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23 **ABSTRACT:** The Volta Basin in West Africa plays a crucial role in supporting the livelihoods
24 of millions of people, and effective management of its water resources is essential for climate
25 change adaptation. This study utilized remote sensing technology, specifically the Gravity
26 Recovery and Climate Experiment (GRACE), to assess Terrestrial Water Storage (TWS) and

its response to climate variability within the Volta Basin. The methodology involved integrating GRACE data with ground-based measurements, climate models, and other satellite observations to enhance the accuracy of TWS assessment. Despite numerous studies conducted within the basin, this research employed additional statistical techniques such as Independent Component Analysis (ICA) and El Niño Southern Oscillation (ENSO). It also utilized Climate Hazard Groups Infrared Precipitation with Station (CHIRPS) to determine variations in TWS and climate variability observed within the Volta Basin.

The results provide valuable insights into TWS dynamics, highlighting the complex interplay between precipitation patterns, groundwater storage, and surface water availability. Also, it was revealed that rainfall signals were strongest in the northernmost part of the basin, reaching a maximum value of 10mm, while the lowest value of 5.5mm was recorded in the southern part of the basin. Similarly, TWS signals were highest in the northern and lowest in the southern part of the basin, exhibiting values related to that of rainfall. Additionally, the highest TWS value of 250mm was identified between 2010 and 2012. The increase in TWS during this period correlates with the occurrence of La Niña that happened between 2010 and 2012. This study offers essential information for water resource management, drought monitoring, flood forecasting, and climate change adaptation strategies not only within the Volta Basin but also in other basins across the globe.

Keywords: Volta Basin, Terrestrial Water Storage, Rainfall, Remote Sensing, Climate change

Introduction

Global hydrological reports reveal that many nations are grappling with the challenge of water scarcity (Awotwi et al., 2021; Skoulikaris et al., 2021; Djebou, 2018; Hanjra and Qureshi, 2010). This presents a critical socio-economic issue with the potential to hinder development. The drastic reduction in rainfall projected for arid and semi-arid areas in the coming years due to climate change has been forecasted by (Sishodia et al., 2017; Awange et al., 2016; Ahmed et al., 2016; Awotwi et al., 2015; Sarr, 2012). Such changes could potentially impact the

livihoods of countless people across the world, particularly in an era where the Earth's atmosphere is undergoing dramatic transformations (Ghazouani and Beldi, 2022; McMichael and Lindgren, 2011).

The severe drought experienced in the Sahel regions of West Africa during the 1970s and 1980s has been attributed to the anomalous Sea Surface Temperature resulting from land-ocean-atmospheric interactions induced by climate change (Tschakert, 2007; Mutai et al., 1998). Additionally, the observed intensification of the water cycle due to climate change has led to changes in the magnitude and timing of floods. Therefore, with the continued progression of climate change, it is expected that the frequency and severity of both floods and droughts will increase. Without the implementation of sustainable measures, the people living within the basin could face economic and livelihoood crises.

The Volta Basin extends from the equatorial forest in Northern Ghana to the Sahel-Savannah in Burkina Faso, supporting approximately 19 million people within the West African subregion who directly or indirectly rely on its resources (Asare-Donkor et al., 2020; Boakye et al., 2016; Martin, 2005). Approximately 85% of the basin is situated between Ghana and Burkina Faso, with smaller portions located in Ivory Coast, Benin, and Togo (Yidana et al 2019; Martin, 2005). Nonetheless, the basin grapples with substantial developmental challenges, beyond issues like poverty and increasing population. These challenges have contributed to the extensive exploitation of the basin's resources, resulting in issues such as river channel siltation, water scarcity, and depletion of the fringing tributaries. For instance, in Ghana, nearly half of the population depends on groundwater sourced from borehole wells, for mostly domestic purposes. Whereas, in Burkina Faso, most groundwater resources are utilized for both domestic and agricultural purposes (Welling et al., 2010).

The West African monsoon stands as the primary determinant of precipitation in the sub-region. The inter-decadal decrease in rainfall has manifested as a significant trend in

precipitation patterns, consequently leading to instances of drought within the region. The depletion of Terrestrial Water Storage (TWS) in the catchment can be attributed to both anthropogenic activities and climatic shifts. Notably, the climatic influence of the Volta basin extends not only within its zone of variation but throughout the entire basin. For instance, a drought occurring in Burkina Faso has repercussions for downstream countries, particularly Ghana. This results in diminished water levels in the Volta Lake, impacting hydropower generation. Additionally, floods experienced in Ghana can be attributed to dam spillage from Burkina Faso. Research conducted by Twerefou et al. (2014) forecasts anticipated changes in annual river flow, including the White Volta River, in Ghana from 2020 to 2040 due to climate change.

Other studies also indicate that the major degradation observed in the basin results from human activities, while the decline in the water level of the Volta Lake is attributed to both inadequate rainfall and reduced runoff from the catchments that supply the lake. These conclusions stem from an investigation into rainfall and streamflow patterns within the Volta basin during the periods of 1950 to 1970 and 1971 to 1991 (Gyau-Boakye and Dapaah-Siakwan, 2000). The first period exhibited years with a lower population and more vegetation, characterized by a mostly consistent rainfall pattern. In contrast, the latter period showed a decrease in vegetation and an increase in land use, leading to a disruption of the rainfall pattern due to global warming.

Ground-based observations of Terrestrial Water Storage (TWS), such as soil moisture sampling using gravimetric techniques, neutron probes, or snow stake depth readings, have been reported to be labour-intensive, prone to human error, and challenging (Rodell, 2000). Ndehedehe et al. (2017) and Awange et al. (2013) have noted that these datasets are ineffective due to their inconsistencies, sparse distribution, and lack of availability. However, the launch of the Gravity Recovery and Climate Experiment (GRACE) satellite has enabled the monitoring of the Earth's gravitational fields, including TWS, on a large scale (Tapley et al., 2004). GRACE has facilitated the measurement of Earth's mass redistribution with a spatial resolution of over

200,000 km² and a monthly temporal resolution (Tapley et al., 2004). Additionally, GRACE offers the capability to monitor and assess TWS-related challenges faced by hydrologists and basin managers, such as investigating perennial floods and droughts.

Estimating changes in Terrestrial Water Storage (TWS) is increasingly essential as countries develop adaptation measures and strategies for economic growth in the context of climate change. Studies focusing on TWS dynamics and its response to climate variability offer valuable insights to decision-makers, enabling them to formulate effective measures for water resource management, drought monitoring, flood forecasting, and climate change adaptation strategies. This, in turn, supports sustainable economic growth within the region amidst evolving climatic conditions. Numerous studies have utilized the GRACE satellite to investigate the impact of drought on TWS in the Volta basin (Ndehedehe et al. 2017; Ndehedehe et al., 2016; Bekoe and Logah, 2013; Fasona et al., 2013; Ferreira and Andam-Akorful, 2012; Oguntunde et al., 2006; Andreini et al., 2002; Giesen et al., 2001; Andreini et al., 2000). However, this research aims to assess spatio-temporal variations in TWS and the effects of climate change on the Volta basin. Specifically, it aims to evaluate the spatio-temporal trends and relationships between rainfall and TWS, while investigating the impact of El Niño-Southern Oscillation (ENSO) on the basin. The research hypothesis is grounded in the premise that the presence of various hydroelectric dams, such as the Bui, Barge, Akosombo, and Kpong dams, could contribute to changes in TWS within the catchment.

Materials and Methods

Study Area

The Volta basin is situated in West Africa and spans across six neighboring countries: Ghana, Burkina Faso, Togo, Mali, Benin, and Cote d'Ivoire (Fig. 1). It stretches from latitude 5°30' N in Ghana to 14°30' N in Mali, with 42% of its expanse located in Ghana, 43% in Burkina Faso, and smaller portions in Cote d'Ivoire, Mali, and Benin. The downstream segment of the basin, situated in Ghana, is marked by its largest tributary, Lake Volta, which holds the distinction of

being the largest man-made lake in terms of surface area. Moreover, the basin's widest section extends from longitude 5°30' W to 2°00' E, narrowing as it approaches the coast of Ghana and enters the Gulf of Guinea. Covering an approximate surface area of 400,000 km², the basin encompasses four key sub-basins: Black Volta, White Volta, Oti River, and the Lower Volta River. These sub-basins span an area coverage of roughly 142,056 km², 106,742 km², 72,778 km², and 71,608 km², respectively (Mul et al., 2015).

The Volta River basin is located within the semi-arid and sub-humid savannah climatic zone, characterized by distinct wet and dry seasons. These seasonal variations are driven by the interaction of two migrating air masses, which significantly impact the region's climate. One of these air masses is the Harmattan, a cool and dry wind that originates from the northeastern part of the Sahara and spreads across the entire study area. The influence of the Harmattan is particularly high from late November to mid-March (Ferreira et al., 2018; Okafor et al., 2019). The second air mass is constituted by the West African Monsoon winds, which travel in a southwestern direction from the Atlantic Ocean, opposite to the trajectory of the Harmattan. These two air masses converge to create a fluctuating band referred to as the Intertropical Convergence Zone (ITCZ). The ITCZ is characterized by robust frontal activity. This intricate interplay of air masses plays a pivotal role in determining both the amount and timing of rainfall within the study area.

Datasets

The dataset employed in this study comprises GRACE, CHIRPS, and the Multivariate ENSO Index (MEI). The GRACE dataset was utilized to extract changes in Terrestrial Water Storage (TWS), while CHIRPS was employed to ascertain variations in precipitation patterns. Furthermore, the MEI was utilized to capture climate variability spanning the years 2002 to 2017.

Gravity Recovery and Climate Experiment (GRACE) Satellite

The GRACE satellite, launched on March 17, 2002, is a collaborative project established by the United States of America and Germany. The satellite detects the Earth's gravity fields through the observation of spatio-temporal variations (Tapley et al., 2004). GRACE products are processed and provided by various institutions. This study utilized the GRACE RL-05 Level-3 dataset, featuring a monthly resolution of $1^\circ \times 1^\circ$, which was processed by three distinct laboratories. These laboratories include the Jet Propulsion Laboratory (JPL) situated at the University of Texas-Austin, the Centre for Space Research (CSR), and GeoForschungZentrum (GFZ).

Significant data processing steps, such as error correction for specific spherical harmonics and addressing post-glacial rebound effects, were executed on the GRACE level-3 dataset by researchers at JPL (Pradhan, 2014). The selected dataset employed in this study covers the timeframe from 2002 to 2017. This dataset can be accessed at <http://gracetellus.jpl.nasa.gov/data/get>. The dataset utilized consisted of 178 months, spanning from April 2002 to January 2017, with 21 months missing (as shown in Table 1). The data was presented as a monthly mean and expressed in terms of Equivalent Water Heights (EWH).

Despite its capability to facilitate continuous TWS monitoring, the utility of this dataset is constrained by the desired spatial scale and the extent of variation. This limitation arises from inherent errors in the instrument (i.e., GRACE). Consequently, estimating TWS for smaller areas becomes unfeasible. Studies suggest that, in order to maintain the errors at an insignificant or minimal level, the area of interest should exceed $200,000 \text{ km}^2$ (Rodell, 2000). Hence, in the context of this study with an area of approximately $400,000 \text{ km}^2$, the associated uncertainty (error) amounts to around 0.7 cm EWH at a monthly time interval. Conversely, in an area spanning about $4,000,000 \text{ km}^2$, the error diminishes to 0.3 cm EWH (Swenson et al., 2003).

Climate Hazard Groups Infrared Precipitation with Station (CHIRPS) Data

The rainfall trends within the Volta basin were analyzed using CHIRPS datasets, and these datasets can be accessed from <ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0>. The CHIRPS dataset has found extensive application in hydrological and climate studies, especially in areas with limited availability of ground-based precipitation measurements. Its effectiveness in capturing the spatial and temporal variations of rainfall has been well-established, rendering it appropriate for evaluating climate-related occurrences like droughts, floods, and irregular precipitation patterns. The precision and consistency of CHIRPS data have been confirmed through validation in numerous research efforts.

For instance, a study conducted by Funk et al. (2015) involved a comparison between CHIRPS data and ground-based observations across diverse regions in Africa, including West Africa. The study revealed a strong correlation between the two datasets, further affirming the reliability of CHIRPS data. Another study conducted by Belay et al. (2019) utilized CHIRPS data to evaluate the spatio-temporal variability of rainfall in the data-sparse western margins of the Ethiopian highlands. This study showcased that the effectiveness of the CHIRPS product can exhibit variability at small basin levels, emphasizing its spatial diversity. The results indicate that CHIRPS serves as a valuable tool for informed decision-making in regions where ground-based measurements are limited. It achieves this by offering valuable insights into the spatial and temporal dynamics of rainfall patterns. Consequently, the selection of CHIRPS data for this study is rooted in its demonstrated accuracy, fine resolution, and successful application in comparable studies conducted across various geographical areas.

The CHIRPS dataset is a historical satellite-based precipitation record available from 1981 to the present day. It is accessible in various Geographic Information System (GIS) formats including GeoTiff, NetCDF, and Esri BIL. While the daily data for Africa offers a spatial resolution of $0.05^{\circ} \times 0.05^{\circ}$, the CHIRPS data for other global regions maintains a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$. The datasets exhibit diverse temporal resolutions, ranging from 6 hours to 3 months, and are categorized into three primary spatial domains. These domains

encompass the Global region (7200 x 2000 pixels, spanning 180°W to 180°E and 50°N to 50°S), the Central America-Caribbean region (720 x 350 pixels, ranging from 93°W to 57°W and 23.5°N to 6°N), and the Africa region (1500 x 1600 pixels, encompassing 20°W to 55°E and 40°N to 40°S) (Funk et al., 2015). CHIRPS incorporates an in-house climatology known as CHPclim, along with in-situ station data and high-resolution satellite imagery at a 0.05° resolution. These components collectively generate gridded rainfall time series, facilitating the assessment of trends and the monitoring of drought conditions.

Climate indices

The influence of climatic indices on the Volta basin was evaluated by utilizing the Multivariate ENSO Index (MEI). This index was acquired from <http://www.esrl.noaa.gov/psd/data/climateindices/list>. The Multivariate ENSO Index (MEI) is a climatic index that serves to differentiate and characterize ENSO events. It achieves this by offering both real-time and historical indications of ENSO intensity within a framework of insightful comparative studies of evolving conditions. El Niño-Southern Oscillation constitutes an inter-annual fluctuation that occurs between the atmosphere and ocean systems in the Pacific region.

ENSO exerts a significant influence on global atmospheric circulation, and its effects on climate are highly dependent on the specific region in question. The impact of ENSO on a given region is contingent upon the prevailing season during its occurrence. Furthermore, the spatial distribution and strength of the ENSO phenomenon play a pivotal role in determining its repercussions. Widely regarded as the most substantial climate variability, ENSO exerts substantial influence over various aspects of Earth's climate (Colberg and Reason, 2004; Clark et al., 2003). The Multivariate ENSO Index (MEI) comprises two primary phases: El Niño and La Niña. El Niño is associated with conditions that can lead to droughts, while La Niña is

linked to circumstances that can result in floods. However, the Multivariate ENSO Index (MEI) stands as a comprehensive index that amalgamates both oceanic and atmospheric parameters to provide a unified assessment of ENSO. Additionally, MEI encompasses six additional variables spanning the Pacific, which are integrated with atmospheric anomalies to create a holistic representation (Mazzarella et al., 2013). This index was acquired to align with the study's timeframe (2002 to 2017).

Data Processing

The summary of the methodology employed in this study is presented in the flowchart below (Fig. 2).

Smoothing of the GRACE dataset

Smoothing and moving averages are statistical techniques used as filters to eliminate random and inconsistent fluctuations in raw time series data plots. In this study, this technique was applied to the GRACE dataset to mitigate noise caused by storage signals from the satellite. The process involved filtering out random variations in the datasets to enhance the trend component, thereby improving the visibility of temporal trends in the data. Additionally, research conducted by Landerer and Swenson (2012) indicates that the use of the moving average technique not only aids in estimating the inherent temporal trend within a dataset but also functions as a straightforward forecasting tool.

Linear Interpolation of the GRACE dataset

Studies indicate that the interpolation of missing data in GRACE datasets can introduce uncertainties when utilizing these datasets for hydrological analysis (Dobi et al., 2021; Scanlon et al., 2016; Ouma et al., 2015; Rodell et al., 2007). However, in this study, a linear interpolation technique was employed to fill the gaps in the GRACE datasets. The root mean square error (RMSE) between the original dataset and the interpolated data was 0.06, which demonstrates the degree of agreement between the interpolated and raw data. This finding

underscores the accuracy of the interpolated data employed in the study. Figure 3 illustrates the graph comparing the interpolated and original GRACE datasets.

Data Analysis

Spatio-temporal Trend Analysis for Rainfall and TWS

Rainfall and TWS trends in the Volta basin were evaluated using the Sen's Trend test algorithm. Sen's trend test is rooted in the Mann-Kendall test algorithm, which finds extensive use in statistical assessments of climatological and hydrological trends (Mavromatis and Stathis, 2011). In this study, Sen's trend analysis was conducted with a significance p-value of $\alpha = 0.05$. This technique facilitated the spatial interpolation of the TWS time series, accommodating the 21 months of unaccounted-for GRACE data. To determine the temporal trends of TWS and rainfall, a moving average of 13 months was employed. The selection of a 13-month moving average was guided by the data's monthly periodicity.

Spatio-temporal Variations of Rainfall and TWS

In this study, Independent Component Analysis (ICA) was employed to assess the spatio-temporal variations of both rainfall and TWS across the Volta basin. ICA represents a more advanced statistical technique, building upon the foundation of Principal Component Analysis (PCA). While PCA generates uncorrelated components based on second-order moments of datasets, ICA components are derived independently by minimizing both second-order and higher-order dependencies within the dataset (Elhabian and Farag, 2009).

In this type of analysis, multivariate data is decomposed into independent patterns or signals (Cardoso, 1999; Cardoso and Souloumiac, 1993). Various algorithms with different levels of complexity have been developed for Independent Component Analysis (ICA), one example being the FastICA algorithm (Stone, 2004). FastICA algorithm also described as a neural network (Elhabian and Farag, 2009) was utilized in evaluating the spatio-temporal variations of TWS in the Volta basin. FastICA is a highly efficient algorithm employed for estimating ICA

and separating satellite gravity signals (Hyvärinen and Oja, 2000). It notably outperforms conventional gradient methods for ICA that use a fixed-point iteration technique in terms of speed. The ICA process was determined based on a linear statistical model expressed using vector-matrix notation, as shown in Eq. 1.

$$\mathbf{x} = \mathbf{A}\mathbf{s} \quad \text{Eq. (1)}$$

where A is a combination of P ($N \geq P$), an independent source represented by a source vector (s and x) which are assumed to be observational vectors collected from A sensors

$$x = \begin{bmatrix} x_1 \\ \cdot \\ \cdot \\ \cdot \\ x_n \end{bmatrix} \quad \text{and} \quad s = \begin{bmatrix} s_1 \\ \cdot \\ \cdot \\ \cdot \\ s_n \end{bmatrix} \quad \text{Eq. (2)}$$

$$A = \begin{bmatrix} a_{11} & \cdot & \cdot & a_{1n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ a_{n1} & \cdot & \cdot & a_{nm} \end{bmatrix} \quad \text{Eq. (3)}$$

In this equation, A represents the mixing matrix, where its elements a_{ij} ($1 \leq i \leq N$, $1 \leq j \leq P$) denote the degree to which the j^{th} source contributes to the i^{th} observation (Frappart et al., 2010; Elhabian and Farag, 2009). The central objective of conducting an Independent Component Analysis (ICA) is to estimate the mixing matrix A and its associated source vector (s) (De Lathauwer et al., 2000). The estimations of these matrices are predicated on two fundamental assumptions: (a) the mixing vectors exhibit linear dependence, and (b) the sources possess statistical independence (De Lathauwer et al., 2000). Furthermore, a significant advantage of employing ICA is its ability to localize signals, enabling the concurrent examination of their corresponding climate modes (Ndehedehe et al., 2017).

Spatial Relationship between Rainfall and TWS

A study conducted by Ndehedehe et al. (2016) highlighted that the relationships among multivariate data are ascertained through various approaches across distinct periods. One of the specific objectives of this research was to discern the spatial correlation between rainfall and TWS. To accomplish this, the Pearson correlation coefficient was utilized to assess the strength of agreement between the Independent Components (ICs) model of one field (e.g., rainfall) and the grid point values of another field (e.g., TWS). This evaluation gauges how effectively grid point values and the original dataset can be predicted from the ICs model (Bjornsson and Venegas, 1997).

Results and Discussions

The Spatio-Temporal Trend for Rainfall and its Significance

The trend in rainfall was assessed using the CHIRPS dataset spanning from 2002 to 2016. This timeframe was selected to investigate the influence of rainfall on the TWS. Spatial trend analysis indicated that approximately 40% of the northern part of the basin experienced the highest recorded rainfall of 10 mm, while the southern zone had the lowest recorded rainfall of approximately 5.5 mm (Fig. 4a). A study conducted by Ndehedehe et al. (2017) revealed that seasonal rainfall predominantly occurs in the upper part of the basin, with an average rainfall exceeding 200mm observed between July and September. In contrast, the lower part of the basin experiences a mean rainfall distribution of around 120mm between January and March. These findings align with the results of the rainfall trend observed in this study, where a higher amount of rainfall was noted in the upper section of the catchment. However, the notable trend depicted in Figure 4b illustrates that both the upper and lower parts of the basin exhibit statistical significance at a p-value of less than 0.05. Consequently, even though the southern section of the catchment experiences lower rainfall, it occurs consistently throughout the seasons, unlike the upper Volta River area where rainfall is more sporadic and confined to specific periods (specifically, July-September).

The temporal trend depicted in Figure 5 indicates that the highest peak of rainfall occurred around mid-2007, followed by peaks in 2010 and 2015. Conversely, the lowest levels of rainfall were observed in 2002, 2005, and 2013, respectively. These fluctuations in rainfall might contribute to the negative anomalies observed in Lake Volta. This finding aligns with the study by Ndehedehe et al. (2017b) which proposes the existence of a coherent cycle lasting 4 to 5 years between the dry and wet seasons of the Volta basin. The same research also highlights that the reduced amplitudes of Akosombo discharge were influenced by decreased streamflow from the Oti River and White Volta River due to lower levels of recorded rainfall.

The Spatio-Temporal Trend of TWS and its Significance

The spatial distribution of TWS reveals higher values in the upper part of the Volta basin, while the lower part exhibits the lowest values (Fig. 6a). To facilitate standardization, an average unit was employed to analyze the spatial distribution of rainfall and TWS within the Volta Basin, as demonstrated in Fig. 6a and Fig. 4a. The reduced TWS observed in the lower part of the basin could be attributed to factors such as geology, the amount of rainfall (Fig. 5), and groundwater potential (Fig. 7).

The statistical significance encompassed the entire basin, with a p-value less than 0.05, and notably elevated significance was noted around the Volta Lake (Fig. 6b). The presence of the aquifer system combined with the impact of the Akosombo dam causing impoundment of water in the Lake contributed to the heightened significance level observed. This suggests that the Lake not only affects TWS signals but also influences other hydrological indicators within the catchment.

Recent studies by Ndehedehe et al., (2016) have highlighted that despite the notable decline in rainfall amplitudes, leading to severe hydrological drought in the basin, there was a substantial increase in TWS around Lake Volta during these periods. Numerous researchers attribute this heightened signal around Lake Volta to the water impoundment induced by the Akosombo dam (Moore and Williams, 2014). Notably, spikes were observed around 2010

and 2012, as depicted in the TWS temporal trend as shown in Figure 8. These spikes subsequently diminished between 2011 and 2016. These occurrences have been associated with La Niña events that transpired during those timeframes, contributing to the elevated amplitudes of TWS (Paeth et al., 2011). Consequently, these fluctuations in TWS resulting from rainfall variations can potentially influence streamflow dynamics, consequently impacting crucial activities such as hydroelectric generation, agriculture, and more, within the basin.

Spatio-Temporal Variations of Rainfall

The initial mode, IC1 (depicted in Figure 9a), exhibits notably high spatial variability across a substantial portion of the basin, particularly within the upper section of the catchment. This region serves as the source for the primary river tributaries, namely the Black Volta River, the White Volta River, and the Oti River. These variations are propelled by the annual climatic variabilities of rainfall, as illustrated in Figure 9b.

The second mode (illustrated in Figure 10a) exhibited pronounced spatial variability primarily centered around Mali, with smaller patches present in certain areas of Burkina Faso and Ghana. Like the first mode, these variations in the second mode are influenced by the annual climatic variability of rainfall, as depicted in Figure 10b.

The third mode, as depicted in Figure 11, prominently displayed a robust signal situated in the southern segment of the basin, spanning from the northeastern region of Ghana to parts of Togo and Benin, which includes the headwater of the lower Volta. This pattern of rainfall variability observed within these areas exhibited a quarterly occurrence.

The rainfall modes represented in Figures 9, 10, and 11 accounted for variances of 44%, 32%, and 13%, respectively, from the cumulative variance. Areas exhibiting diminished rainfall levels suggest a propensity for aridity in those regions. Additionally, as highlighted by Ndehedehe et al. (2016), a multitude of factors contribute to the temporal variations in rainfall

across the Volta basin. These factors encompass annual cycles of rainfall, climatic teleconnections, the influence of West African Monsoon rainfall, and the impact of ocean warming originating from the Coast of Guinea and extending to the central Sahel regions.

Spatio-Temporal Variations of TWS

The first mode of TWS (depicted in Fig. 12a) exhibited a notable spatial variability in the southeastern region of the catchment. This variability is a consequence of annual rainfall fluctuations across the entire basin, as illustrated in Fig. 12b. In contrast, the second mode (Fig. 13a) demonstrated spatial variability encompassing the southwestern and upper parts of the Volta basin. This variability is influenced by both inter-annual rainfall fluctuations and the presence of a tropical forest in the sub-humid area of the lower basin, as shown in Fig. 13b. The third mode (Fig. 14a) displayed spatial variation in the lower region of the basin, particularly around Volta Lake. This analysis indicates that beyond the influences of annual and inter-annual rainfall variations (as seen in Fig. 14b), the hydrological signals around the lake are also influenced by the presence of adjacent wetlands and water bodies.

This result aligns with the findings of the study by Ndehedehe et al. (2017), which similarly identified a pronounced hydrological signal around Volta Lake in its IC2 analysis. Consequently, they concluded that alterations in the TWS within the basin were attributed to the substantial contribution of the Volta River system, which relies on various small reservoirs, wetlands, and coastal river tributaries.

The analysis also revealed that while there were prominent signals detected in the northern region of the catchment, fewer signals were recorded in terms of TWS. This phenomenon could be attributed to the elevated evaporation rate occurring in the upper parts of the basin, driven by the high temperatures prevalent in those areas, particularly towards the Sahel regions. These elevated temperatures could stem from factors such as extensive deforestation, occurrences of bushfires, and the arid nature of the region.

Furthermore, the undulating topography of the basin could be another contributing factor to the elevated TWS signals observed. This topographical characteristic facilitates the movement of water from the upstream regions to the downstream areas, eventually reaching the ocean. Additionally, the construction of artificial lakes for purposes such as hydropower generation and irrigation, exemplified by the Bui, Akosombo, and Aval Bagre dams, has the effect of impounding surface water and promoting infiltration. Consequently, this could result in heightened groundwater recharge in proximity to the dam sites (Ndehedehe et al., 2016).

Furthermore, anthropogenic activities like groundwater extraction could contribute to the reduction in recorded TWS, especially in the northern region of the basin. Additionally, a significant factor affecting TWS within the Volta basin is the substantial contribution of water flow from the Black and White Volta River systems into the Volta Lake. This contribution amounts to about 30% of the total annual flow. Moreover, the flow from the Lower Volta River and Oti River also contributes to the annual flow into the Volta Lake. These combined factors have implications for the TWS variations observed in the basin (Barry et al., 2005). During periods of heavy rainfall, high flows drain from these tributaries into Volta Lake. However, a reduction in streamflow and baseflow recessions into the lake, even when there is no decline in rainfall, can be attributed to the increased irrigation schemes upstream where these main rivers are sourced for agricultural purposes (Ndehedehe et al., 2017b).

Relationship Analysis

Relationship between Rainfall variations and TWS

Precipitation is believed to be one of the most vital climatic factors influencing TWS variations. Volta basin consists of a large area and is located in the semiarid and subhumid region of low slope such that evaporation is very high. The estimated GRACE-TWS patterns in Fig. 8, reveal increased TWS in the study area between 2003 and 2003 as well as between 2006 and 2010, at a rate of 47.8 mm/year and 25.3 mm/year respectively. The increase in the TWS between 2002 and 2003 could be attributed to the increase in total annual rainfall

within the period (Fig. 5). However, between 2006 and 2010, rainfall did not show significant increase which will warrant a TWS surge, therefore the increase in TWS between from 2006 to 2010, could be attributed to a reduction in evaporation. Between 2003 and 2006, and between 2012 and 2016, TWS variations depicted reductions at a rate of 9.5 mm/year and 20.2 mm/year respectively. These could be attributed to the reduction in the annual rainfall amount within the periods (Fig. 5), as well as increase in the evaporation. Also, the trend of the spatial distributions of both GRACE-TWS and CHIRPS rainfall (Fig. 4a and 6a) are similar, they are all increasing northwards, which reveals that rainfall affects TWS.

The Spatial Relationship between Rainfall ICs and TWS

The relationship between Rainfall IC1 and the original TWS dataset was correlated to determine the existing relationship between them. The analysis revealed a strong correlation in the upper parts of the basin, while the least correlation was observed in the lower part of the basin (Fig. 15). This strong correlation is attributed to the prominent annual signal recorded in the spatial pattern of Rainfall IC1 in (Fig. 11a), indicating that TWS in these areas is dependent on annual rainfall variability.

In terms of Rainfall IC2, and TWS, a higher correlation was observed in the central parts of the basin (i.e., Burkina Faso, Ghana, Benin and Togo), with a weak correlation in the lower and upper parts of the basin (Fig. 16). The central part of the basin recording a higher correlation may not necessarily be attributed to the interannual rainfall but rather the impoundment of water from nearby dams (i.e., Bui, and Bagre) causing an increase in the signal of the TWS in these areas.

Furthermore, the correlation between Rainfall IC3 and the TWS dataset was recorded to be high in the entire lower basin (Fig. 17). This is attributed to the interannual rainfall variability recorded around the Volta Lake as seen in (Fig. 11), aside from the wetlands, the coastal rivers, and the tropical forest that influences the TWS within these areas.

Impact of ENSO on the Volta Basin

The wetter conditions experienced in the basin from 2007 as shown in (Fig. 5) were induced by external climatic events such as La Niña. This rising trend in TWS is in line with the increasing trend in rainfall observed (Fig. 8). Studies by Crowley et al., (2008) state that, the La Niña event that occurred in 2007 caused a major flood which affected the whole of West Africa. In addition, this ENSO event recorded in the MEI (Fig. 18) induced a higher wet condition in the latter part of 2010. Despite the increased rainfall recorded, there was a spike in the drought between 2015 and 2016 due to El Niño which studies show that it also influenced the variability of the TWS in the basin. The effect of this phenomenon indirectly led to food insecurity in most parts of the infringing countries within the basin. For example, in Ghana, there were severe power outages faced by the country from 2015 to 2016 and this was attributed to the limited water flow into the Akosombo hydropower dam. However, these results indicate that the occurrence of these two climate indices (El Niño, and La Niña) affected water storage in the Volta basin.

Conclusions

The spatio-temporal variations of TWS and the impact of climate variability on the Volta basin from 2002 to 2017 were analysed using the Sen's Trend Test, ICA and Climate index. The outcome of the analysis is to help the efficient management of regional water resources and provide a basis for effective transboundary water-sharing discussions.

Conclusions drawn from this study include the fact that the upper part of the basin recorded a higher spatial rainfall trend with the lower part recording the least amount of rainfall trend. These were tested at a p-value of 0.05 and they both were statistically significant. In terms of the TWS, a greater portion of the basin showed relatively strong spatial variability driven by interannual climatic variations. Also, the highest TWS signal was observed around the Volta Lake and this is attributed to several factors such as; the rainfall variability, the type of geology,

and the coastal river bodies within these areas. This shows that Volta Lake has a great influence on the TWS, therefore it must be considered if one is interested in estimating the groundwater variations, and drought characterization.

Also, in terms of the correlation between rainfall ICs and TWS, rainfall mode 1 showed a strong correlation in the upper parts of the basin while mode 2 showed a higher correlation in the central parts. Mode 3 on the other hand recorded a higher correlation towards the entire lower basin. This correlation analysis showed that aside from rainfall variability, the TWS of the basin is influenced by the surrounding coastal rivers, wetlands, tropical forests, and impoundment from dams. Furthermore, the wetter conditions experienced in the basin in 2007 were because of the occurrence of the La Niña event and the dry condition between 2015 and 2016 was due to the severe El Niño experienced. These climatic events experienced have led to some parts of the basin especially Ghana, facing severe flooding and drought incidences resulting in power crises and increased food insecurity. This proves that variations in the rainfall patterns as a result of climate change will affect the Volta basin, therefore, the need for immediate and sustainable actions to preserve and protect the resources of the basin.

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Data Availability Data and material can be provided on request.

Code availability Not applicable

Declarations

Competing interests, The authors declare no competing interests.

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References

Ahmed, A., Lawson, E.T., Mensah, A., Gordon, C. and Padgham, J., (2016). Adaptation to climate change or non-climatic stressors in semi-arid regions? Evidence of gender differentiation in three agrarian districts of Ghana. *Environmental Development*, 20, 45-58.

Ahmed, M. Sultan, M. Wahr, J. and Yan, E., (2014). The use of GRACE data to monitor natural and anthropogenic induced variations in water availability across Africa. *Earth-Science Reviews*, 136, 289–300.

Awange, J. L. Anyah, R. Agola, N. Forootan, E. and Omondi, P., (2013). Potential impacts of

529 climate and environmental change on the stored water of Lake Victoria Basin and
 530 economic implications. *Water Resources Research*, 49, 8160–8173.

531 Awange, J. L. Ferreira, V. G. Forootan, E. Andam-akorful, S. A. and Agutu, N. O., (2016).
 532 Uncertainties in remotely sensed precipitation data over Africa. *International Journal of*
 533 *Climatology*, 36, 303–323.

534 Awange, J. L. Forootan, E. Kuhn, M. Kusche, J. and Heck, B., (2014). *Advances in Water*
 535 *Resources* Water storage changes and climate variability within the Nile Basin between
 536 2002 and 2011. *Advance Water Resources*, 73, 1–15.

537 Awotwi, A., Anornu, G.K., Quaye-Ballard, J.A., Annor, T., Nti, I.K., Odai, S.N., Arhin, E. and
 538 Gyamfi, C., (2021). Impact of post-reclamation of soil by large-scale, small-scale and
 539 illegal mining on water balance components and sediment yield: Pra River Basin case
 540 study. *Soil Tillage Research*, 211, 105026.

541 Awotwi, A., Kumi, M., Jansson, P.E., Yeboah, F. and Nti, I.K., (2015). Predicting hydrological
 542 response to climate change in the White Volta Catchment, West Africa. *Journal of Earth*
 543 *Science Climate Change*, 6, 249.

544 Barry, B. Obuobie, E. Andreini, M. Andah, W. and M., P., (2005). *The Volta River Basin.*
 545 *Comprehensive assessment of water management in agriculture - Comparative study of*
 546 *river basin development and management.* Colombo, Sri Lanka: International Water
 547 *Management Institute (IWMI).*

548 Belay, A. S. Fenta, A. A. Yenehun, A. Nigate, F. Tilahun, S. A. Moges, M. M. and Walraevens,
 549 K. (2019). Evaluation and Application of Multi-Source Satellite Rainfall Product CHIRPS
 550 to Assess Spatio-Temporal Rainfall Variability on Data-Sparse Western Margins of
 551 Ethiopian Highlands. *Remote Sensing*, 11(22), 2688.

552 Bjornsson, H. and Venegas, S. A., (1997). *A Manual for EOF and SVD Analyses of Climatic*
 553 *Data.* McGill University.

554 Boakye, E.A., Gebrekirstos, A., Hyppolite, D., Barnes, V.R., Kouamé, F.N., Kone, D.,

555 Porembski, S. and Bräuning, A., (2016). Influence of climatic factors on tree growth in
556 riparian forests in the humid and dry savannas of the Volta basin, Ghana. *Trees*, 30(5),
557 1695-1709.

558 Cardoso, J. F., (1999). High-order contrasts for independent component analysis. 11, 157–192.

559 Cardoso, J.F. and Souloumiac, A., 1993, December. Blind beamforming for non-Gaussian
560 signals. In *IEE proceedings F*, 140(6), 362-370).

561 Clark, C.O., Webster, P.J. and Cole, J.E., (2003). Interdecadal variability of the relationship
562 between the Indian Ocean zonal mode and East African coastal rainfall anomalies. *Journal*
563 *of Climate*, 16(3), 548-554.

564 Colberg, F., Reason, C.J.C. and Rodgers, K., (2004). South Atlantic response to El Niño–
565 Southern Oscillation induced climate variability in an ocean general circulation model.
566 *Journal of Geophysical Research: Oceans*, 109(C12).

567 Crowley, J.W., Mitrovica, J.X., Bailey, R.C., Tamisiea, M.E. and Davis, J.L., (2008). Annual
568 variations in water storage and precipitation in the Amazon Basin. *Journal of Geodesy*,
569 82(1), 9-13.

570 De Lathauwer, L., De Moor, B. and Vandewalle, J., (2000). An introduction to independent
571 component analysis. *Journal of Chemometrics: A Journal of the Chemometrics Society*,
572 14(3), 123-149.

573 Dobi, F.B., Kouakou, E.K., Nazoumou, Y., Abdou Boko, B., Edimo, S.N., Maina, F.Z. and
574 Konaté, M., 2021. Aquifer Depletion in the Arlit Mining Area (Tim Mersoï Basin, North
575 Niger). *Water* 13, 1685

576 Elhabian, S. and Farag, A., (2009). A Tutorial on Data Reduction: Independent Component
577 Analysis (ICA).

578 Ferreira, V.G., Gong, Z. and Andam-Akorful, S.A., (2012). Monitoring mass changes in the
579 Volta River basin using GRACE satellite gravity and TRMM precipitation. *Boletim de*
580 *Ciências Geodésicas*, 18, 549-563.

581 Ferreira, Vagner G. Asiah, Z. Xu, J. Gong, Z. and Andam-Akorful, S. A., (2018). Land Water-
582 Storage Variability over West Africa: Inferences from Space-Borne Sensors. *Water*,
583 10(4), 380.

584 Frappart, F., Ramillien, G., Leblanc, M., Tweed, S.O., Bonnet, M.P. and Maisongrande, P.,
585 (2011). An independent component analysis filtering approach for estimating continental
586 hydrology in the GRACE gravity data. *Remote Sensing of Environment*, 115(1), 187-204.

587 Funk, C. Peterson, P. Landsfeld, M. Pedreros, D. Verdin, J. Shukla, S. Husak, G. Rowland, J.
588 Harrison, L. Hoell, A. and Michaelsen, J., (2015). The climate hazards infrared
589 precipitation with stations - A new environmental record for monitoring extremes.
590 *Scientific Data*, 2, 1–21.

591 Ghazouani, T. and Beldi, L., (2022). The impact of income inequality on carbon emissions in
592 Asian countries: non-parametric panel data analysis. *Environmental Modeling &*
593 *Assessment*, 27(3), 441-459.

594 Gordon, C. Nukpezah, D. Tweneboah-Lawson E., Ofori, B. D. Yirenya-Tawiah, D. Pabi, O.
595 and Mensah, A. M., (2017). West Africa? Water Resources Vulnerability Using a
596 Multidimensional Approach: Case Study of Volta Basin.

597 Gyau-Boakye, P. and Dapaah-Siakwan, S., (2000). Groundwater is a source of rural water
598 supply in Ghana. *Journal of Applied Science and Technology*, 5(1), 77-86.

599 Hanjra, M. A. and Qureshi, M. E., (2010). Global water crisis and future food security in an
600 era of climate change. *Food Policy*, 35(5), 365–377.

601 Hyvärinen, A. and Oja, E., (2000). Independent Component Analysis: Algorithms and
602 Applications. *Neural Networks*, 13, 411–430.

603 Landerer, F. W. and Swenson, S. C., (2012). Accuracy of scaled GRACE terrestrial water
604 storage estimates. *Water Resources Research*, 48(4).

605 Martin, N., (2005). Spatial distribution of groundwater production and development potential
606 in the Volta River basin of Ghana and Burkina Faso. *Water International*, 30(2), 239–249.

607 Mavromatis, T. and Stathis, D., (2011). Response of the water balance in Greece to temperature
608 and precipitation trends. *Theoretical and Applied Climatology*, 104(1), pp.13-24.

609 Mazzarella, A., Giuliacci, A. and Scafetta, N., (2013). Quantifying the Multivariate ENSO
610 Index (MEI) coupling to CO₂ concentration and the length of day variations. *Theoretical*
611 *and Applied Climatology*, 111(3), 601-607.

612 McMichael, A.J. and Lindgren, E., (2011). Climate change: present and future risks to health,
613 and necessary responses. *Journal of internal medicine*, 270(5), 401-413.

614 Moore, P. and Williams, S. D. P., (2014). Integration of altimetric lake levels and GRACE
615 gravimetry over Africa: Inferences for terrestrial water storage change 2003–2011. *Water*
616 *Resources Research*, 50(12), 9696–9720.

617 Mul, M. Obuobie, E. Appoh, R. K. and Kwabena Kanka, Y., (2015). *Water Resources*
618 *Assessment of the Volta River Basin* International Water Management Institute IWMI
619 *Working Paper*.

620 Mutai, C.C., Ward, M.N. and Colman, A.W., (1998). Towards the prediction of the East Africa
621 short rains based on sea-surface temperature–atmosphere coupling. *International Journal*
622 *of Climatology: A Journal of the Royal Meteorological Society*, 18(9), 975-997.

623 Ndehedehe, C. Awange, J. Agutu, N. Kuhn, M. and Heck, B., (2016). Understanding changes
624 in terrestrial water storage over West Africa between 2002 and 2014. *Advance Water*
625 *Resources*, 88, 211–230.

626 Ndehedehe, C. E. Awange, J. L. Corner, R. J. Kuhn, M. and Okwuashi, O., (2016). On the
627 potentials of multiple climate variables in assessing the spatio-temporal characteristics of
628 hydrological droughts over the Volta Basin. *Science of the Total Environment*, 557, 819–
629 837.

630 Ndehedehe, C.E., Awange, J.L., Kuhn, M., Agutu, N.O. and Fukuda, Y., (2017). Analysis of
631 hydrological variability over the Volta River basin using in-situ data and satellite
632 observations. *Journal of Hydrology: Regional Studies*, 12, 88-110.

- Okafor, G., Annor, T., Odai, S., & Agyekum, J. (2019). Volta basin precipitation and temperature climatology: evaluation of CORDEX-Africa regional climate model simulations. *Theoretical and Applied Climatology*, 137(3), 2803-2827.
- Paeth, H. Fink, A. H. Pohle, S. Keis, F. Mächel, H. and Samimi, C. (2011). Meteorological characteristics and potential causes of the 2007 flood in sub-Saharan Africa. *International Journal of Climatology*, 31(13) 1908–1926.
- Pradhan, G.P., (2014). Understanding interannual groundwater variability in North India using GRACE (Master's thesis, University of Twente).
- Rodell, M. Chen, J. Kato, H. Famiglietti, J. S. Nigro, J. and Wilson, C. R. (2007). Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE. *Hydrogeology Journal*, 15, 159–166.
- Rodell, M. (2000). *Estimating Changes in Terrestrial Water Storage*. The University of Texas at Austin.
- Scanlon, B. R. Zhang, Z. Save, H. Wiese, D. N. Landerer, F. W. Long, D. and Chen, J. (2016). Global evaluation of new GRACE mascon products for hydrologic applications. *Water Resources Research*, 52(12), 9412–9429.
- Skoulikaris, C., Makris, C., Katirtzidou, M., Baltikas, V. and Krestenitis, Y., (2021). Assessing the vulnerability of a deltaic environment due to climate change impact on surface and coastal waters: The case of Nestos River (Greece). *Environmental Modeling & Assessment*, 26(4), 459-486.
- Stone, J. V. (2004). *Independent Component Analysis: A Tutorial Introduction*, MIT Press: Bradford Book.
- Swenson, S. Wahr, J. and Milly, P. C. D. (2003). Estimated accuracies of regional water storage variations inferred from the gravity recovery and climate experiment (GRACE). *Water Resources Research*, 39(1223).
- Tapley, B.D., Bettadpur, S., Watkins, M. and Reigber, C., (2004). The gravity recovery and

659 climate experiment: Mission overview and early results. *Geophysical research letters*,
660 31(9).

661 Tschakert, P., (2007). Views from the vulnerable: understanding climatic and other stressors
662 in the Sahel. *Global Environmental Change*, 17(3-4), 381-396.

663 Twerefou, D. K. Adjei-Mantey, K. and Strzepek, N. L. (2014). The economic impact of climate
664 change on road infrastructure in sub-Saharan Africa countries: Evidence from Ghana (No.
665 2014/032). WIDER Working Paper.

666 Ouma, Y.O., Aballa, D.O., Marinda, D.O., Tateishi, R. and Hahn, M. (2015). Use of GRACE
667 time-variable data and GLDAS-LSM for estimating groundwater storage variability at
668 small basin scales: A case study of the Nzoia River Basin. *International Journal of Remote*
669 *Sensing* 36, 5707–5736.

670 Welling, R. Cartin, M. Baykono, D. and Diallo, O. (2010). Volta River Basin Ghana & Burkina
671 Faso: Transboundary water management through multi-level participatory governance
672 and community projects.

673 Yidana, S.M., Vakpo, E.K., Sakyi, P.A., Chegbeleh, L.P. and Akabzaa, T.M., (2019).
674 Groundwater–lakewater interactions: an evaluation of the impacts of climate change and
675 increased abstractions on groundwater contribution to the Volta Lake, Ghana.
676 *Environmental Earth Sciences*, 78(3), 1-16.