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Groundwater storage variability in West Africa using gravity recovery and climate experiment (GRACE) and global land data assimilation system (GLDAS) data

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Abstract
The study integrates Gravity Recovery and climate Experiment (GRACE) satellite data which provides Terrestrial Water Storage with Global Land Data Assimilation System (GLDAS) which provide the hydrological components of surface water and soil moisture and investigated groundwater storage variability in West Africa Between April, 2002 to March, 2024 (240) months. Groundwater storage is a critical component of hydrological circle which has a significant implication for water availability and sustainability especially in areas where surface water is scare like some parts of west Africa, however, the spatiotemporal of groundwater storage is poorly understood in west Africa. The results reveal significant variability in groundwater storage across the study area, the analyses shows that the groundwater storage is primarily influence by regional hydrological components including surface water and soil moisture as well as climatical factors (precipitation and temperature). The study also highlights the impact of climate variability on groundwater storage in West Africa. Significant correlations are observed between groundwater storage and hydrological components, indicating that changes in SW and SM play a crucial role in driving fluctuations in groundwater storage. The results provide valuable insights into the dynamics of groundwater storage in West Africa and contribute to a better understanding of the region's water resources. This information is of vital importance for water resource management, particularly in the face of ongoing climate change and increasing water demand. The study emphasizes the need for comprehensive monitoring and management strategies to ensure sustainable groundwater use in West Africa.

Keywords
GRACE, GLDAS, Gravity, Recovery, Climate, Experiment, Assimilation

Introduction

Groundwater (GW) is the largest reserve of fresh water in the world that is favorably accessible and less disposed to quality degradation and droughts in comparison with surface water (Meghwal *et al.*, 2019). Many regions of the world rely on GW for agriculture, industry, and urban living, mainly because of its abundance and low-cost to exploit. The GW is one of the world's vital natural resources, its usage is fundamental to meet the rapid demand for water due to the expansion of urban, industrial, and agricultural areas especially in arid areas where surface water (SW) is scarce and seasonal. However, the patterns of groundwater storage (GWS) have changed due to changes in the climate, land use, and human activities (Pande, *et al.*, 2021; Kumar, 2022; Scanlon *et al.*, 2022). Thus, with climate change, rapid urban growth, and

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increased water demands (Yin *et al.*, 2019; Yin *et al.*, 2020; Liu *et al.*, 2021) emphasize that monitoring GWSV is of the utmost importance in understanding the water cycle and predicting the climate. Groundwater storage is the holding or storing of GW beneath the Earth's Surface, it can be found anywhere on Earth's surface, including beneath hills, mountains, plains, and deserts. It is not always readily available or fresh enough to use without treatment, and it can be difficult to locate, measure, and define. Water at very shallow depths may be only a few hours old; at moderate depths, it may be 100 years old; and at high depths or after flowing long distances from points of entry, water may be several thousand years old. Aquifers, which are moderately to extremely permeable rocks, store and transport GW slowly (Grönwall *et al.*, 2020). Groundwater monitoring (GWM) involves tracking the quality and quantity of GW over time to understand its dynamics, detect changes, and make informed decisions, it is crucial because it informs on the trends in GW availability and quality, on which basis timely interventions can be made it will also tell whether GW is suitable for consumption or not. According to Masood, *et al.* (2022) GWM has undergone changes in technology over time. Three distinct phases have led to the evolution of many methods and tools: point-based measurement (used to measure groundwater levels); satellite-based monitoring (used to measure groundwater storage); and regional groundwater estimate through modeling (used to measure regional groundwater levels). Various methods of GWM includes Water Level Monitoring (Alley, *et al.*,1999), Water Quality Monitoring (Hounslow *et al.*, 1995), Piezometers Monitoring Wells (Chambers *et al.*,2021) and Satellite method of GWM which involves the use of satellite-based remote sensing methods to gather information on the quantity and quality of GW and use same to monitor GWS (Longuevergne, *et al.*, 2011), this method proves to be more advantageous than other methods due to it wider coverage, Integration with other data sources and easy accessibility (Masood, *et al.*, 2022). The conventional method of measuring GWS variability (GWSV) involves daily observations of the water level in observational wells. The lack of in-situ measurements, or observational wells, makes it challenging to monitor GWSV and other water budget components in West Africa. Although this approach offers GW-level measurements with high spatial and temporal resolution, it also has numerous practical limitations (Yin *et al.*, 2019). For example, it is expensive and time-consuming to set up and maintain observation stations; moreover, the distribution of monitoring wells is uneven; and measurements of the ground-water level at a particular site are limited to representing the situation in a specific area of interest.

the application of contemporary methods like geographic information systems (GIS), especially GRACE, and remote sensing (RS). In recent decades, global and regional water storage monitoring efforts have been greatly advanced by the emergence of GRACE, despite the fact that numerous satellite-based remote sensing data were actively used for hydrological monitoring and prediction. The capacity to track changes in GW without the need for any kind of in situ monitoring data has been the most important discovery revealed by this new data (Rodell & Famiglietti, 2002). GRACE has demonstrated the feasibility of being used to estimate groundwater storage fluctuation in addition to being used to remotely monitor groundwater storage. In the United States of America, for example (Rodell et al., 2009; Strassberg et al., 2009). Pakistan (Iqbal et al., 2016), China (Yang et al., 2017) GRACE has been used to study groundwater storage variability globally. It has produced accurate results in the Tigris–Euphrates basin (Voss et al., 2013), the California Valley (Scanlon et al., 2012), India (Rodel et al., 2009), Africa (Hassan et al., 2016), East Africa (Nanteza et al., 2016), and West Africa (Grippa et al., 2011). For this reason, understanding the GWS and recharge variability is crucial to the sustainability of the water resource. For human activity and ecosystems to be supported, GW resources must be sustainable and readily available. However, a variety of geological, climatic, and human factors affect GWSV. Maintaining sufficient water supplies and reducing the hazards related to water shortages and global warming depletion require an understanding of and ability to manage these variations. The world's freshwater resources are under threat due to the world's population growth, urbanization, overuse, and improper management of water resources. These factors can result in a number of negative environmental effects, including GW contamination, land subsidence, aquifer depletion, seawater intrusion, and degradation of GW quality (Scanlon et al., 2022). A review of the literature demonstrates that further research is required to fully grasp GWSV in West Africa. A thorough investigation is necessary to fully appreciate GWSV in West Africa.
Despite extensive global research, few GRACE ap-

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plications have been used to study GWSV over Africa since 2002. The most noteworthy of these is the estimate of TWS for the African Congo Basin from April 2002 to May 2006, provided by Crowley et al. (2006). This estimate showed noteworthy long-term trends and a total loss of approximately 280 km^3 of water throughout the research period, with a seasonal signal of 30.6 mm $year^1$ of EWT. Grippa et al. (2011) evaluated land water storage over West Africa by utilizing estimates of SM from regional land surface models (conducted within the African Monsoon Multidisciplinary Analysis Land Surface Inter-comparison Project ALMIP) and five years' worth of GRACE data (2003-2007).

Their results showed a significant correlation. Ayman et al. (2016) used hydrologic models and data from GRACE to examine changes in water storage and balances throughout Africa between January 2003 and July 2013. According to their findings, there are variations in the inter-annual trend variability, but overall, TWS estimations at seasonal timescales are consistent. (Barbosa et al., 2022; Skaskevych et al., 2020). In order to improve understanding of GWSV in West Africa and facilitate efficient resource management, this study examines GWSV in the region from 2002 to 2022 using monthly GRACE data.

Material and Methods

The Study Area

The study area comprises of sixteen countries of Benin, Burkina Faso, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo, with a total area of around 6.14 million km^3 (Figure 1). West Africa is situated between latitudes 4^ON and 27^O N and longitudes 15^O W and 16^O E. The southern boundary of this location is the Atlantic Ocean. The Sahara Desert is located to the north, and the Cameroon Mountains border the eastern boundary (Amani et al., 2007).

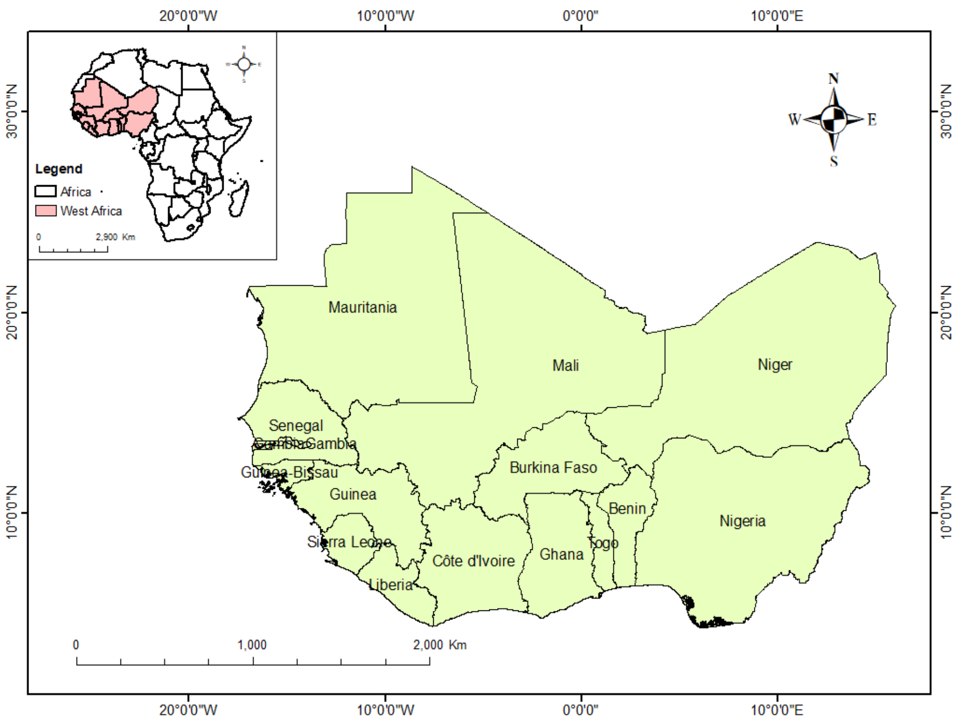

Figure 1
Map of the study area

West Africa's climate is determined by two air masses that interact differently all year long and are influenced by the north-south migration of the Intertropical Convergence Zone (ITCZ). Over most of West Africa, dusty Harmattan winds are caused by hot, dry continental air masses migrating toward high-pressure systems above the Sahara Desert between November and February. Nicholson (2013) claims that the annual summer monsoon rains are caused by humid equatorial air masses originating from the Atlantic Ocean. West Africa has a precipitation pattern that is characterized by decreased rain and shorter rainy seasons at different latitudes as a result of the interaction of these air

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masses. The Gulf of Guinea experiences year-round precipitation and lacks a definite dry season (Muhammed, 2011). The highlands of Guinea and the Jos plateau in central Nigeria receive more precipitation than do lowlands at the same latitude. While Ouagadougou, Burkina Faso (12° northern latitude) records 700 mm during a 5-month rainy season and Agadez, Niger (18° northern latitude) records 165 mm annually during a brief 2.5-month rainy season, Abidjan, Côte d'Ivoire (5° north latitude) records a mean annual rainfall of 1,600 mm along the south-north gradient of decreasing rainfall. West African lowlands experience continuously high temperatures, with annual averages that often exceed 18°C. In the Sahel, maximum temperatures can soar above 40°C. In general, the soils in West Africa lack nutrients, especially in the northern section of the continent where the Sahara Desert is encroaching. Plant growth is hampered by the soils' lack of organic content and tendency to be sandy. According to Amani et al. (2007), soils in the south often have higher quantities of organic matter and nutrients, making them more fruitful. From 316 million in 2007 to 391 million in 2021, the population of the region is expected to increase to 796 million by 2050. The population is growing faster in urban regions than in rural ones, mainly as a result of migration and infrastructural issues such garbage management and water supply (Worldometer, 2023). According to the most recent United Nations estimates (Worldometer, 2023), the population of West Africa is 430,721,028. With an annual growth rate of roughly 3%, this means that the population will double every 25 years and account for 5.16% of the world's total population. The distribution of aquifers in West Africa is varied, and these groundwater resources are vital to the region's ecosystems and inhabitants. In West Africa, aquifers are found in a variety of geological formations, and the availability of these resources is impacted by geology, climate, and human activities (Ndehedehe, et al., 2019). Coastal aquifers, Sahelian aquifers, transboundary aquifers, sedimentary aquifers (Nicholson et al., 2013), and crystalline rock aquifers (Okpara et al., 2013) are among the various types of aquifers found in West Africa. Aquifers in West Africa are essential for supplying the region with water.

Data

This section provides descriptions of data type and their sources Table 1 that were used in the study covering the period of April, 2002-March, 2022 (240 months), the monthly TWS for West Africa obtained from GRACE, while the monthly SM and SW was derived using GLDAS NOAH.

GRACE and GRACE-FO Data

The GRACE and GRACE-FO missions consist of two identical satellites moving in tandem, trailing each other at a distance of 220 km, and at an initial altitude of 500 km, which decreased down to 330 km. Near-global coverage is guaranteed by the almost circular orbit at 89° inclination. 30 days of nonstop observations result in a dense spatial coverage during the 94-minute orbital period. After around 15 years, the first GRACE mission came to a conclusion, supplying data from 2002 to 2017 (Tang et al., 2020). The GRACE Follow-On (GRACE-FO) project was launched in May 2018 and, like the original GRACE mission, has been providing monthly gravitational anomaly data till now (Landerer et al., 2020; Callery *et al.*, 2020). The distance between the leading and trailing satellites grows as the leading satellite gets closer to a gravitational anomaly, and then reduces when the trailing satellite becomes drawn to the anomaly as well. A dual one-way K-Band Microwave Ranging (KBR) system is used to measure the intersatellite range with an accuracy of 1μm. Range measurements, GPS coordinates, satellite orientation from star cameras, and accelerometer readings of non-gravitational forces are used to calculate the Earth's gravity field. According to Mo-

Table 1. *Data set and their sources*

Variable	Data type	Data source	Spatial Resolution	Temporal Resolution (Monthly)
TWSA	GRACE JPL RL06 GRACE CSR RL06 GRACE GFZ RL06	https://grace.jpl.nasa.gov/data https://grace.csr.nasa.gov/data https://grace.gfz.nasa.gov/data	1^{O} x 1^{O}	2002-2022
SM SW	GLDAS NOAH	https://disc.gsfc.nasa.gov/	0.25^{O} x 0.25^{O}	2002-2022

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ghim (2020), GRACE is capable of measuring time-dependent gravity fields, which can be used to represent variations in surface mass and water storage. The detected temporal changes can provide equivalent water thickness, which is a mass departure from the baseline and can be used to indicate variations in water storage. According to Springer et al. (2023), three processing centers CSR, JPL, and GFZ offer monthly solutions of the GRACE gravity fields in three distinct formats: (1) as SH or Stokes coefficients; (2) as gridded time series of TWSA with post processing already applied; and (3) as regularized solutions based on so-called mascons, which are exclusive to CSR and JPL. GRACE/GRACE FO's tracks variations in Earth's gravity field to measure mass changes, the hydrological cycle has been seen on a broad regional scale since its launch (Nanteza et al., 2016; Thomas et al., 2019). TWS is a vertically integrated water storage system comprising GWS, SM, SW, snow water equivalent (SWE), and canopy water storage (CWS). GRACE-derived variability in all forms of water storage above and below the Earth's surface which are represented by changes (Swenson, 2002). Therefore, it can estimate GWS changes when subtracted from other TWS components, like SM, SWE and SW. Due to a battery issue, 11 months of data from the GRACE were missing: June 2003, January and June 2011, May and October 2012, March, August and September 2013, February, July, and December 2014 (Sun, et al., 2020). The data of the missing months and the data gap between GRACE and GRACE were interpolated using the mean value of two nearby months and for the product gap between June 2017 to May 2018 GRACE and GRACE FO were filled by using the mean values of the same month from two adjacent years. While this method is straightforward, it is widely used and effective for time-series analyses of TWS and GWS (Liu, et al., 2021). The mean of these GRACE datasets was utilized to reduce uncertainties associated with processing CSR, JPL, and GFZ individually. This is an efficient technique for noise decreasing for GRACE observations, and it can also increase accuracy (Ali et al., 2021). utilizing equation [1], this also improves the spatial and temporal coverage of the assessment of GW dynamics. (Ferreira et al., 2019).

$$GRACE = 1/3\ (GRACE_{CSR}+GRACE_{JPL}+GRACE_{GFZ}) \quad [1]$$

Global Land Data Assimilation System output

GLDAS is a land surface model system that uses sophisticated modeling approaches to integrate satellite and ground-based observational data in order to produce ideal land surface fields. (Rodell & colleagues, 2017). The Community Land Model (CLM), Mosaic, Noah, and Variable Infiltration Capacity (VIC; Koster et al., 2004) are the four land surface models that GLDAS presently runs. The NOAH model was used for this study because, compared to other GLDAS models, it simulates changes in water storage with reduced bias and uncertainty (Liu, et al., 2021). A 1° resolution GLDAS covering the period from April 2002 to March 2022 was used. The monthly SW and SM values from the GRACE data were utilized to distinguish GWS from TWS using the GLDAS (Liu, *et al.*, 2021). GLDAS of 1° resolution covering April 2002 to March 2022 was utilized. The GLDAS contains SW and SM monthly values that was used in separating GWS from TWS provided by GRACE data. A 1° resolution GLDAS covering the period from April 2002 to March 2022 was used. The monthly SW and SM values from the GRACE data were utilized to distinguish GWS from TWS using the GLDAS. The total accumulated SW and SM variability for a given month is expressed as a GLDAS grid in relation to a baseline average that was gathered between January 2004 and December 2009. Since the GRACE data time baseline spans from January 2004 to December 2009, the GRACE and GLDAS readings must fall within the same time frame in order to guarantee a reliable data analysis.

Methods

Figure 2 is a flowchart of the methodological approach that was used to achieve the stated objectives.

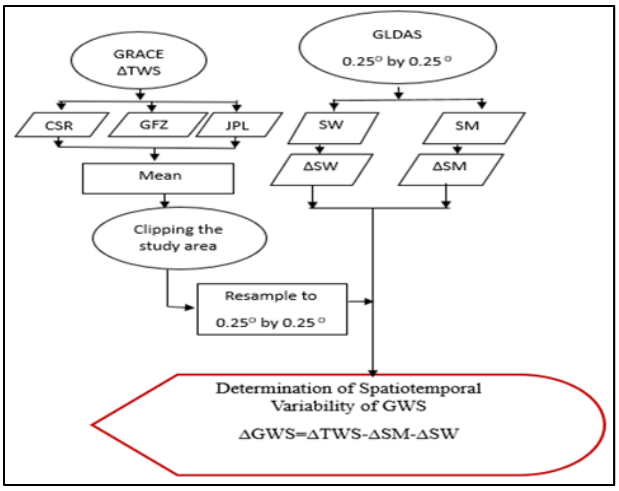

Figure 2. *Flow chart of the methodology*

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Determination of Groundwater Storage Variability using GRACE data

TWS measures vertically integrated water storage changes, representing the sum of SM, GW, SW, and SWE (Rodell *et al*, 2002). The monthly ΔTWS anomalies was obtained from three GRACE solutions. The absolute monthly SM and SW were derived from GLDAS NOAH. The GRACE solutions do not primarily consist of the absolute monthly values but are in terms of monthly anomalies in their base mean period from January 2004 to December 2009 (Liu, et al., 2021; Shao & Liu, 2023) It was done by averaging the monthly gravity data between January 2004 and December 2009 and removing the mean value from each month to compute the anomalies. The GLDAS NOAH components have a spatial resolution of 0.25° x 0.25° with absolute monthly values for SM and SW were converted into monthly anomalies by subtracting the values from the base mean period (2004-2009). According to Yin *et al.* (2019) GWS, SM, and SWE are the significant contributors responsible for the variation in regional water storage. Moreover, West Africa, being in an arid region, where SWE is uncommon it is therefore neglected (Hassan, *et al.*, 2016). Contributions from canopy storage is also not significant therefore can be neglected over West Africa (Springer, *et al.*, 2023). The region has SM and SW as an essential factor responsible for the variations in the ΔTWS. Therefore, ΔGWS in West Africa was obtained by subtracting the ΔSM and ΔSW from ΔTWS, according to TWS balance equation [2] (Scanlon, *et al.*, 2012 and Voss, *et al.*, 2013).

$$\Delta GWS = \Delta TWS - \Delta SM - \Delta SW \qquad [2]$$

Results and Discussion

Spatiotemporal variability of TWS in West Africa

Examining three GRACE derived TWS the result shown in Figure 3 shows the annual TWS in West Africa in terms of equivalent water heights from 2002-2022, the TWS derived from CSR, JPL and GFZ are almost unanimous, they exhibited a high consistency with slopes of 0.001x-37.39, 0.001x-38.46, 0.001x-37.55 and coefficient of determination R^2 of 0.155, 0.184 and 0.172 respectively for the entire study period, with all the three-solution showing slight increasing trend this is consistent with the result of (Jing, *et al.*, 2019; Werth, *et al.*, 2017). In addition, trends in spatial variability of TWS patterns over the region indicates a slight increased between 2002 and 2022.

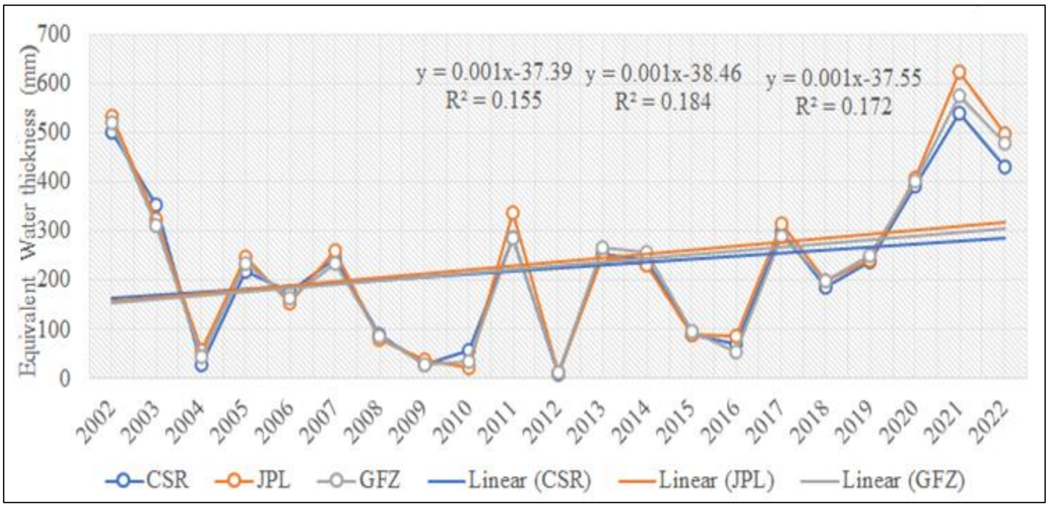

Figure 3
Long-term trends of TWS from three different GRACE solutions

Averaged data from the three gridded releases were used, they exhibited similar accuracy even though they were processed using different algorithm. The mean variability of TWS in West Africa from 2002 to 2022 is displayed in Fig. 4, which makes it clear how seasonal TWS variation occurs. Figure 4's long-term signal mean for the three solutions from 2002 to 2022 indicates an increasing trend of 7.28 cm $year^{-1}$ with an R^2 of 0.736. According to the findings of (Jing et al. 2019), the highest TWS is observed in the year 2021 with an EWT of up to 600 mm, while the lowest TWS is observed in the year 2012 with the TWS <50mm this agrees with the result of (Jing *et al.*, 2019).

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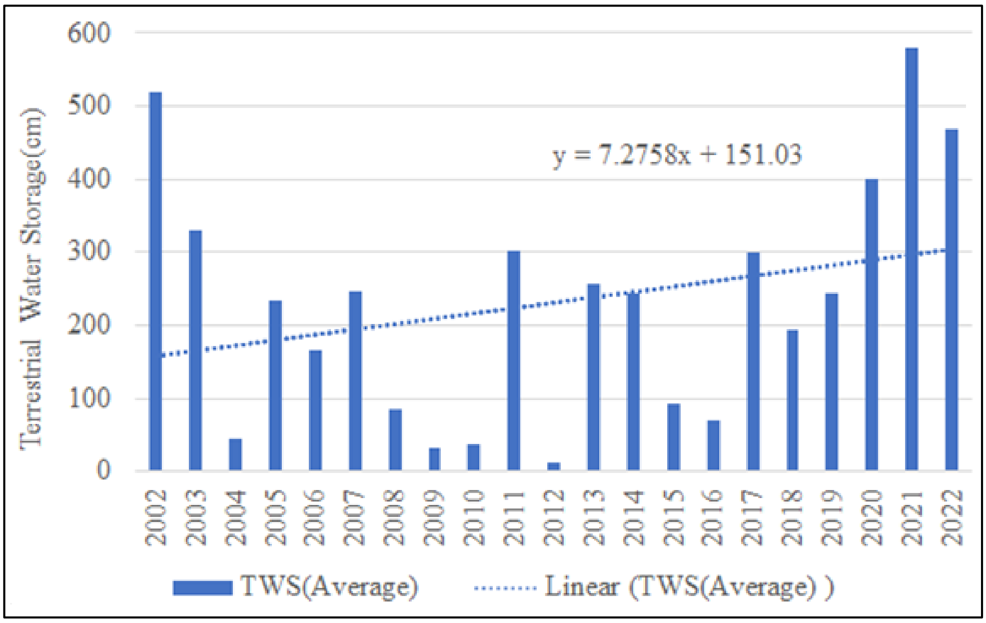

Figure 4
GRACE TWS from mean solutions and its linear trend

The yearly spatiotemporal pattern of TWS over the study area during 2002-2022 is shown Fig.ure 5 with 2002, 2021 and 2022 showing highest spatiotemporal distribution of TWS up to 600mm while 2012 is having least spatiotemporal distribution with values of <50mm respectively this is also in consistent with the results obtained by (Jing *et al.*, 2019).

Figure 6 showing accumulated spatiotemporal distribution of TWS for the entire study period with the lowest TWS in areas of Mauritania, Northern Mali and Northern Niger with a magnitude of (0-300mm), while North-Western part of Nigeria and in some part of Burkina Faso and small portion of Mali, Niger and northern part of Benin are showing the highest TWS according to the mean of the three GRACE product with a magnitude of (451-600mm) and this agrees with a results of (Barbosa *et al.*, 2022).

Overall, the results indicates that the West African regions of the Guinea Coast, Middle Belt, and West Sahel exhibit the most prominent patterns of TWS variability, high precipitation rates at seasonal and interannual time scales brought on by physiographic features, altitude, and ocean circulations are most likely the source of the variability. in general, the spatial distribution of TWSA decreased in the north and increases in the south from 2002 to 2022.

The low and high values of terrestrial water storage in West Africa in various years can be attributed to several factors:

a) Climate variability: Seasons and precipitation patterns vary significantly from year to year in West Africa. For example, low rainfall years have less water available for storage, which lowers TWS values. On the other hand, years with a lot of rainfall have more water available and higher storage values. West Africa sees two distinct seasons: the wet season, which usually lasts from May to September, is characterized by high rainfall that increases total water stored (TWS), while the dry season, which often lasts from October to April, is characterized by lower rainfall that decreases TWS (Ferreira et al.,2019).

b) Temperature and evaporation: While lower temperatures can lower evaporation rates and boost storage values, higher temperatures can increase evaporation rates and lead to accelerated water loss from the land surface, which will affect TWS (Barbosa et al., 2022).

c) Variations in groundwater levels (GWLs), which are impacted by recharge, extraction, and flow, are a major factor in total water storage (TWS). Years with higher GWLs will have higher TWS values, while years with lower GWLs will show lower TWS values (Jing et al., 2019).

d) Land use and land cover changes: Changes in land use and land cover can affect evapotranspiration rates, soil moisture, and runoff patterns, which can affect TWS values. Anthropogenic activities like deforestation, urbanization, and agriculture can also affect TWS by changing the hydrological cycle and land surface properties (Ahamed et al., 2023).

Surface water changes between 2002-2022

Figure 7 shows yearly spatiotemporal variability of surface water in the study area with the highest surface water occurring in 2002-2006 showing similar

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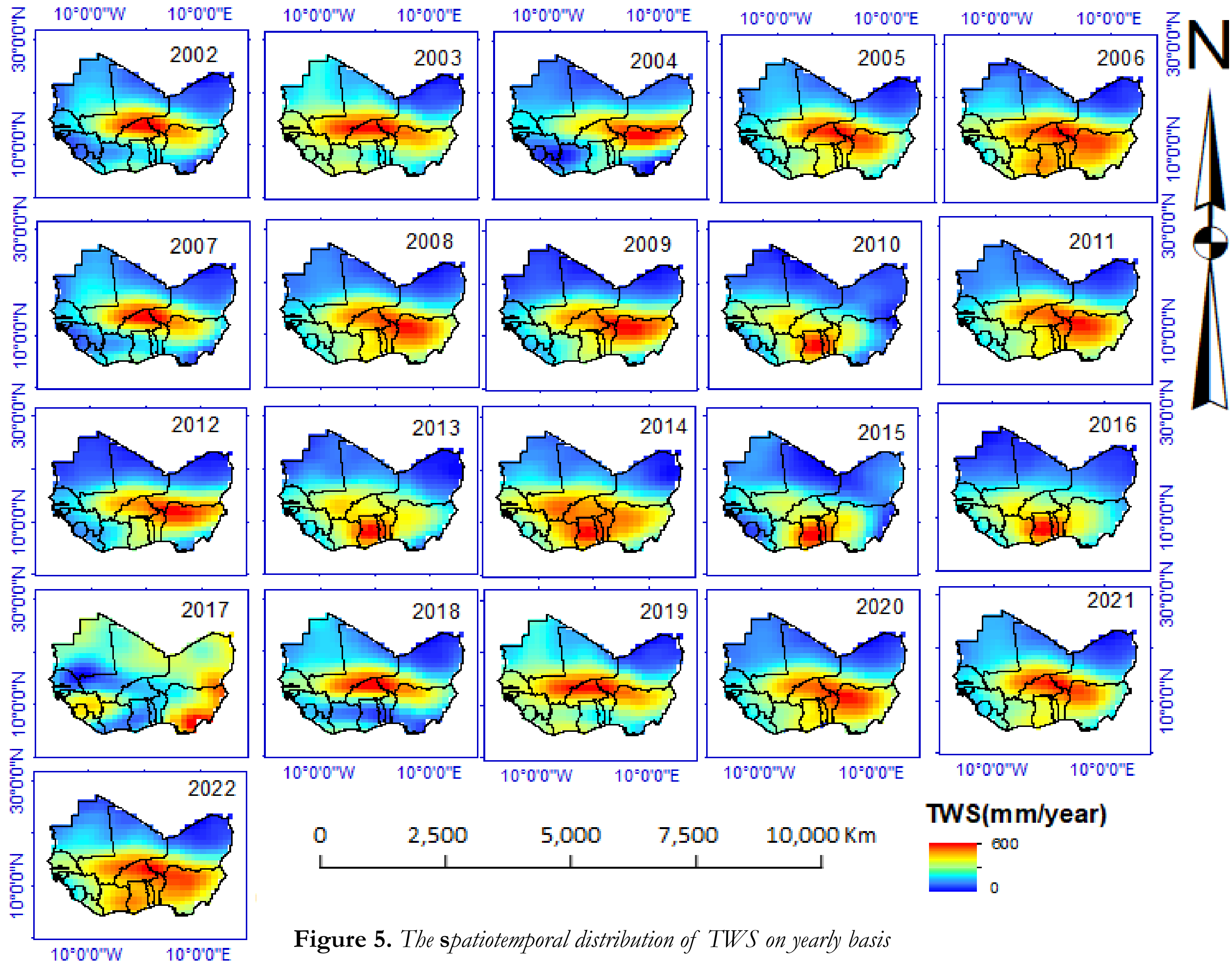

Figure 5. *The spatiotemporal distribution of TWS on yearly basis*

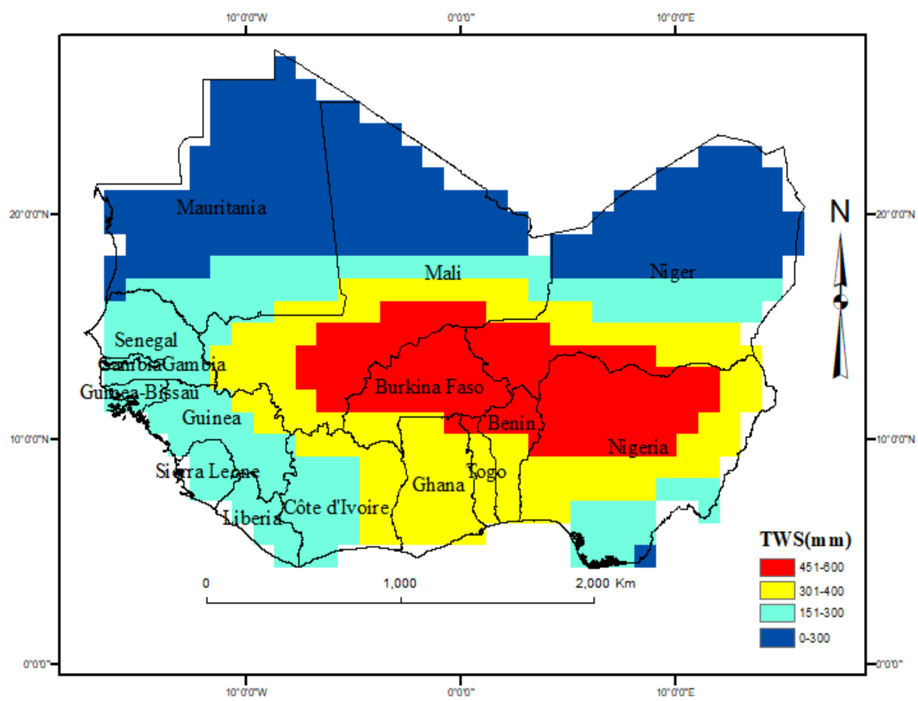

Figure 6
Spatiotemporal distribution of TWS over the entire study period

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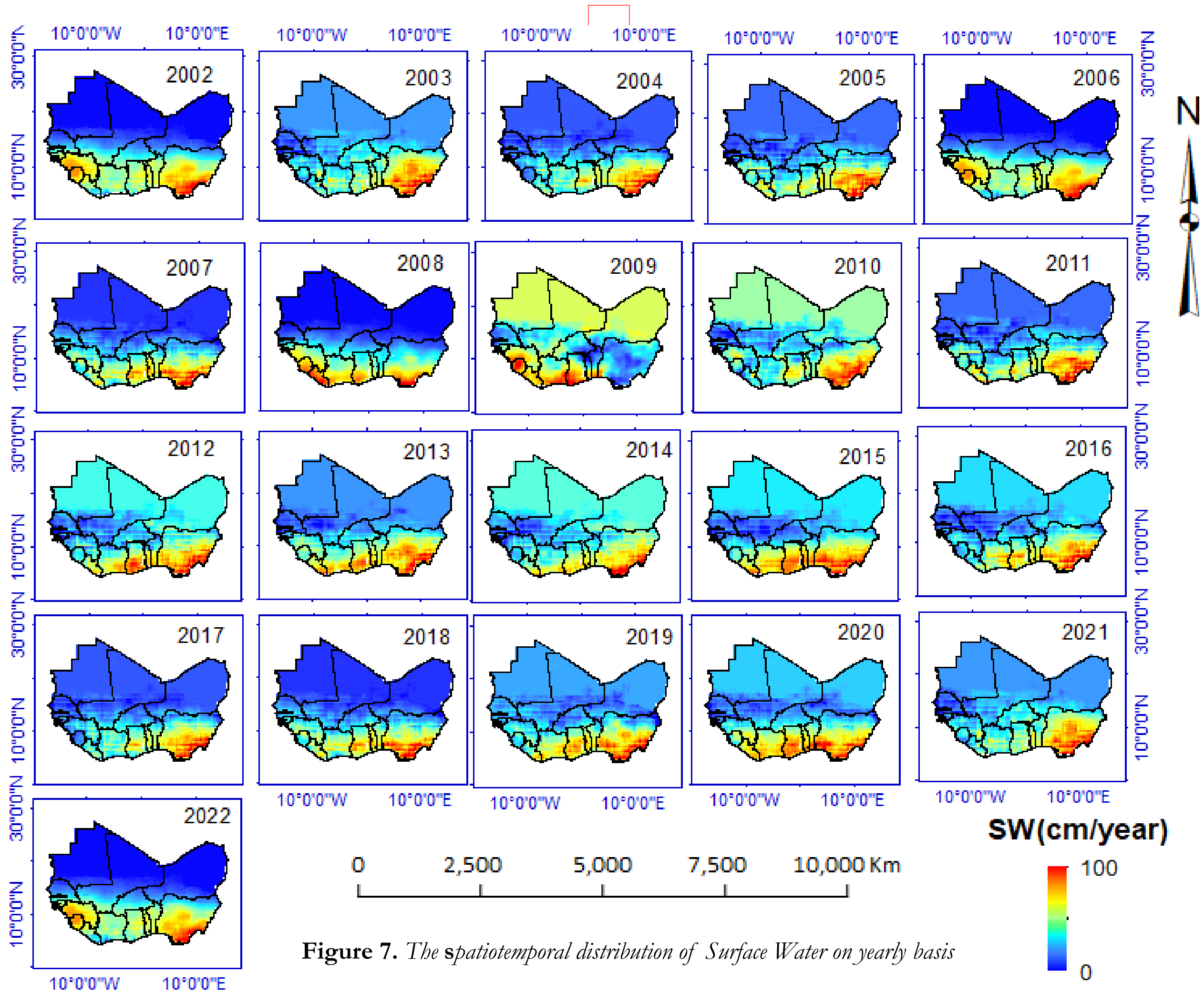

Figure 7. *The* **s***patiotemporal distribution of Surface Water on yearly basis*

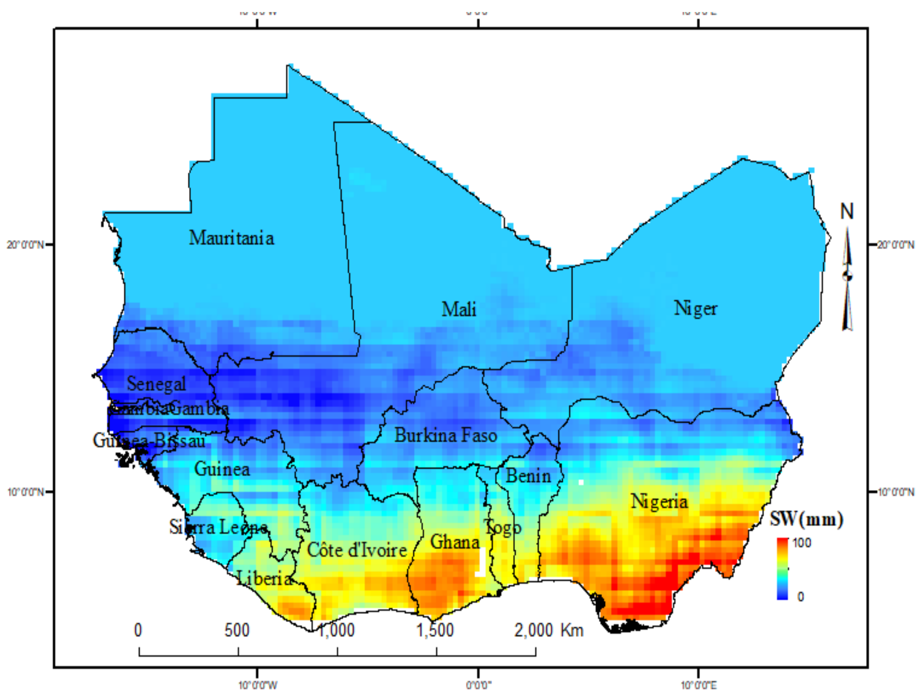

Figure 8
Spatiotemporal distribution of Surface Water for the entire study period

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spatial distribution while the lowest surface water appears to be more prominent in 2008 followed by 2022 and 2018 respectively. Furthermore, the spatiotemporal distribution of surface water from GLDAS NOAH Fig. 8 shows the cumulative amount of SW for the entire study area from 2002 to 2022 with the highest value in southern part of Nigeria, Liberia and Ghana likely because of the dams and rivers around the area while the lowest points are located in part of Mauritania and Niger respectively this result is conformed with the research of Ndehedehe (2016), the annual variability of the SW is attributed to changes in precipitation patterns and temperature increase (Huber *et al.*, 2019), inter annual and decadal fluctuations in rainfall (Lebel *et al.*, 2003), deforestation, agriculture, and urbanization (Faye *et al.*, 2019), floods and droughts (Sene *et al.*, 2019), water extraction, damming, and pollution (Kongo *et al.*, 2019).

Changes in soil moisture over West Africa between 2002 and 2022

Spatiotemporal distribution of soil moisture from GLDAS NOAH, the result in Figure 9 shows annual distribution of soil moisture in the study area with the highest soil moisture clearly shown in 2005 follows by 2004, 2003 and 2021 respectively while the lowest SM appear to be more prominent in 2013 followed by 2012 and 2007 respectively, and Figure 10 is showing the accumulated spatiotemporal distribution for the entire study area with the highest value in areas of Southern Cote d'Ivoire, Ghana and small portion in South eastern part of Nigeria with up to 200mm and the lowest points are located in northern Mali, part of Niger and Mauritania with values almost 0mm respectively. The strong moisture can be seen around Volta area in Ghana and Cote d'Ivoire with a little portion in Nigeria this area is called West African Guinea coast (West African Southern coastline) because of the influence of ocean warm moist air blowing in the direction of the West African southern coastline that is why the area have highest SM as confirm by (Mohammed, 2011). Generally, the variability in SM is attributed to inter annual and decadal fluctuations in changes in precipitation patterns and temperature increase (Huber, *et al.*, 2019), different soil types and properties affect water holding capacity and infiltration (Sene, *et al.*, 2019), deforestation, agriculture, and urbanization impact soil moisture (Faye, *et al.*, 2019), changes in vegetation cover influence soil moisture through evapotranspiration (Niasse, *et al.*, 2019).

Variability of GWS in West Africa 2002-2022

GWS of each year was obtained by the accumulating of GWS of January to December of that year, the GWS is obtained by subtraction the hydrological components of NOAH model (SM and SW) from TWS obtained from mean of three GRACE solutions equation [1]. The results were expressed in the form of equivalent water height. Figure 11 show the spatio-temporal distribution groundwater storage in the study area during 2002-2022, while Figure 12 shows the accumulated GWS for the entire study period. The major factors responsible for GWSV in West Africa includes rainfall variability (Faivre, *et al.*, 2017), soil and land cover (Descroix, *et al.*, 2018), land use changes (Faye, *et al.*, 2019), Geology and hydrogeology (Pallas, *et al.*, 2018), aquifer management (Foster, *et al.*, 2019). There is a significant GWS within 2002-2004 these years in the study area, however there are some particular years where we observe high values around Guinea Cost 2007 upward which is the southern flank of the region.

Spatiotemporal variability in trends of groundwater storage changes

The per-pixel trend analysis showed groundwater rises in the entire study area from 2002 to 2022 in a long term timeseries Figure 13 with positive slope of $y=0.29x+0.058$ this is in line with the result obtained by (Lotfata, 2019). The highest values of GWS occurs in 2021 this is so because there is high TWS Figure6 and low SW and SM whereas the lowest GWS is observed in the year 2012 because of the low TWS and high SM and SW. this agrees with the result of Ndehedehe, (2016) and Lotfata, (2019) respectively, this indicates a significant increase in groundwater storage in the region. This was discuss by many scholars among them are Scanlon et al. (2022) have documented a rise in the overall trends of water storage in West Africa, with a focus on the Iullemeden aquifer. Southwest Niger has seen a constant rise in the water table, according to Favreau et al. (2009). Moreover, an increase in groundwater in the Sahelian aquifers was reported by Bonsor et al. (2018) and Cuthbert et al. (2019). Each of these writers explained this occurrence in part by pointing to a change in land use where the removal of native vegetation concentrates and improves runoff in the ponds, increasing infiltration and replenishing the aquifer.

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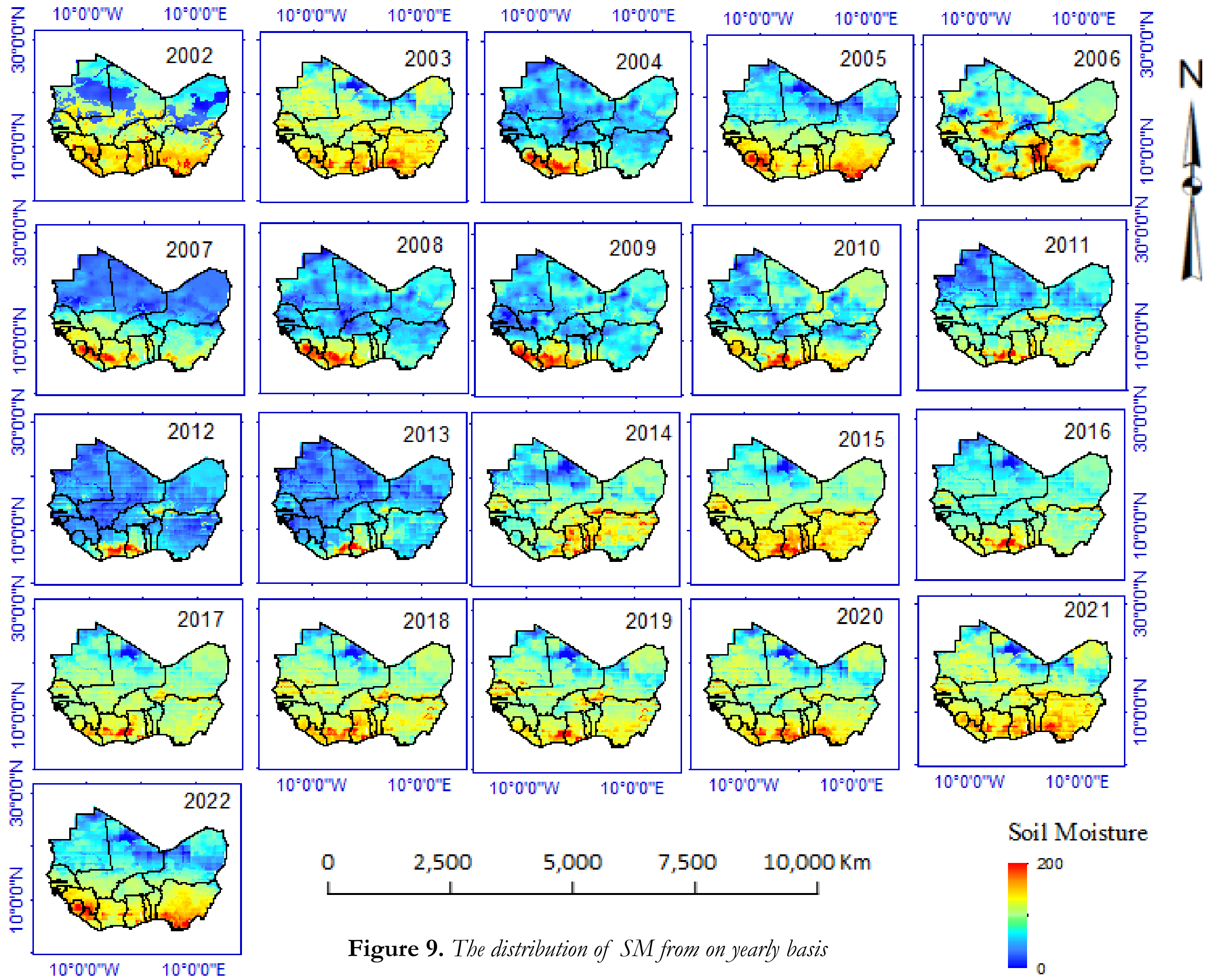

Figure 9. *The distribution of SM from on yearly basis*

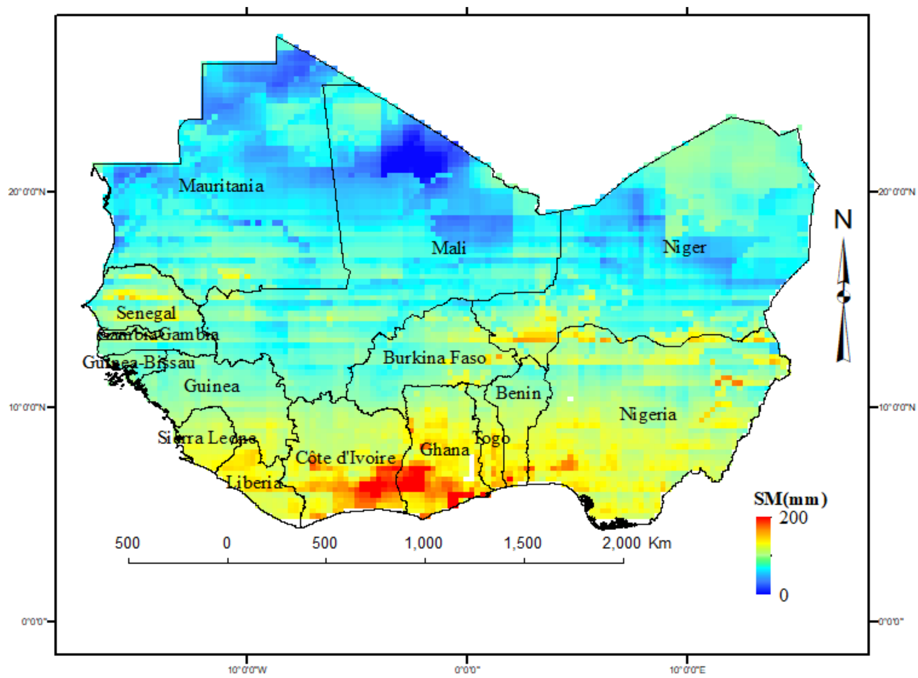

Figure 10
The distribution of SM from for 2002-2022

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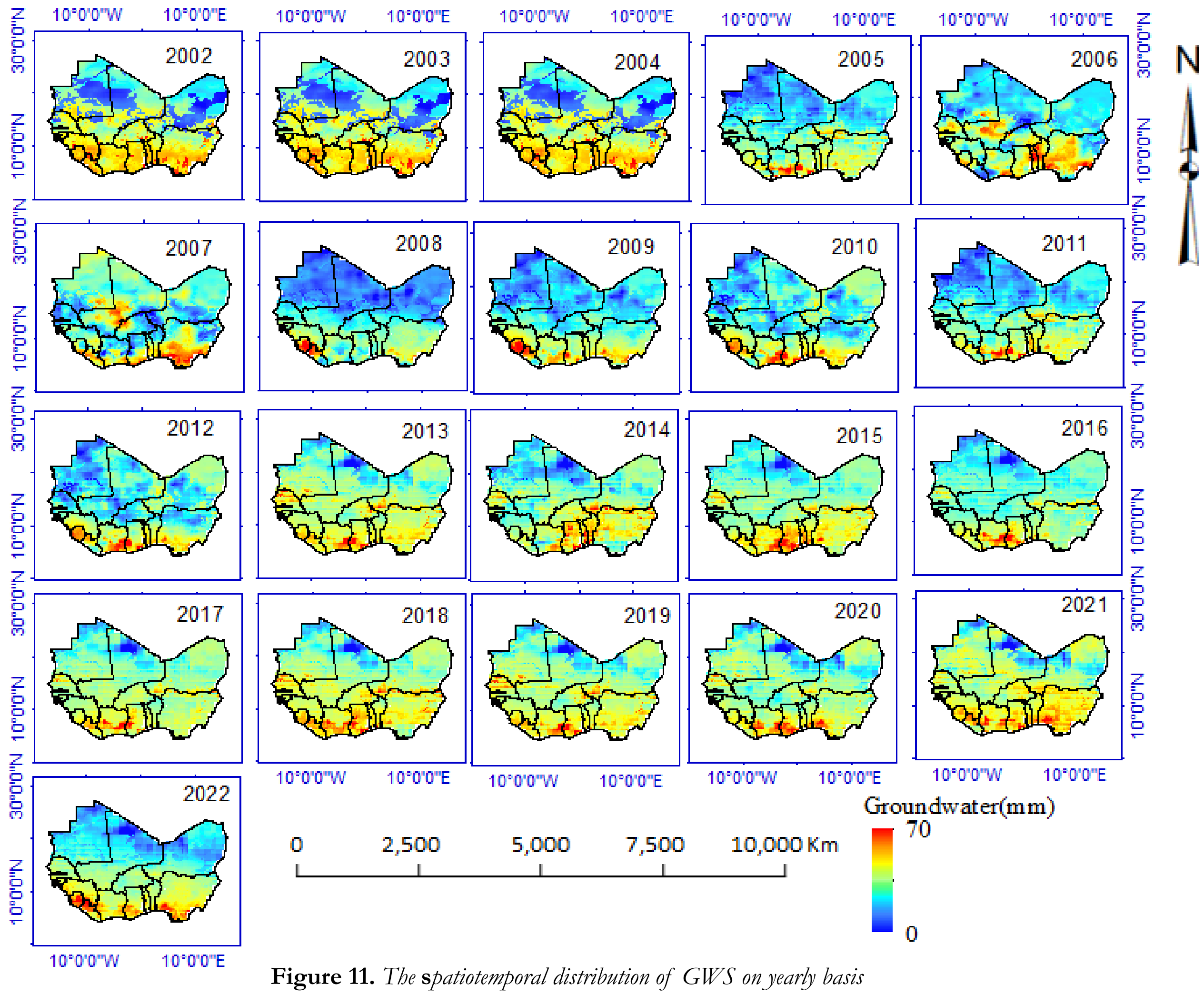

Figure 11. *The* **s***patiotemporal distribution of GWS on yearly basis*

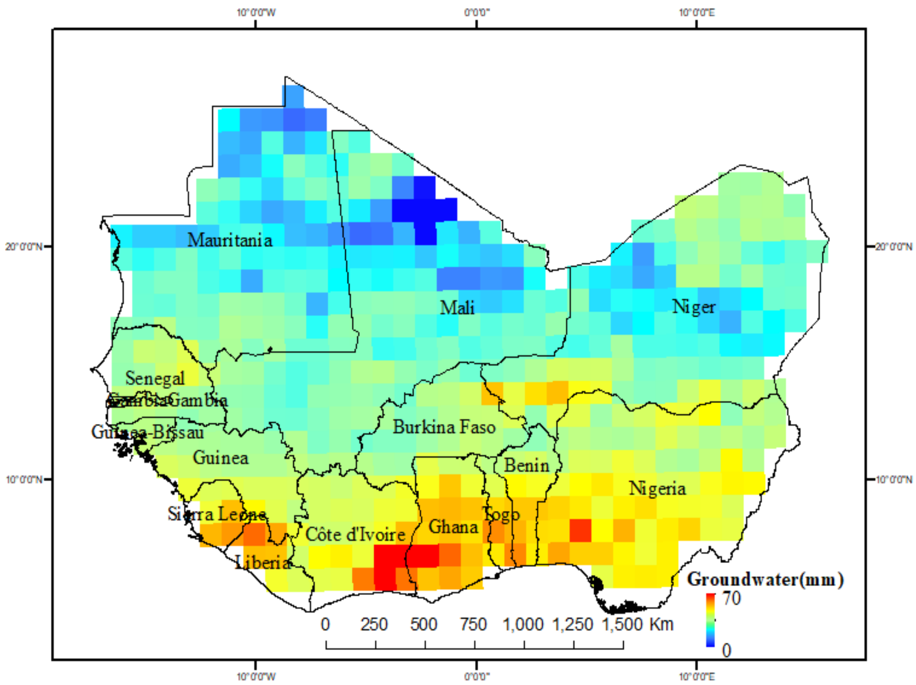

Figure 12
The mean distribution of GWS for 2002-2022

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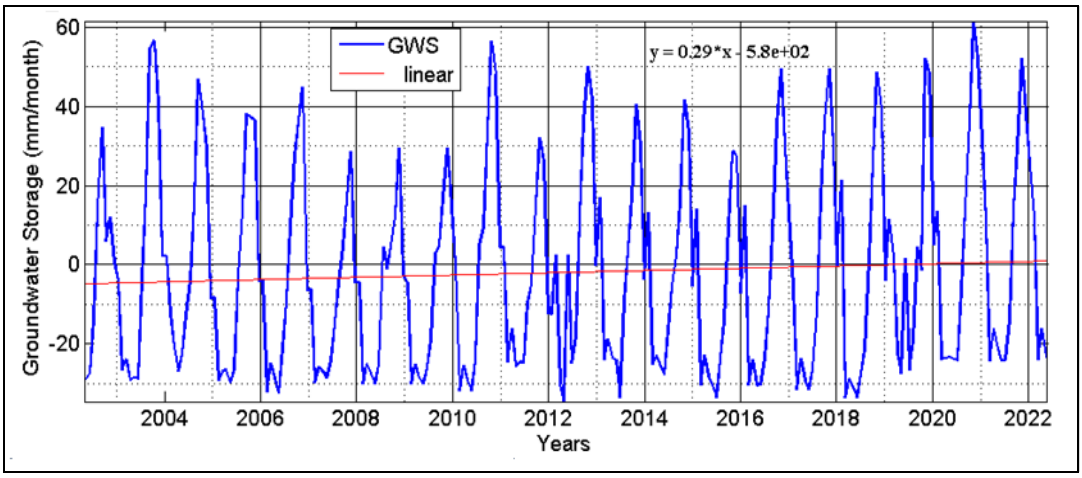

Figure 13 *Timeseries of monthly GWS from Three GRACE Solutions over the study area*

Conclusions

Using information from the GRACE and GLDAS, this study concludes with a thorough examination of groundwater storage variability in West Africa from 2002 to 2022. A thorough evaluation of the spatio-temporal variations in groundwater storage throughout the region has been made possible by the integration of various satellite observations, and the analysis that resulted from this study offered insightful information about the changes in GWS over time. The findings showed that over the study period, groundwater storage in West Africa varied. A number of variables, such as changes in land use, human activity, and climate variability, might be the causes for this variability. The study also emphasizes how critical it is to comprehend the dynamics of groundwater storage in an area where freshwater scarcity is a major problem. Moreover, the study high-lights the effectiveness of GRACE satellite data and the outputs of the GLDAS hydrological model in tracking and measuring variations in groundwater storage. By combining these two datasets, a novel method for evaluating and analyzing groundwater dynamics is presented, giving rise to a thorough comprehension of the hydrological processes in the area. Overall, this study emphasizes the significance of West African groundwater storage and the demand for efficient management techniques. The results underline the significance of sustainable practices and ongoing monitoring by highlighting the effects of both naturally occurring and human-induced factors on groundwater supply. This study has shed light on the dynamics of groundwater in the area by combining ground-based data with cutting-edge satellite technologies. These observations can direct future research and groundwater management decision-making procedures.

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