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Estimating Long-Term Groundwater Storage Change in the Chad Basin, Nigeria, Using GRACE/GRACE-FO and GLDAS Terrestrial Water Storage Anomalies

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Abstract

The Chad Basin is the main source of fresh water to over 30 million people in the semi-arid Sahel region, and long-term evaluation of groundwater resources is crucial for sustainable abstraction of fresh water, water security for the region, and humanitarian resilience. Using the GRACE/GRACE-FO satellite gravimetry and GLDAS land surface modelling, this study was used to assess the hydrological variations in one of the least data-rich and most water-drafted transboundary basins in the world. Results show an important hydrogeological paradox. The overall trend in the basin-scale water mass, as revealed by Total Water Storage Anomaly (TWSA), is a strong increase of +5.91 mm/year ($R^2 = 0.70$). However, recoverable water components are diminishing, with surface water, soil moisture, and Groundwater Storage Anomaly (GWSA) decreasing at −1.04, −1.02, and 0.02 mm/year, respectively. This means that a higher absolute amount of water stored does not necessarily lead to an increase in groundwater recharge, probably because of high evaporation, extraction pressures, and hydrogeological conditions. Spatial analysis also reveals areas of critical groundwater depletion along the western boundary of the basin, especially across the northeastern part of Nigeria, where groundwater extraction is high. Rainfall trends are weak (+1.65 mm/year) and not significantly correlated with groundwater storage ($r = -0.176$), indicating that recharge efficiency to the deep aquifers is poor. The overall conclusion is that the anthropogenic pressures on water scarcity are growing, and the use of evidence-based transboundary governance, regulation of groundwater abstraction, and targeted Managed Aquifer Recharge strategies is needed.
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1. Introduction

Remote sensing is used for a wide range of applications in agriculture, forestry, and the documentation of landscape changes, as well as in hydrology, which is closely linked to the aforementioned fields (Schultz, G.A, Engmann, E.T 2000, Raeva, Pavelka jr., 2020). Chad Basin is an endorheic drainage basin of Africa, which covers Nigeria, Chad, Cameroon, and Niger with an area of approximately 2.4 million km 2 and a population of more than 30 million (Lemoalle et al., 2012; Coe and Foley, 2001). It is also hydrologically sensitive despite its size, with low and extremely variable rainfall, high evapotranspiration, and decreasing surface water, with the most notable example of Lake Chad having lost more than 90% of its surface area since the 1960s as a result of lower inflows via the Chari-Logone system and human extraction (Lemoalle and Magrin, 2014; Rodell et al., 2018). Hydrological stress factors have been exacerbated by climate variability, diminished precipitation, and groundwater abstraction, which pose a threat to water security, food production, and ecosystem resilience (Buma et al., 2022; Mahmood et al., 2020). The rising groundwater use rate has contributed to the exploitation of both the Quaternary and Pliocene aquifers of the Chad Formation, which causes the sub-basin groundwater reduction (Goni et al., 2015; Mohamed et al., 2023). This data-sparse area can be evaluated on terrestrial and groundwater storage anomalies with the support of satellite gravimetry concepts such as GRACE/GRACE-FO and GLDAS (Tapley et al., 2019; Rodell et al., 2018; Li et al., 2022; Save et al., 2016). The paper will utilize the data to determine the long-term groundwater changes and water management and climate change adaptation using GRACE/GRACE-FO mascon (2002-2024) and GLDAS, trend analysis, and correlation of precipitation.

1.1 Study Area

The Chad Basin (Figure 1) is in the heart of Africa, and its extension is roughly between 6.00°N and 24.00°N latitude and 8.00°E and 24.00°E longitude. It occupies the basin parts of the countries, namely Chad, Nigeria, Niger, and Cameroon, and covers an area of approximately 2.4 million square kilometres.

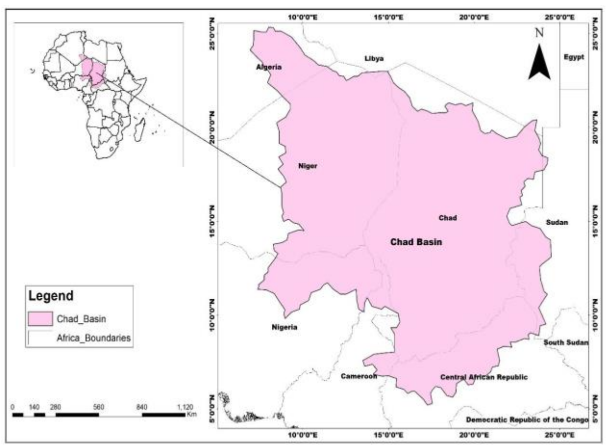

Figure 1. Study area map (Chad basin).

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The basin flows inwardly in the direction of Lake Chad, which is located close to the centre at about 13.00°N latitude and 14.00°E longitude. The relief of the region is mainly characterized by a gently undulating plain of low heights varying from 200 to 500 meters above sea level. However, the place is experiencing a hefty list of problems, like water levels going down, desertification, and climate change, causing hydrological stress.

2. Research Methodology

2.1 Data Sources and Description

Multi-sensor and gridded data sets, which were accessible in Earth observation archives, were used in the analysis. The selected datasets will cover the last 22 years (2002-2024), which intersect both in terms of time coverage and space representation (Table 1).

2.2 Data Collection and Preprocessing

The proposed study used a combined geospatial and statistical method to determine the spatio-temporal variability and relationship of principal hydrological elements of the Chad Basin between 2002 to 2024. It was analysed with the help of satellite-derived data on rainfall, total water storage anomaly (TWSA), surface water storage, and groundwater storage anomaly (GWSA) on the Google Earth Engine (GEE) platform, ArcGIS, and Python (Jupyter Lab). The workflow consisted of several steps.

2.2.1 Satellite data.

Data Type	Sensor/ Products	Source	Temp. Res.	Spatial Res.	Variable Used
Rainfall	CHIRPS v2.0	Climate Hazards Group (UCSB)	Monthly	5 km	Rainfall /mm/ month)
Total Water Storage Anomaly (TWSA)	GRACE /GRACE-FO	NASA JPL	Monthly	110 km	TWSA (cm conv. to mm)
Suraface Water and Soil Moisture	GLDAS-NOAH v2.1	NASA GSFC Hydrology Lab	Monthly	25 km	Surface Water (mm)
Ground-water Storage Anomaly (GWSA)	Derived (GRACE-GLDAS)	Computed in GEE	Monthly	25 km	GWSA (mm)

Table 1. Datasets used

2.2.2 Data Preprocessing in Google Earth Engine (GEE)
All the satellite data was pre-processed and integrated on the Google Earth Engine (GEE) cloud-computing platform, as it works best with large geospatial data sets.

2.2.3 Region of Interest (ROI)
The study area of Chad, Nigeria, Niger, and Cameroon was overlaid as a Feature Collection Geometry on GEE as a polygon of the Chad Basin.

2.2.4 Data Filtering and Masking
All sets of data were filtered in time, from 1 January 2002 to 31 December 2024. Missing or invalid pixels (NaN or negative value) were masked, conforming to quality control.

2.2.5 Unit Conversion
GRACE TWSA was converted from centimeters to millimeters. Variables of GLDAS (e.g., soil moisture and canopy water) were transformed into the water height in millimeters of equivalent water.

2.2.6 Derivation Groundwater storage anomaly (GWSA)
GRACE TWSA in terms of GLDAS surface water and soil moisture was computed: the difference between the surface water and the soil moisture was the residual used to compute groundwater storage:
GWSA=TWSA−SW−SM, and SW and SM are the surface water and the soil moisture, respectively.

2.2.7 Temporal Aggregation
The monthly images were added up in annual means using ee.ImageCollection.reduce(ee.Reducer.mean) on a yearly basis. This permitted consistency in time with the annual statistical analysis.

2.2.8 Export Map and Visualization
The visualisation of annual rainfall, TWSA, surface water, and GWSA in GEE with the assistance of the same colour pallets was exported as GeoTIFF files to further process as cartographs in ArcGIS.

2.2.9 Spatial Analysis and Mapping in ArcGIS
The raster output of GEE was input to ArcGIS Pro 3.x, and spatial analysis and visualization of the output were conducted, and a layout was created.

2.2.10 Projection
All rasters were reprojected to the WGS 1984, so they are all in the same spatial reference.

2.2.11 Hydrological Mapping
Composites (i.e., 2002-2008, 2009-2015, 2016-2024) were calculated on an annual and decadal basis to show the change in space.

2.2.12 Spatial Statistics
The Raster Calculator tool and Zonal Statistics tool was applied to compute each variable in basin-wide mean on a yearly basis.

2.2.13 Cartographic Representation
Thematic maps were created, which revealed the spatio-temporal differences in rainfall, surface water, TWSA, and GWSA. The positive and negative anomalies were represented by colour scales divergence (blue - brown).

2.2.14 Temporal Analysis and Statistical Processing in Jupyter Lab
The data in the CSV format of the values of the annual mean of the yearly mean of the results were processed in Python (Jupyter Lab) using the assistance of the Pandas, NumPy, Matplotlib, and SciPy libraries. The main steps included:

2.2.15 Data Integration
The data in the four CSVs was merged into a single DataFrame (where Year (2002-2024) is the key).

2.2.16 Annual Trend Visualization

Using markers and regression trendlines, there were line plots of each variable (that is, Rainfall, Surface Water, TWSA, and GWSA) and regression trendlines. The slope of each of the trendlines was estimated using the least-squares regression method, and the coefficient of determination (R2) was presented to quantify the trend.

2.2.17 Correlation Analysis

To establish the intensity and direction of correlation, pair-wise correlation was calculated using the Pearson correlation coefficient (r) among all the hydrological components.

2.2.18 Rainfall-Groundwater Interaction

Scatter plots were drawn to show how rainfall and groundwater storage were linear to indicate statistical significance, and regression equations, R^2, and p-values were attached.

2.2.19 Temporal Sampling

The gaps between the X-axis points were adjusted at two-year intervals (2002, 2004..., 2024) to ensure that there is equal readability between the plots.

2.3 Validation and Accuracy Checks

To be able to reduce data and methodological errors:

- GRACE and GLDAS temporal overlaps were checked to ensure that there is always consistent monthly coverage.
- Spatial accuracy of the water storage anomalies was confirmed by visual comparison of the GEE maps of the exports with the data portal of NASA.
- GEE reducer statistical outputs were compared to Python calculations to reduce rounding or conversion errors.

3. Results

The results of the spatial and temporal analysis of water storage components and precipitation within the Chad Basin for the period 2002-2024 are detailed in this section (Table 2). The findings reflect the satellite-derived datasets that were processed in Google Earth Engine and visualized in ArcGIS to expose the patterns and trends in total water storage, groundwater storage, surface water, and precipitation in the basin.

Year	Rainfall mm	Surface _mm	TWSA _mm	GWSA_ mm
2002	622.8644	433.3662	6.788944	-420.075
2003	636.2226	437.2966	4.433898	-421.614
2004	604.6205	434.5163	-7.68945	-431.353
2005	621.4758	435.6838	-2.8521	-431.209
2006	658.6936	439.168	-3.78222	-434.788
2007	626.0884	438.6273	3.768971	-427.83
2008	626.9734	436.8599	8.503296	-425.475
2009	614.082	426.8261	0.415745	-431.465
2010	672.5849	434.5585	11.24811	-424.471
2011	618.0863	423.7138	11.99484	-415.844
2012	682.8266	431.31	22.91593	-411.066
2013	580.1028	433.4064	23.43575	-401.346
2014	589.7921	427.1838	44.34915	-398.624
2015	583.068	415.5384	14.95698	-421.711
2016	626.933	400.9614	21.01892	-431.546
2017	604.287	380.1482	-13.9729	-431.86
2018	663.8664	384.7945	59.77715	-434.56
2019	697.6142	406.3826	66.52398	-427.824
2020	657.1455	432.9412	91.45929	-426.475
2021	638.0133	425.9673	90.89935	-431.016
2022	656.5505	433.9045	116.7145	-422.987
2023	656.5189	428.5472	134.5485	-418.587
2024	678.1355	426.4621	144.5581	-407.075

Table 2. Water storage results

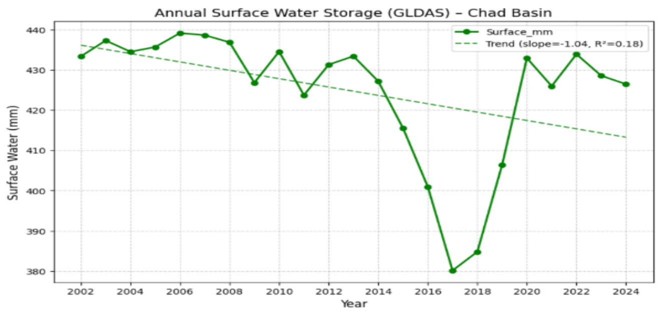

Figure 2. Chad Basin Rainfall chart

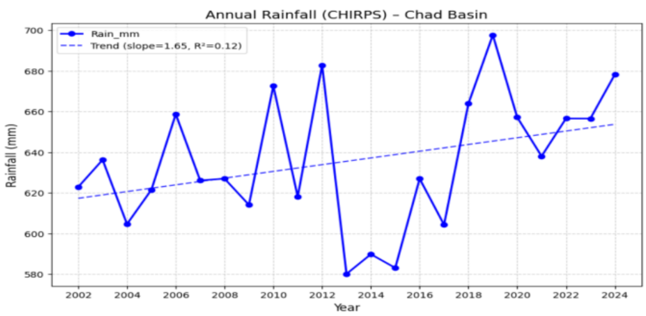

Figure 3. Surface water/ soil moisture storage Chart of the Chad Basin

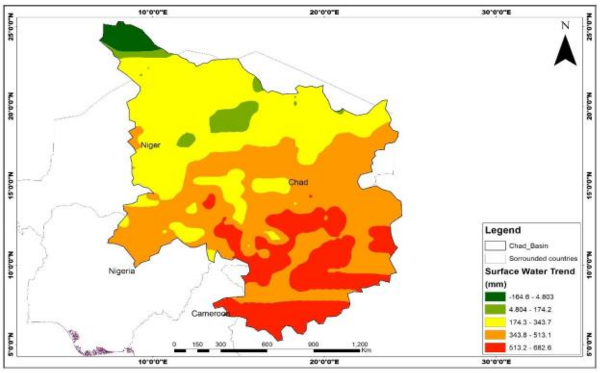

Figure 4. Surface water/ soil moisture map of Chad Basin

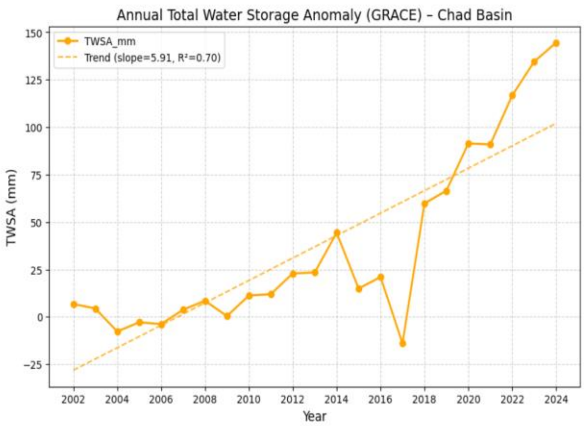

Figure 5. Total Water Storage Anomaly Chart of Chad Basin

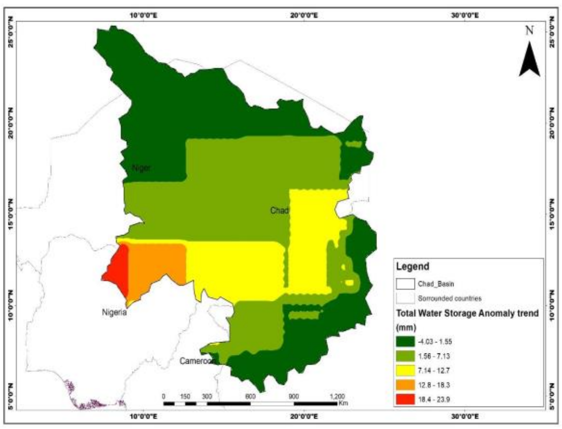

Figure 6. Total Water Storage Map of Chad Basin

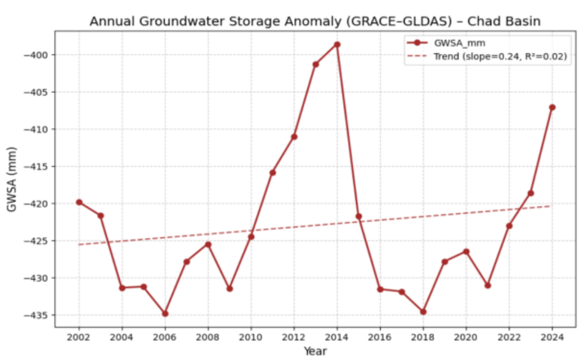

Figure 7. Groundwater Storage Anomaly Chart of Chad Basin

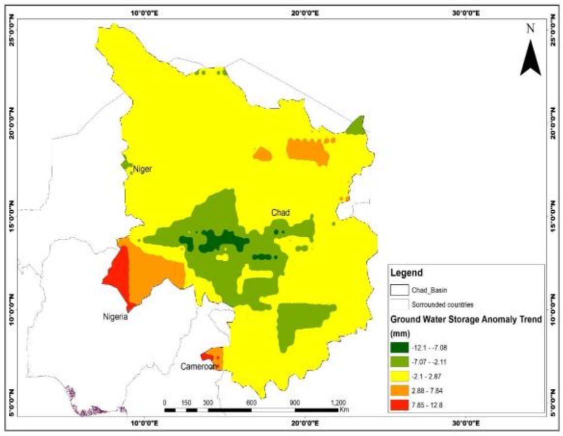

Figure 8. Groundwater Storage Map of Chad Basin

Analysis of hydroclimatic and hydrological changes in the Chad Basin (2002–2024) using CHIRPS, GLDAS, and GRACE/GRACE-FO datasets reveals contrasting trends across rainfall, surface water, total water storage, and groundwater. Annual rainfall exhibits strong interannual variability (≈580–698 mm) but shows a weak positive long-term trend of +1.65 mm yr^{-1} ($R^2 = 0.12$), indicating a slight increase in precipitation despite pronounced dry years, particularly during 2013–2015 and 2019 (Figures 2, 3, 4, 5, 6, 7, and 8). Surface water storage (Figure 3) derived from GLDAS ranges approximately between 380 and 440 mm and displays a declining trend of −1.04 mm yr^{-1} ($R^2 = 0.18$), with pronounced depletion between 2014 and 2018. This decline aligns with earlier studies attributing surface water reduction in the Chad Basin to increased evaporation, reduced groundwater inflows, climate variability, and human activities such as irrigation and dam construction (Leblanc et al., 2011; Okonkwo and Demoz, 2014; Coe and Foley, 2001). In contrast, GRACE-based Total Water Storage Anomaly (TWSA) (Figures 5 and 6) shows a strong increasing trend of +5.91 mm yr^{-1} ($R^2 = 0.70$), rising from near-zero or negative values in the early 2000s to over +140 mm by 2024. Spatially, positive TWSA trends (Figure 5) dominate central and northern parts of the basin (Chad and Niger), while localized declines persist in northeastern Nigeria, consistent with intense groundwater abstraction (Rodell et al., 2018; Tapley et al., 2019; Voss et al., 2013; Ahmed et al., 2022; Mohammed et al., 2020; Syed et al., 2021). Groundwater Storage Anomaly (GWSA) (Figures 7 and 8) shows large interannual fluctuations (−435 to −398 mm) but only a negligible long-term increase (+0.24 mm yr^{-1}; $R^2 = 0.02$). Spatial patterns indicate relative stability or weak recovery in southern and central areas (Cameroon and southern Chad), contrasted with significant depletion along the western margins, particularly northeastern Nigeria, and parts of northern Niger. These findings are consistent with previous GRACE-based studies linking groundwater decline to unsustainable abstraction and climatic stress, with localized post-2018 recovery associated with wetter years and flooding around Lake Chad (Rodell et al., 2018; Mohamed et al., 2020; Ahmed et al., 2021; Ibrahim et al., 2022; Pokhrel et al., 2021).

	Rain mm	**Surface _mm**	**TWSA _mm**	**GWSA _mm**
Rain mm	1	-0.00567	0.495554	-0.17617
Surface_mm	-0.00567	1	-0.01326	0.279056

TWSA_mm	0.495554	-0.01326	1	0.263227
GWSA_mm	-0.17617	0.279056	0.263227	1

Table 3. Correlation matrix of GWSA and Rainfall

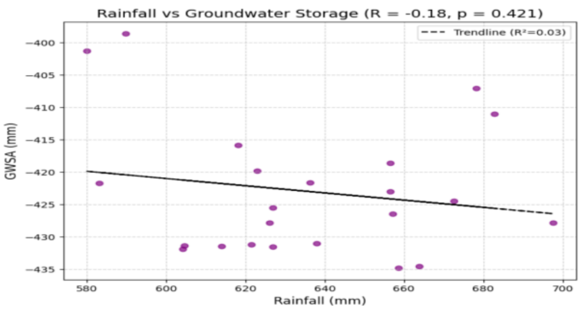

Figure 9. GWSA and Rainfall Correlation map

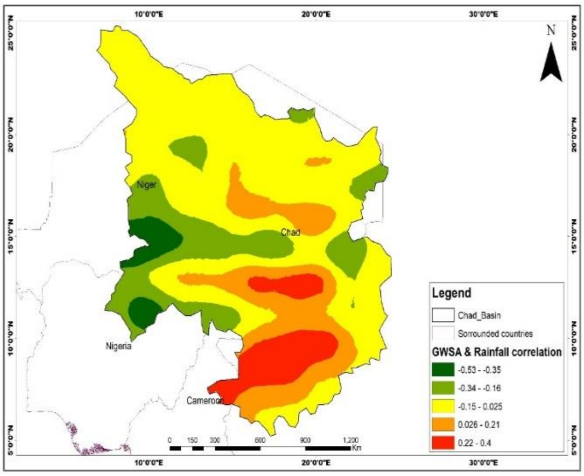

Figure 10. GWSA vs. Rainfall Chart

As Figures 9 and 10 and Table 3 depict, the correlation between precipitation and groundwater storage anomaly (GWSA) in the Chad Basin is weak and spatially discontinuous in general. The spatial correlation analysis shows that there are negative correlations (−0.728 to -0.47) in the central and north locations, meaning that the higher the rainfall is, the less it results in a corresponding recharge in the groundwater. This is contrasted by limited areas in the southern and southwestern basin (especially along the Cameroon-Nigeria border) that show weak to moderate positive correlations (up to 0.562), presumably due to more permeable geological formations that are conducive to infiltration.

The scatter plot also proves this weak correlation between rainfall and groundwater with a low correlation coefficient (R = -0.18) and R 2 =0.03, which means that rainfall only accounts for a 3 percent variation of groundwater. This is supported by the correlation matrix, indicating weak correlation of GWSA with rainfall (r = 0.176) and TWSA (r = 0.263) and slightly strong with surface water storage (r = 0.279), suggesting that surface-subsurface interactions are few. The findings can be compared to the past research on arid and semi-arid areas, where evapotranspiration and anthropogenic water use are among the primary controls of the groundwater dynamics that minimize the impact of precipitation (Rodell et al., 2018; Scanlon et al., 2019; Ahmed et al., 2020).

4. Discussion

Analysis of GRACE and GLDAS data (2002–2024) reveals a paradoxical hydrological condition in the Chad Basin with critical implications for global water management, transboundary governance, and climate adaptation. Total Water Storage Anomaly (TWSA) shows a strong positive trend (+5.91 mm yr^{-1}; R^2 = 0.70), indicating an overall increase in basin-scale water mass and an apparent improvement in water security. However, this masks a decline in accessible resources: surface water and soil moisture exhibit a negative trend (−1.04 mm yr^{-1}; r = 0.18), driven by evaporation and human abstraction, while Groundwater Storage Anomaly (GWSA) remains effectively stagnant (+0.24 mm yr^{-1}; r = 0.02), contradicting assumptions that increased total storage leads to effective groundwater recharge.

The weak rainfall–GWSA correlation (r = −0.176) highlights the dominance of anthropogenic controls and hydrogeological constraints over climatic variability. The findings emphasize a shift in policy from climate-driven narratives to governance-focused management, prioritizing protection of surface water, spatially explicit abstraction limits, transboundary monitoring, and high-efficiency Managed Aquifer Recharge (MAR). Collectively, the results support proactive, evidence-based adaptation and cooperative water governance under the Lake Chad Basin Commission framework.

5. Conclusion

This study analysed long-term hydrological changes in the Chad Basin with GRACE datasets and GRACE-FO datasets, as well as GLDAS data from 2002 to 2024. The results indicate a hydrological paradox of rising trends of Total Water Storage Anomalies (TWSA) while surface water and groundwater resources are still decreasing or weakly replenished. Groundwater recharge is small despite some higher rainfall, as reflected in the weak relationship between water and rainfall (r = −0.176), implying that the recovery of groundwater can not only be sustained by climatic inputs, but that groundwater is additionally being depleted. Spatial analysis also highlighted the presence of severe hotspots of groundwater depletion, mainly associated with anthropogenic abstraction pressures and hydrogeological constraints, mainly in the north-east of Nigeria. The results highlight the need for evidence-based transboundary water management, groundwater abstraction control, and targeted Managed Aquifer Recharge (MAR) programmes as part of the Lake Chad Basin Commission (LCBC) programme framework.

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