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Hydrological Evaluation of Lake Chad Basin Using Space Borne and Hydrological Model Observations

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Abstract: Sustainable water resource management requires the assessment of hydrological changes in response to climate fluctuations and anthropogenic activities in any given area. A quantitative estimation of water balance entities is important to understand the variations within a basin. Water resources in remote areas with little infrastructure and technological knowhow suffer from poor documentation, rendering water management difficult and unreliable. This study analyzes the changes in the hydrological behavior of the Lake Chad basin with extreme climatic and environmental conditions that hinder the collection of field observations. Total water storage (TWS) from the Gravity Recovery and Climate Experiment (GRACE), lake level variations from satellite altimetry, and water fluxes and soil moisture from Global Land Data Assimilation System (GLDAS) were used to study the spatiotemporal variability of the hydrological parameters of the Lake Chad basin. The estimated TWS varies in a similar pattern as the lake water level. TWS in the basin area is governed by the lake's surface water. The subsurface water volume changes were derived by combining the altimetric lake volume with the TWS over the drainage basin. The results were compared with groundwater outputs from WaterGAP Global Hydrology Model (WGHM), with both showing a somewhat similar pattern. These results could provide an insight to the availability of water resources in the Lake Chad basin for current and future management purposes.

Keywords: GRACE; Lake Chad basin; GLDAS; WGHM; groundwater; altimetry; hydrological changes

1. Introduction

In some developing parts of the world, very limited and low quality ground water data often hinder proper water management studies [1]. Moreover, the estimation of large-scale water balance using these limited ground-based measurements is prone to inaccuracies [2]. Sometimes, obtaining these datasets from the appropriate authorities involves lengthy administrative procedures, rendering studies extremely difficult.

Some, if not all of these, are associated with the Lake Chad Basin (LCB). Its scale and lack of modern infrastructure are major challenges for data collection, analysis and management [3]. Under these circumstances, satellite gravimetric, altimetry and hydrological models have proven useful in the study of these water bodies.

The Gravity Recovery and Climate Experiment (GRACE) is a joint mission between Deutsche Forschungsanstalt fur Luft und Raumfahrt (DLR) and National Aeronautics and Space Administration (NASA) that was launched in 2002. It records the Earth's time variable gravity field with a temporal and spatial resolution usually within a few hundreds of kilometers. These products together with the products [data] from satellite altimetry, Global Land Data Assimilation System (GLDAS), and WaterGAP Global Hydrology Model (WGHM) were used for this study. Satellite and hydrologic model products have widely been used for ground-based hydrological measurements and studies, and they also serve as inputs to land surface and atmospheric models [4,5]. They are also used to verify these models.

Lake Chad Basin (LCB) extends between latitude 6° N and 24° N, and between longitude 8° E and 24° E (Table 1). It covers an area of about 2,400,000 km^2, which is equivalent to 8% of the total area of the African Continent. About 20% of this total area is the conventional basin, which is under the mandate of the Lake Chad Basin Commission (LCBC).

Table 1. Morphometric data for Lake Chad.

Parameter	Lake Chad Basin
Location	6° N and 20° N, 7° E and 25° E
Catchment area	2.4×10^6 km^2
Conventional Basin	427,500 km^2
Lake area	1350 km^2

Lake Chad itself occupies the central region of the LCB. It is a closed lake, predominantly fed by two perennial rivers (the Chari and the Logone) and an ephemeral one (the Komadugu Yobe) (Figure 1). It serves as a source of freshwater and fish, and also aids pastoral and agricultural land for a population of 30 million across the basin by offering a relatively easy and permanent access to water [6].

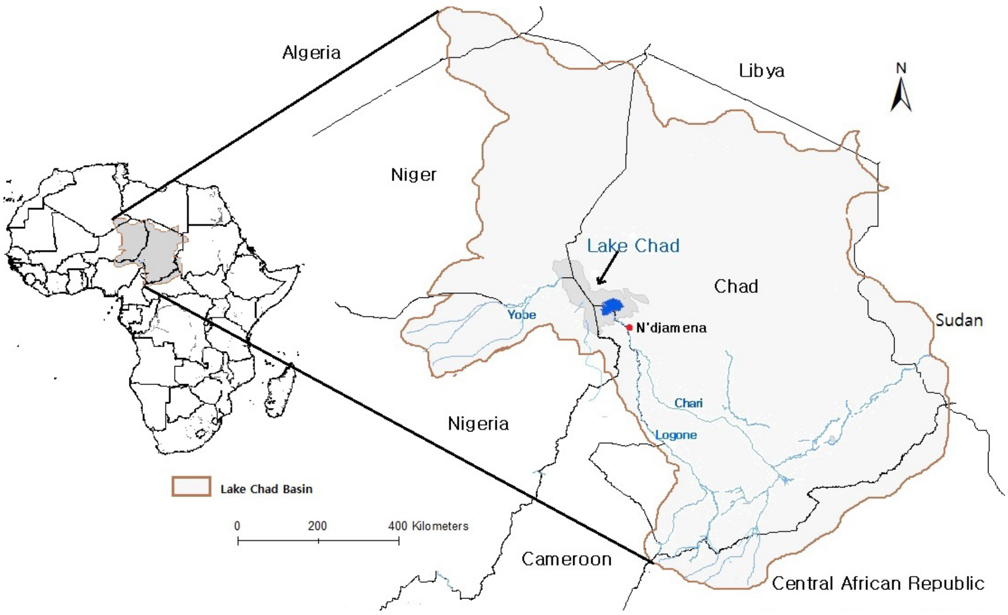

Figure 1. Locations of the Lake Chad Basin.

Increase in population, dam constructions, and irrigation development facilities during the last four decades have caused the surface area of Lake Chad to shrink from 24,000 km^2 to 1300 km^2 [7,8] (Figure 2). Studies have shown that the decrease was due to persistent drought and irrigation activities in the area [9–11].

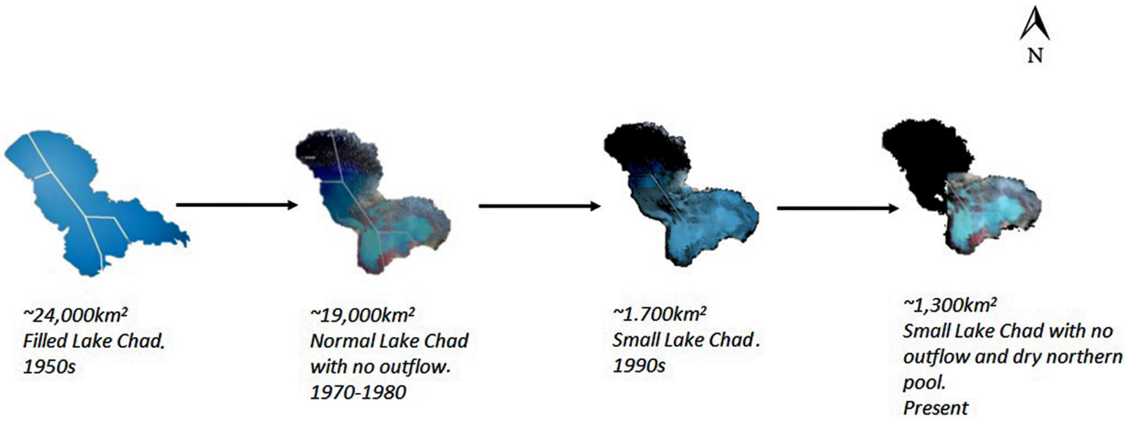

Figure 2. Schematics of the state of Lake Chad from Landsat 5 images; courtesy of NASA. Modified after [12].

In an attempt to manage and reduce the persistent droughts in this area, the water transfer project, whose main objective is halting the shrinkage of Lake Chad through an inflow of water coming from the Ubangi River, was introduced by the LCBC.

Water scarcity triggers food insecurity, poverty, migration and conflicts. As such, it is very important for a population or nations as a whole to secure stable and reliable water resource management techniques. A step towards this would be to understand the changes experienced by the water body in their vicinity. With limited and unreliable *in situ* data collection, understanding and documenting these changes can be very challenging and costly prompting researchers to rely on the use of satellite gravimetric, altimetry and hydrological models in monitoring water resources in such remote areas (Table 2).

Previous studies have applied remote sensing and satellite data to the Lake Chad region-some of which focused on the changes in stream flow patterns connected to the lake [9,13–15], Leblanc *et al.* [16] reported on the existence of a mega-lake Chad. They used satellite images from Landsat and Moderate Resolution Imaging Spectrometer (MODIS) for their studies. Thermal remote sensing techniques, such as the Meteosat thermal maximum composite data, was used to account for the variability of inundated areas within the lake under flooded vegetation [17]. Satellite imagery and GRACE data were used to study the regional hydrogeology and made an attempt at estimating the actual evapotranspiration over the LCB [5]. Altimetry data and ground-based information were used to predict the downstream lake and marsh heights using imperial regression techniques [18].

Few studies have used remote sensing data for investigating groundwater recharge around this area like [3,6] used satellite images (Meteosat thermal data) combined with hydrogeological data to identify the thermal change of groundwater in the depression zones, and then estimated values of recharge and discharge of the area. We try to define time series data of groundwater depending on the nature and fluctuation of this property in time and space.

In this study, we combined updated remotely sensed and hydrological model datasets. These datasets have been used to study the diverse aspects of basin hydrology within the continent [6,7,11,19–24]. Some of these point out the lack of readily available *in situ* data for these studies [5,22], some cases validated the *in situ* measurements in Lake Chad and other parts of Africa (Table 2).

Table 2. Literature review of remotely sensed data sets used in the studies of some watershed in Africa.

Study Area	Data Products			Reference
	Terrestrial Water Storage	Rainfall	Lake Height	
Lake Chad	GRACE [1]	GPCP [2]	–	[5]
Lake Chad	–	–	Sat. Alt. [3]	[25]
Lake Chad	–	NOAA [4], TRMM [5]	–	[12]
East African Great Lake	GRACE, WGHM [6]	GPCP	Sat. Alt.	[25]
Lake Victoria, Malawi and Tamganyika	GRACE	GLDAS, TRMM	Sat. Alt.	[26]
Okavango catchment	GRACE	TRMM	Sat. Alt.	[27]
Congo river basin	GRACE	GLDAS, TRMM	Sat. Alt.	[26]
Lake Victoria, Tamganyika and Malawi	GRACE, WGHM	GLDAS, TRMM	Sat. Alt.	[28]

[1] GRACE: Gravity Recovery and Climate Experiment; [2] GPCP: Global Precipitation Climatology Project; [3] Sat. Alt.: Satellite Altimetry; [4] NOAA: National Oceanic and Atmospheric Administration; [5] TRMM: Tropical Rainfall Measuring Mission; [6] WGHM: WaterGap Hydrological Model.

We utilized satellite gravimetric, altimetric and hydrological models products over the Lake Chad basin to characterize the spatiotemporal and multiscale variability in its hydrological cycle, to infer the effect of rainfall on water storage in this region, and, finally, to investigate subsurface water variations within this region and perform comparison with groundwater outputs from a global hydrological model.

2. Materials and Methods

2.1. Terrestrial Water Storage (TWS) from GRACE

GRACE is known for estimating high-precision time-varying gravity field and the changes of Earth's surface mass at a high degree of accuracy on a time scale ranging from months to a decade [29,30]. These variations are mainly due to redistribution of water mass in the surface fluid envelopes of the earth. It provides estimates of TWS, which encompasses surface water, soil moisture, groundwater and snow. However, experimental errors while using GRACE increase rapidly and concurrently as the degree of the spherical harmonic coefficients, causing inaccurate results at higher degree terms of the spherical harmonic coefficients [31,32]. Spatial averaging functions are normally used to reduce the high degree of noise in the GRACE gravity field. This provides researchers with accurate surface mass changes. An additional de-stripping averaging filter is used for suppressing the "N–S" stripping noise in the GRACE data. There is also a leakage effect, which is caused by the spatial averaging functions. This causes some signals of the GRACE mass anomalies to leak outside the region of interest. The accuracy of GRACE is high enough to detect surface mass variations corresponding to hydrological loads of 1 cm at monthly and longer time scales, with horizontal dimensions of hundreds of kilometers and larger [30].

Numerous studies on the reliability of its data sets has been carried out by comparing its TWS products to that of Land Surface Models or *in situ* land observations-India [31], the Korean Peninsula [33,34], the East African lakes [25], Mali in Africa [35]. It has also been widely used in the studies of lakes around the world [36–39].

The GRACE Level 3 (Release 05) is the latest and more accurate of GRACE products. It provides processed time variability gravity field products. These products are provided as sets of spherical harmonic coefficients averaged on a monthly scale.

For this study, we used the monthly land mass grid observations (Level 3) provided by the Center of Space Research (CSR), University of Texas, at Austin from January 2003 to December 2013. The data are available as monthly $1^{\circ} \times 1^{\circ}$ grids of TWS over our study area [40]. The data set was truncated at 60 degrees and smoothed with the Gaussian filter of 300 km. GRACE data enhancement techniques provided [30] were also included to improve the accuracy of these TWS estimates.

For the time frame of our study, we encountered six months of missing data during these dates: June 2011, May and October 2012, and March, August, and November 2013. For these missing datasets, the temporal linear interpolation was done between them since they were not contiguous.

2.2. Lake Height from Altimetry

Generally, satellite altimeters are nadir-pointing instruments that record the average surface "spot" height directly below the satellite as it transverses over the Earth's surface. It basically determines the distance from the satellite to a target surface by measuring the satellite-to-surface round-trip time of a radar pulse. The altimeter emits a radar wave and analyzes the return signal that bounces off the surface. The surface height is calculated as the difference between the satellite's positions on orbit with respect to an arbitrary reference surface, *i.e.*, the Earth's center is represented by a reference ellipsoid and the range between the satellite and the surface is obtained by calculating the time taken for the signal to return. From this, the measurements of the sea surface height and other characteristics of oceans, lakes, floodplains, and rivers can be obtained. A lot of information can be extracted from satellite altimetry.

Institutions like the Foreign Agricultural Services (FAS) of the United States Department of Agriculture, Hydroweb, and European Space Agency (ESA) have been making available the up-to-date and reliable user-friendly data sets.

Lakes, rivers and oceans have all been monitored over the years using these data sets [9,11,41–44]. Surface water level data sets are sometimes given in the form of graphs and tables for major water bodies based on combination of various radar altimetry sensors. These data sets are made available free of charge via web applications, such as USDA's Global Reservoir and Lake Monitor (http://www.pecad.fas.usda.gov), Hydroweb of Geodesy, Oceanography and Hydrology from Space (GOHS; http://www.legos.obs-mip.fr/), and River and Lake system provided by ESA (http://tethys.eaprs.cse.dmu.ac.uk). Repeat track methods used in the derivation of time series of the lake surface height variation uses the reference lake height profile. This is derived from averaging all height profiles across the lake within a given time span. This effectively smoothens out any varying effects of tide and wind set-up. These resulting time series of height variations are expected to have an accuracy of about 20 cm root mean square (RMS) for lakes with minimal tides and limited dynamic variability.

For our study area, the satellite altimetry data has widely been used in the studies of the lake in which *in situ* datasets were compared with these altimetry products. The results showed accurate water level variations for Lake Chad in the two data sets [11,40,41]. Altimetry missions with a 10-day repeat track, such as TOPEX/Poseidon (1992–2006), Jason-1 (2001–2013), and Jason-2 (2008–present), or those with a 35-day repeat track, such as ERS-2 (1995–2000) and ENVISAT (2002–2010), can be used to extract lake height variations. ENVISAT altimetry estimates were used for this study.

2.3. Soil Moisture from GLDAS

Operated by NASA and the National Oceanic and Atmospheric Administration (NOAA), GLDAS is a land surface simulation system that aims to ingest satellite and ground-based observational data products, using advanced land surface modeling and data assimilation techniques, in order to generate optimal fields of land surface state (e.g., soil moisture and surface temperature) and flux (e.g., evaporation and sensible heat flux) products [4]. It adopts four advanced land surface models (LSMs): The Community Land Model (CLM), Mosaic, Noah, and Variable Infiltration Capacity (VIC). GLDAS executes spatial resolutions globally at both 0.25° and 1.0°, with temporal resolutions of three hours and monthly products since 1979. GLDAS data are widely used for land-surface flux simulations. As such, the simulation accuracy using GLDAS dataset is largely contingent upon the accuracy of the GLDAS dataset. The data are available from the Goddard Earth Sciences Data and Information Services Center (GES DISC).

In this study, we used Noah 1.0° grid data which has four layers of vertical soil moisture. The monthly average soil moisture is computed as the sum of all the layers [45].

2.4. Groundwater Estimates from the WaterGap Hydrological Model

The WaterGAP Global Hydrological Model (WGHM) is a submodel of the global water use and availability model WaterGAP 2.2 It computes groundwater recharge, surface runoff and river discharge as well as storage variations of water in canopy, rivers, soil, lakes, wetlands, groundwater and snow at a spatial resolution of 0.5° [46].

WGHM is based on the best global data sets currently available, and it is able to simulate variations in water bodies. It computes the water storage in the snow pack, rooted soil zone, groundwater, on vegetation surfaces, and in surface water reservoirs. Here, the simulated estimates provided by [47] were used. In order to obtain a reliable estimate of water availability, they tuned the model against the observed discharge at 1235 gauging stations, which represent 50% of the global land area and 70% of the actively discharging area. In Africa, most basins north of the equator do not perform well [47]. Detailed information about the modelling concept and its corresponding assumptions can be found in [48].

Model outputs assessment performance was not carried out in the LCB due to limited data availability. However, the Chari and Komadougou Yobe river basins, which predominantly feed the lake, were included in the calibration scheme of this region. Too much water was modeled for both basins. The Chari-Logone river system, which supplies most of the water into the southern part of LC, has a Nash-Sutcliffe efficiency of around 0.6, which is quite good. On other hand, inland water bodies in Africa showed a good match with the WGHM model output-for instance, the East African great lakes as reported by [46].

For this study, outputs from the WaterGap 2.2a model forced with precipitation from the Global Precipitation Climatology Centre (GPCC) and data from the European Center for Medium-Range Weather Forecast (ECMWF) integrated forecast system were used. These outputs include; global-scaled gsssroundwater storage, total water storage, baseflow, and groundwater recharge (diffused and below surface water bodies). There is no data available after 2009 (Table 3). This can be found on the website (https://www.uni-frankfurt.de/49903932/7_GWdepletion) [49].

Table 3. Summary of data sets used for this study.

Variable	Dataset	Resolution		Period
		Spatial	Temporal	
Terrestrial Water Storage	GRACE	1° × 1°	1 month	2003–2013
Lake Height	Sat. Alt.	1° × 1°	30 days	2003–2013
Rainfall	GLDAS	1° × 1°	1 month	2003–2013
Soil moisture	GLDAS	1° × 1°	1 month	2003–2013
Groundwater	WGHM	0.5° × 0.5°	1 month	2003–2009

2.5. Data Processing

2.5.1. Variability in TWS and Lake Height

Seasonal-Trend Decomposition Procedure based on Loess (STL) method is a filtering procedure that decomposes a time series into its additive components of variation (trend, seasonal and the remainder components) by the application of Loess smoothing models [50]. This was used to model GRACE monthly storage variations as well as the time series of altimetric lake height.

In brief, the steps performed during STL decomposition are as follows:

1. Cycle-subseries smoothing: series are built for each seasonal component, and smoothed separately.

2. Low-pass filtering of smoothed cycle-subseries: the subseries are put together again, and smoothed.
3. Detrending of the seasonal series.
4. Deseasonalizing the original series, using the seasonal component calculated in the previous steps; and Smoothing the deseasonalized series to get the trend component.

In R statistical software, the STL algorithm is available through the *stl* function. We use it with its default parameters. The degrees for the Loess fitting are $d = 1$ in steps (iii) and (iv), and $d = 0$ in step (ii).

The parameter values must be chosen by the data analyst. We assume each observation X_i in time series is the sum of these components:

$$X_i = T_i + S_i + I_i \tag{1}$$

where T_i = Trend, S_i = Seasonality and I_i = Interannual components.

Often, six parameters determine the degree of smoothing in trend and seasonal components. For detailed information on method and parameters, consult [50] paper on STL methods. For our study, these parameters are:

$n_{(p)}$: The number of observations in each seasonal cycle, = 12 months (yearly periodicity with monthly data);
$n_{(i)}$: The number of passes through the inner loop (usually set to equal one or two) = 1 month;
$n_{(o)}$: The number of robustness iterations of the outer loop (Values qual one or two) = po robustness while a zero value has no robustness iteration) = 5 months;
$n_{(l)}$: The span of the loess window for the low-pass filter (computed as the next odd number to $n_{(p)}$) = 13 months;
$n_{(s)}$: The smoothing parameter for the seasonal component, = 12 months (seasonal length is same as the periodic length);
$n_{(t)}$: The smoothing parameter for the trend component, = 22 months.

$$n_{(t)} \geqslant \left[\frac{1.5 n_{(p)}}{1 - 1.5 n_{(s)}^{-1}} \right] \times 2 \tag{2}$$

For this analysis, R statistical software was used [51]. It is a free software environment and a programming language for statistical computing and graphics. It is widely used among statistics and data miners for developing statistical software and data analysis. MS excel was also used for subsequent data representation and analysis.

2.5.2. Subsurface Water Volume Change

Subsurface water volume (Groundwater + Soil moisture) was investigated. GRACE data provides changes in total water storage, which includes Lake water storage (LS), Snow water equivalent storage (SWES), soil moisture storage (SMS), and groundwater storage (GWS) within the basin. With satellite and model-based estimates of LS and SMS, subsurface water volume can be estimated. SWES was ignored for our study area since this area is humid.

Estimates of the subsurface water changes was evaluated using the following disaggregation equation,

$$\Delta SSW = \Delta SM + \Delta GW = \Delta TWS - \Delta LS \tag{3}$$

Here, ΔSSW = Subsurface Water, ΔGW = Groundwater, ΔLS = Lake water, ΔTWS = Terrestrial Water Storage, ΔSM = Soil Moisture.

In an attempt to express ΔSSW and ΔLS in terms of volume, both were multiplied by the LCB area and Lake Area, respectively.

3. Results and Discussions

3.1. TWS and Altimetry Lake Height

Based on our study period, the STL trend of the time series of monthly GRACE TWS shows a decrease in average TWS of the Lake Chad basin (Figure 3) for the periods 2003–2005 and 2009–2010 with the latter being the lowest water estimates at −0.54 cm/year. There is an increase in TWS concentrations from 2006 to 2008, and 2010 through 2013, with the latter being the highest storage estimates of 0.69 cm/year.

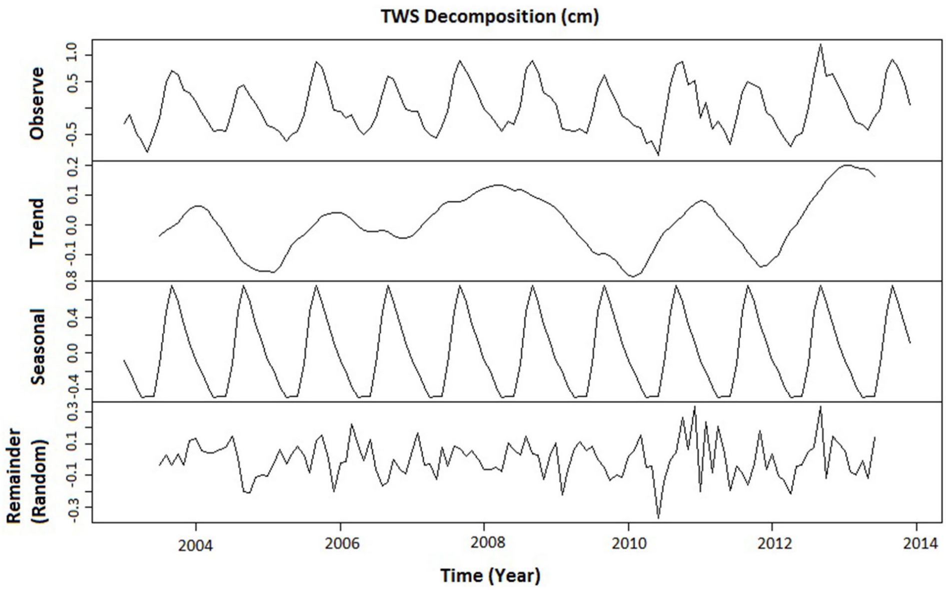

Figure 3. STL decomposition of the time series of monthly GRACE TWS.

The STL trend of the time series of altimetric lake height (Figure 4) shows a decrease in lake level from 2003 through 2005 and a steady increase until after 2008 with an average height of about 0.3 m/year. From this point, it begins to slope down towards 2010. From 2010 to 2012, the Lake experiences its lowest height averaging to about 0.23 m/year. Different rates are shown in Table 4.

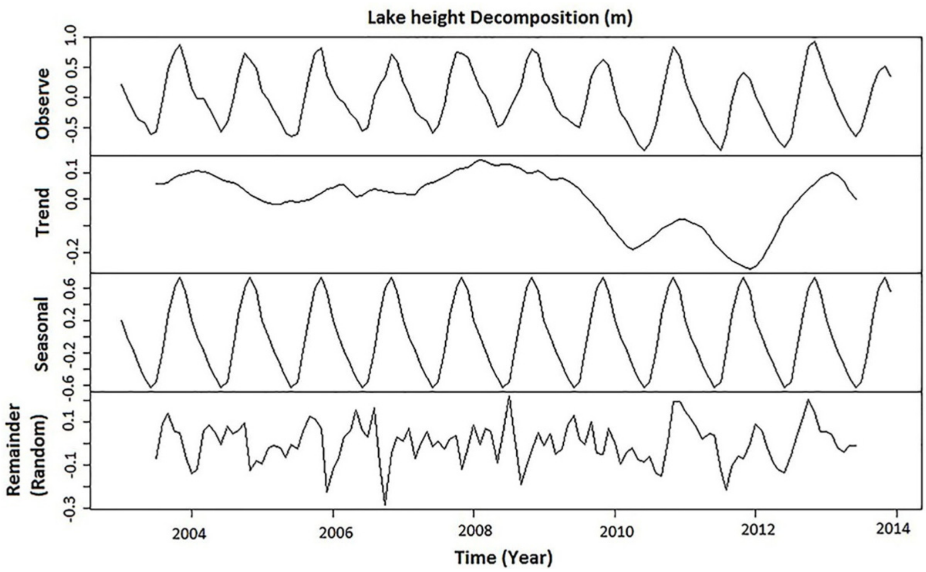

Figure 4. STL decomposition of the time series of monthly lake altimetric height.

Table 4. STL fitted trend of the time series of TWS and lake height.

Period	TWS (cm)	Lake Height (m)
2003–2005	0.25	0.32
2006–2009	0.84	0.62
2010–2013	0.38	−0.78

The STL decomposition plot of the monthly TWS estimates and lake altimetric height shows a similar pattern with their seasonal components suggesting an annual increase from the months of July–September as well as a decrease from October–June. This implies the Lake's height follows the seasonal pattern of the rainfall cycle around this area. There is a correlation (>80%) between them which points out the similarity in their pattern (Figure 5a).

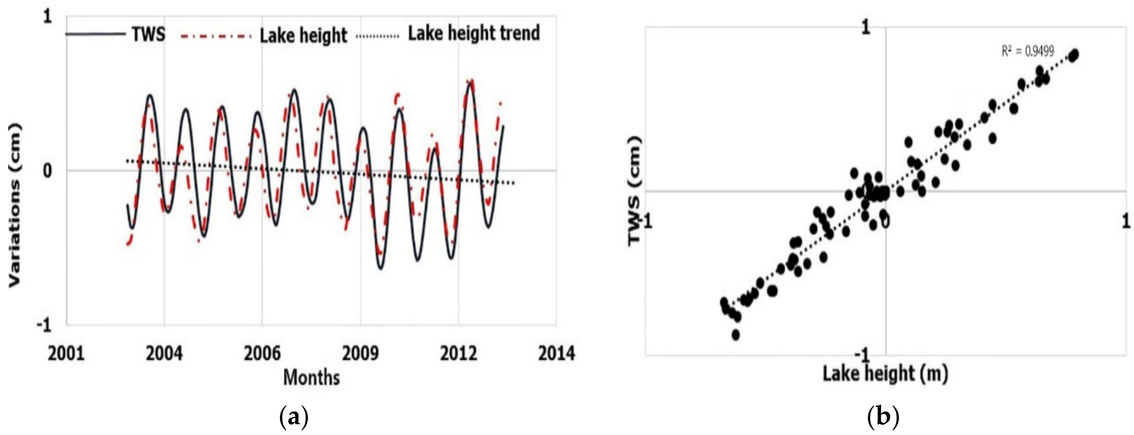

Figure 5. (**a**) Represents TWS and lake height after smoothing with a six-month window; (**b**) Represents the autocorrelation between TWS and lake height.

Their seasonal component suggests an average annual increase in September and a main annual drop exists in November. This is due to the rainfall regime that exists over the Lake region. This relationship will be discussed in Section 3.2. The largeness and uniform size of the seasonal cycle of Lake Chad means that, over the years, Lake Chad has a fast water renewal process.

3.2. TWS and Rainfall

Rainfall estimates from GLDAS were compared to GRACE TWS over the LCB. During the wet season (July–September), there is an increase in seasonal pattern of rainfall over the study region with 2012 having the maximum annual averages. Figure 6 shows a comparison between the time series of the monthly estimated GLDAS rainfall and the change in GRACE TWS and, as expected, both curves show a good agreement during most of the study period in terms of pattern.

Based on Figure 6, we can clearly see the existence of a phase shift between GLDAS rainfall and GRACE TWS. This phase shift is about a month and a half. Their lagged correlation was also high (>0.9). From trend analysis, rainfall that precedes TWS increases throughout the study period. Its seasonal cycle goes ahead to confirm this phase shift that exists between rainfall and TWS in this region.

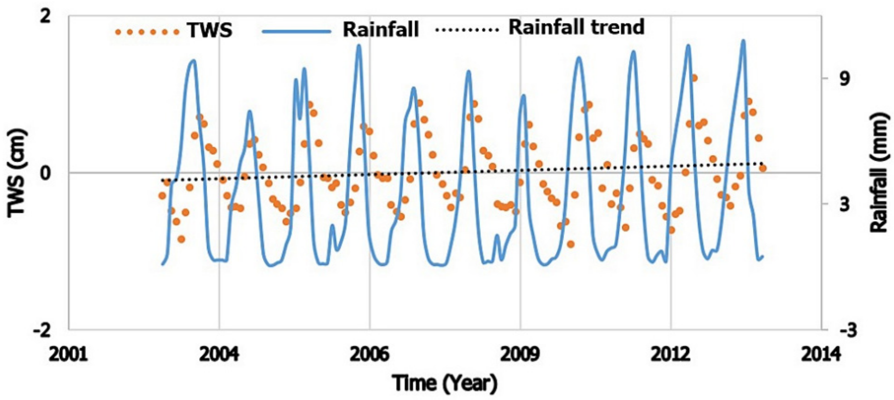

Figure 6. Comparisons between the yearly estimates of rainfall and TWS.

Figure 7 also confirms the bimodal rainfall regime that exists within this region with most of its heavy rainfall occurring between July–September and shorter rains from October–December.

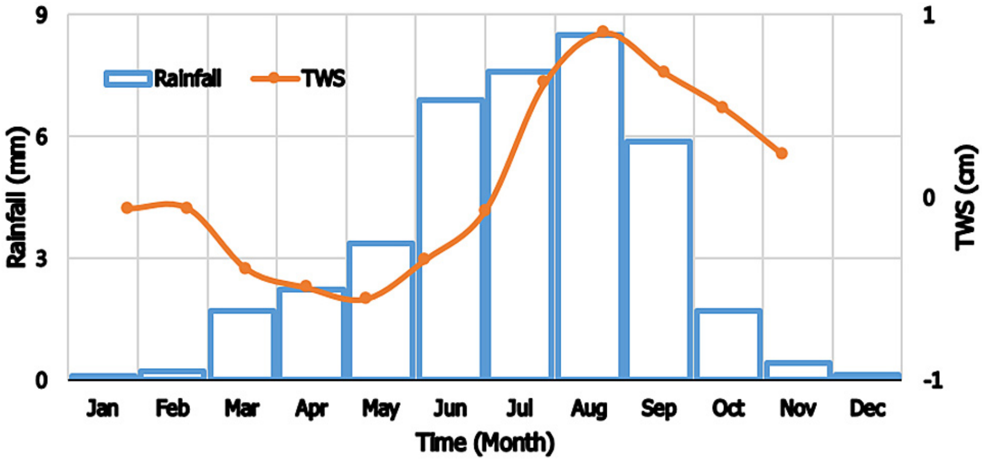

Figure 7. Comparisons between the monthly average rainfall and TWS.

3.3. TWS and Soil Moisture

Terrestrial water storage (TWS) of the Lake Chad Basin and the lake's surface water volume change from altimetry are critically analyzed. Due to its improved precision, GRACE can detect gravitational changes within an area of 200,000 km^2 or larger [44]. Hence, it is suitable for our study area which is 427,500 km^2.

Figure 8 shows a good agreement between altimetric lake water volume with GRACE basin water volume with a correlation of about 73%. There is also a good agreement in their seasonal cycles (Figure 9). We can infer that surface water of Lake Chad governs the volume of water in the basin area.

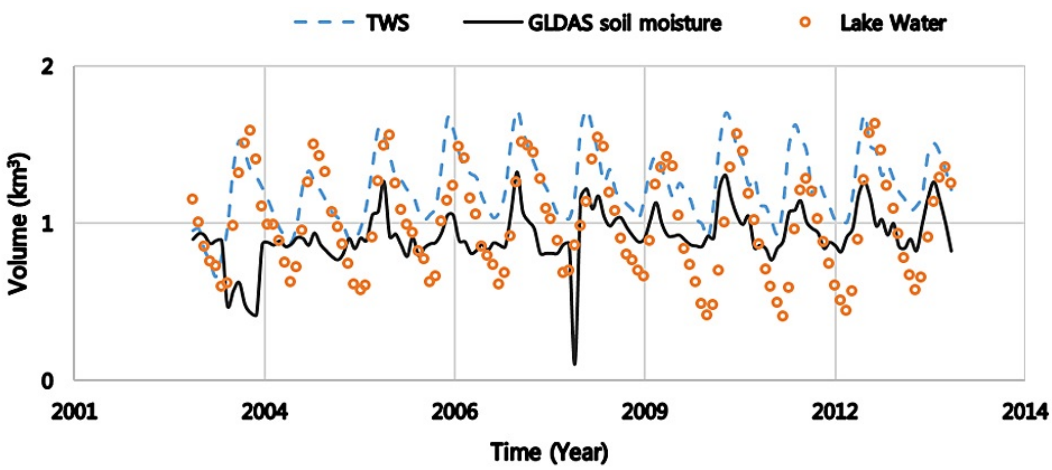

Figure 8. Effect of altimetric lake water and soil moisture on TWS.

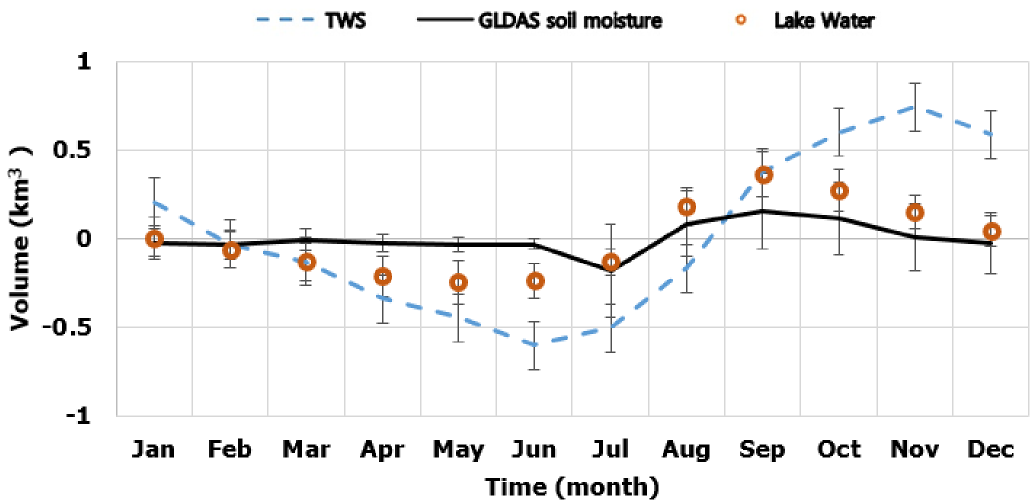

Figure 9. Monthly averaged seasonal cycle of the Lake Chad. Error bars represent the standard deviation for each month.

GLDAS outputs of soil moisture estimates can also be seen in Figure 8. It has a weak agreement with basin water volume with a correlation of about 35%. Hence, soil moisture content plays little or no role in the variability in water volume stored in the Lake Chad Basin. It is solely governed by surface water of the Lake Chad.

Additionally, investigated were the changes in subsurface water volume, which comprises of groundwater and soil moisture (Section 2.5.2). In early 2003 and 2007, there is a dissimilarity between volume estimates of WGHM groundwater and subsurface water estimates. The results obtained were compared with WGHM outputs (Figure 10). It shows two peak periods at approximately mid-2005 and 2006. Both curves have a somewhat similar pattern with a correlation coefficient of about 47% between them.

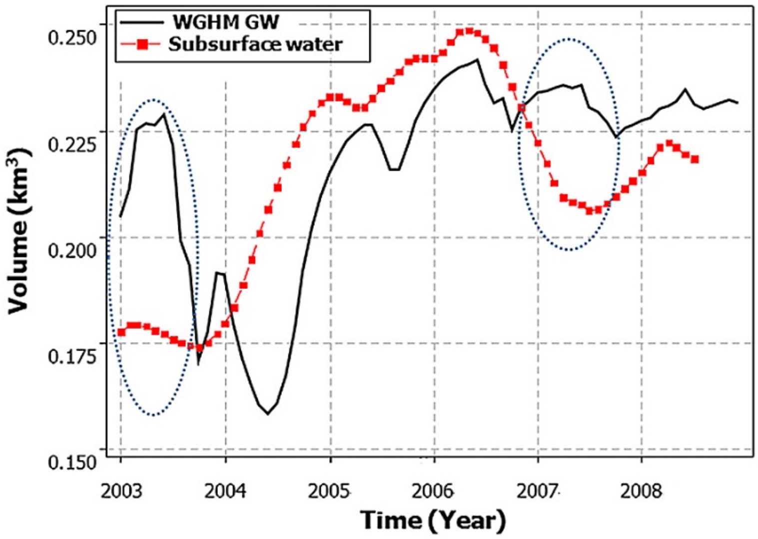

Figure 10. Changes in subsurface water (groundwater and soil moisture) and WGHM GW outputs. The annual signal is removed and data are smoothed with a six-month window.

4. Conclusions

In this study, we see how the use of GRACE TWS data along with other data sources could be of great value in the hydrological studies of remote areas. We investigated hydrological variability associated within the LCB from January 2003 to December 2013. GRACE TWS and altimetric lake volume showed a similar pattern for the majority of the study period. After comparing TWS with soil moisture content, we found that the discharge in this area is governed by surface water of the lake. This is the first attempt in which these remotely sensed datasets were used to study the varying patterns of the lake's hydrology. Deriving this characteristic spatiotemporal analysis of surface mass anomalies across the LCB, future improvements can be made in the management of water resources in this area.

For much of the study period, GRACE TWS variations within the basin show a similar pattern of variation as the averaged lake height variation from altimetry. A trend analysis showed increasing precipitation with maximum annual average increase in August but decreasing water level in the lake from altimetry with the minimum annual average occurring in 2012 with a value of 0.2 m. Our study also showed that altimetry-based volume with TWS from GRACE provides information on soil moisture and groundwater. This could help in detecting subsurface water storage changes in relation to climate variability or anthropogenic activities especially in situations where *in situ* measurements are not available. This could also lead to new research prospects, where researchers could try to find out the main cause behind the lake's decreasing trend.

This characterization can help in the proposed Water Transfer Project from the Ubangi River to Lake Chad in a number of ways. For instance, the primary objective of this project is to halt the shrinkage of Lake Chad through an inflow of water coming from the Congo basin. The association between LC level and precipitation will enable managers to plan for the total water volume that can be released and retained based on future forecasts.

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Author Contributions: Willibroad G. Buma developed the methodology and conducted the work under the supervision and review of Sang-Il Lee. Jae Young provided technical assistance and helped in developing the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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