in groundwater storage observed in the Niger Delta and southern coastal aquifers are likely driven by a combination of stressors, including increased groundwater abstraction to support rapid urbanization and potential shifts in precipitation patterns over these typically humid regions [39] [40]. While

these areas have traditionally benefited from abundant rainfall and favorable aquifer conditions, the growing demand for water, particularly in densely populated urban centers, is placing significant pressure on the groundwater systems [41] [42].

The southwestern transitional zone is especially vulnerable to these dynamics due to its complex and heterogeneous hydrogeological framework. In this region, the unconsolidated coastal aquifers of Lagos and Ogun States are experiencing substantial groundwater extraction, driven by accelerating urban growth and expanding industrial activities [43] [44]. Simultaneously, the crystalline basement complex formations that underlie parts of this zone are likely experiencing increased abstraction from weathered and fractured zones, particularly in areas lacking access to reliable piped water infrastructure. These contrasting aquifer types, porous coastal sediments versus discontinuous basement aquifers, respond differently to stress, compounding the challenge of sustainable groundwater management in the region.

Despite pronounced temporal fluctuations in groundwater accumulation rates, the persistent spatial distribution patterns observed throughout the study period underscore the dominant and enduring influence of Nigeria's major geological frameworks on groundwater availability. This spatial stability reflects the fundamental role of hydrogeological controls in governing regional groundwater resources, even amid the perturbations introduced by climate variability and anthropogenic activities.

While water balance dynamics may shift in response to changing climatic conditions and human interventions, the structural and lithological characteristics of the aquifer systems remain the principal determinants of groundwater storage and distribution. The differential responses of Nigeria's aquifer systems to contemporary trends such as the notable augmentation in the Chad Basin, the relative stability observed in the Middle Belt, and the decline recorded in the southern sedimentary basins highlight the varied resilience and sensitivity of these systems to external pressures.

Sedimentary aquifers, with their relatively high porosity and transmissivity, appear to be more responsive to environmental and anthropogenic changes. In contrast, the crystalline basement complex regions exhibit a more muted response, attributable to their inherently low storage capacities and reliance on discontinuous weathered and fractured zones. This structural limitation both constrains water availability and dampens the system's responsiveness to short-term changes, contributing to a form of hydrogeological inertia. These findings underscore the importance of considering aquifer-specific properties in the development of sustainable groundwater management strategies across Nigeria.

The observed trends in groundwater dynamics are consistent with recent findings by Nasara *et al.*, 2025. The result underscores the need for locally adaptive management strategies that align with the specific characteristics and trajectories of each major aquifer system. Given the diversity in hydrogeological conditions

across Nigeria, a one-size-fits-all approach is unlikely to be effective. Instead, tailored strategies that reflect the spatial heterogeneity of aquifer responses are essential for sustainable groundwater governance.

In particular, the southwestern transitional zone warrants specialized attention due to its complex juxtaposition of unconsolidated coastal aquifers and interior crystalline basement formations. Effective management in this zone will require a dual approach: one that addresses the high-demand, high-yield coastal sedimentary aquifers where over-extraction and salinization may be key concerns, and another that recognizes the limited storage and vulnerability of basement aquifers, which rely on localized weathered and fractured zones for water supply. Developing aquifer-specific policies and interventions in such heterogeneous settings is critical to ensuring long-term groundwater sustainability in the face of both climatic and anthropogenic pressures.

The relatively stable groundwater regime observed within the Middle Belt zone, particularly centered near 6°E longitude, suggests that this region may represent Nigeria's most dependable groundwater province. Given its demonstrated resilience and consistent storage capacity, this area warrants designation and conservation as a strategic national water reserve to support long-term water security.

Furthermore, the identified transition zone approximately between 10° and 11°N latitude serves as a natural hydrogeological boundary for implementing differentiated groundwater management strategies across Nigeria's diverse aquifer systems. This transitional corridor coincides with the geological interface between the crystalline Basement Complex and the expansive sedimentary basin aquifers, underscoring the dominant influence of underlying lithological and structural controls on groundwater distribution patterns. The clear alignment of hydrogeological variability with geological framework boundaries highlights the importance of tailoring management approaches to the specific characteristics of each aquifer system to optimize sustainable groundwater use.

6. Conclusion

The groundwater storage research using data from GLDAS has provided significant details on the spatiotemporal patterns in groundwater storage across Nigeria's aquifer system from 2003 to 2023. The findings underscore the predominant influence of hydrogeological settings on groundwater distribution and dynamics nationwide. The dramatic twelve-fold rise in accumulation rates from the early (1.2401 mm/year) to the late period (14.5361 mm/year) points towards an enormous transformation in the hydrologic regime and its attendant critical implications for water resource sustainability. This study identified significant groundwater storage increases of approximately 80% - 100% in the northeastern Chad Basin aquifer system, indicating improved recharge conditions in regions previously characterized by water scarcity. In contrast, modest declines in groundwater storage ranging from 1% to 20% were observed in the southern Niger Delta Basin and coastal aquifers, including the southwestern transitional zone between Lagos

and Ondo, highlighting emerging vulnerabilities in historically water-rich areas. The delineation of a pronounced transition zone around 10 - 11°N latitude, which separates regions of increasing and decreasing groundwater storage, provides a critical spatial reference for implementing regionally differentiated water management strategies. Likewise, the southwestern transition zone, where unconsolidated coastal aquifers gradually give way to crystalline basement formations represents a complex hydrogeological boundary that warrants tailored management approaches to address its heterogeneous aquifer characteristics. The findings of this study carry important implications for Nigeria's water resources management policies. The results support the need for regionally tailored strategies that account for both the intrinsic hydrogeological characteristics of each aquifer system and its observed temporal trends. In northern regions experiencing significant increases in groundwater storage, policy efforts should prioritize sustainable utilization and monitoring of these emerging reserves. Conversely, in southern regions particularly the rapidly urbanizing coastal zones management strategies must address ongoing declines through demand regulation, recharge enhancement, and infrastructure development. While the spatial resolution of GLDAS data imposes limitations on fine-scale local analysis, the strong correspondence between the observed storage patterns and the known characteristics of Nigeria's major aquifer systems lends credibility to the findings and supports the validity of the study's outcomes. Future research should focus on high-resolution mapping combined with the integration of groundwater level monitoring and climatic data to more precisely elucidate the underlying mechanisms driving the observed changes, especially the abrupt acceleration in national groundwater accumulation rates since 2013.

Conflicts of Interest

The authors declare no conflicts of interest.

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