

Article

Lake Chad Total Surface Water Area as Derived from Land Surface Temperature and Radar Remote Sensing Data

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Abstract: Lake Chad, located in the middle of the African Sahel belt, underwent dramatic decreases in the 1970s and 1980s leaving less than ten percent of its 1960s surface water extent as open water. In this paper, we present an extended record (dry seasons 1988–2016) of the total surface water area of the lake (including both open water and flooded vegetation) derived using Land Surface Temperature (LST) data (dry seasons 2000–2016) from the NASA Terra MODIS sensor and EUMETSAT Meteosat-based LST measurements (dry seasons 1988–2001) from an earlier study. We also examine the total surface water area for Lake Chad using radar data (dry seasons 2015–2016) from the ESA Sentinel-1a mission. For the limited number of radar data sets available to us (18 data sets), we find on average a close match between the estimates from these data and the corresponding estimates from LST, though we find spatial differences in the estimates using the two types of data. We use these spatial differences to adjust the record (dry seasons 2000–2016) from MODIS LST. Then we use the adjusted record to remove the bias of the existing LST record (dry seasons 1988–2001) derived from Meteosat measurements and combine the two records. From this composite, extended record, we plot the total surface water area of the lake for the dry seasons of 1988–1989 through 2016–2017. We find for the dry seasons of 1988–1989 to 2016–2017 that the maximum total surface water area of the lake was approximately 16,800 sq. km (February and May, 2000), the minimum total surface water area of the lake was approximately 6400 sq. km (November, 1990), and the average was approximately 12,700 sq. km. Further, we find the total surface water area of the lake to be highly variable during this period, with an average rate of increase of approximately 143 km² per year.

Keywords: Lake Chad; total surface water area; land surface temperature; radar

1. Introduction

1.1. Lake Chad and Environment

Lake Chad is a large endorheic lake located in central Africa and intersecting the Sudan-Savanna, Sahelian, and Saharan agro-climatic zones [1]. In 2014, over two million people lived along the

shoreline of Lake Chad [2], and by 2015, the lake provided a livelihood for an estimated thirteen million people [3]. The Lake Chad Basin (Figure 1), at approximately 2.5 million km², is the world's largest endorheic basin, though much of the basin lies in the Sahara Desert and only about one-third of the basin (the southern portion) is hydrologically active [3]. Roughly ninety percent of the water reaching Lake Chad is provided by the Chari-Logone River [4]. The Chari and Logone Rivers join at N'Djamena, Chad and flow a short distance to discharge through a delta formation into Lake Chad. The Chari contributes roughly sixty percent of the flow to the Chari-Logone River, with the remaining forty percent coming from the Logone [5]. An additional two percent of Lake Chad's water comes from the Komadougou-Yobe River (also known as the Yobe River) [6], which flows through Niger and Nigeria to the west of the lake. The remaining water input comes from direct rainfall on the lake and some smaller tributaries. Water leaves the lake primarily through evapotranspiration, though an undetermined amount is believed to exit through infiltration [7].

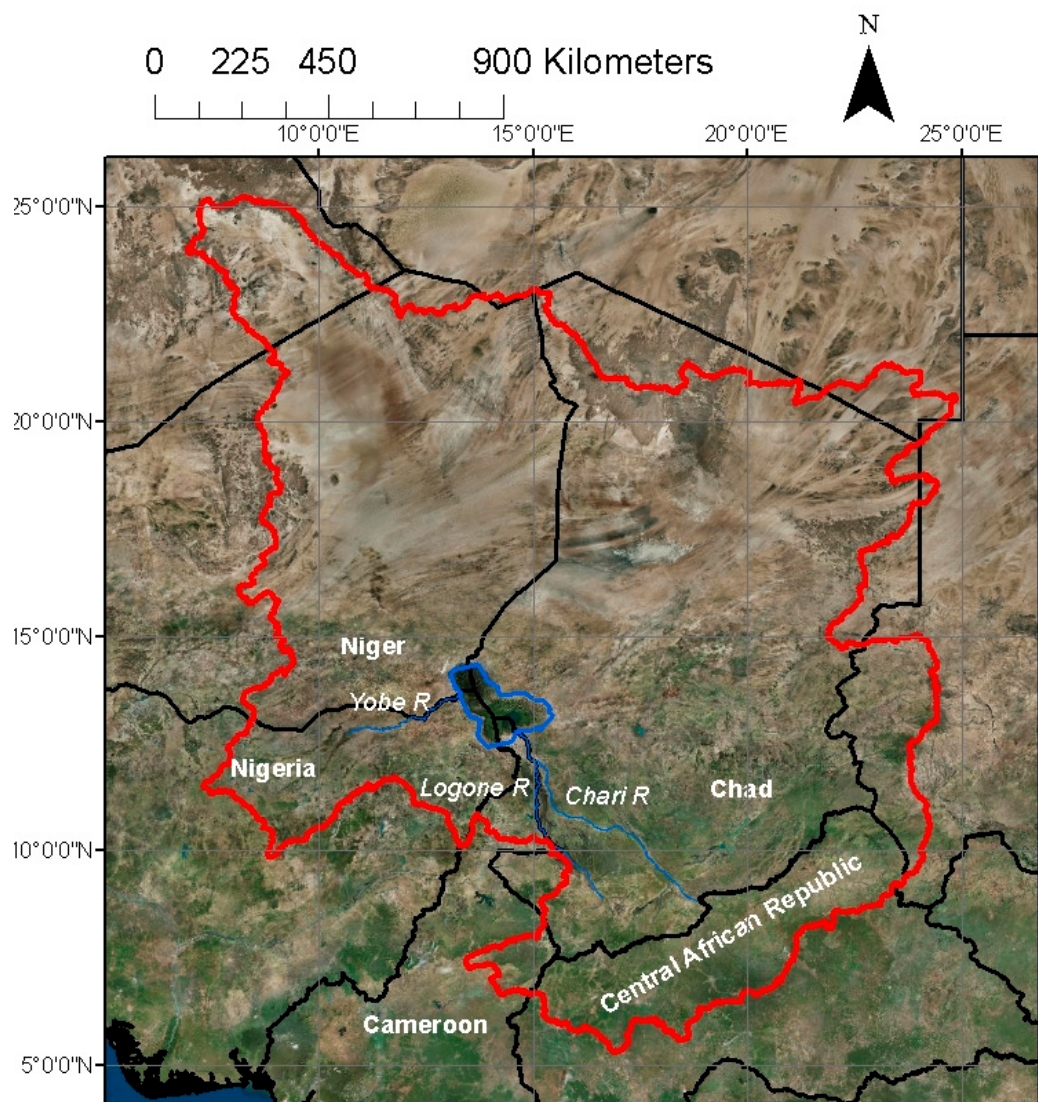


Figure 1. Lake Chad Basin (red line), Lake Chad and its main rivers (blue lines).

Lake Chad is shared by Chad, Niger, Nigeria, and Cameroon, while the basin additionally includes parts of the Central African Republic, Algeria, Sudan, and Libya. The surface level of the lake is roughly 282 m above sea level [4], and the average depth of the lake is less than 2 m [8].

Lake Chad is well known for the dramatic decrease in surface area that occurred in the 1970s and 1980s [9], particularly the open (unvegetated) area of the lake, which is most readily visible from optical satellite images.

Lake Chad has marked wet and dry seasons. The wet season lasts from June to October, although due to the time lag of water flowing through the Chari and Logone River systems, the annual flooding occurs during the dry season [10]. The lake rises about 1–2 m during the annual flooding season [4] and provides livelihoods to fishermen who are most productive following the floods, to “recession farmers” who farm in the rich soils of the receding floodwaters, and to those who raise livestock [1].

1.2. Background

Grove (1996) [9] states that “One of the most spectacular results of the increased aridity was the shrinkage of Lake Chad from its highest level and greatest extent this century, about 25,000 square kilometers in the 1960s to about one tenth that area in the mid 1980s.” According to [11], “Lake Chad’s surface area decreased from 22,902 km² ... in 1963 to a mere 304 km² ... in 2001.” According to [6], “Over the last 40 years, Lake Chad ... has decreased by more than 90% in area.” Lemoalle et al. (2012) [12] cite a changing lake area between 1973 and 2011 “ranging between 1800 and 15,000 km².” These statements (Table 1) are not necessarily inconsistent; however it is difficult to get a clear picture of the recent total surface water area trends and variability from these sources.

Table 1. Descriptions of Lake Chad area changes for extended periods found in the literature.

Source	Approx Dates	L. Chad Area Change (km ²)	L. Chad Area Change (%)
Grove, 1996 [9]	1960s–mid 1980s	−22,500	−90%
UNEP, 2006 [11]	1963–2001	−22,598	−99%
Gao et al., 2011 [6]	1971–2011	N/A	More than −90%
Leblanc et al., 2011 [10]	1986–2001	(+) 3500 *	(+) 33% *

* difference between 1st data point (May 1986) and last data point (May 2001).

According to the World Lakes Database of the International Lake Environment Committee [13], Lake Chad covers 1540 km². Because they do not say how and when they measured that area, it is not possible to know if there was an attempt to include flooded vegetation and whether that figure represents a minimum, a maximum or an intermediate level for the year.

The only sources found providing significant observation-based time series of area for Lake Chad are [4,10]. Their results differ significantly. Leblanc et al. (2011) [10] used 5 km resolution Land Surface Temperature (LST) data from the Meteosat satellites operated by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). Using this data, Leblanc et al. [10] developed a monthly record of the lake area from 1986 to 2001, differentiating water vs. non-water using a 2-cluster unsupervised classification process. Note that this lumps dry soil, wet soil, and dry vegetation classes into a single non-water class, and water and flooded vegetation into a single water class. They avoided making the analysis during the wet season, which presumably limited misidentification of wet soil with the water classes. They suggest that the use of satellite-based radar data may be helpful for mapping both open water and water under vegetation, but cite a number of reasons for not using it, notably the limitation of available radar data at the time of their research. They conclude that during the study period, the lake minimum size was 4600 km² in October 1987, the maximum size was 16,300 km² in February 2000, the 25th percentile area was 8800 km², and the 75th percentile area was 13,700 km².

Birkett (2000) [4], on the other hand, used 1.1 km resolution Near InfraRed (NIR) data from NOAA’s AVHRR on-orbit sensor to estimate the total lake surface water area from 1995 to 1999. The estimate frequency was sub-monthly. Based on the fact that water absorbs strongly in the NIR part of the spectrum, whereas healthy vegetation reflects strongly in NIR, Birkett [4] distinguishes marshland and open water as the darkest pixels vs. dry land as brighter pixels. As a threshold between the two, she chose the midpoint between the two characteristic peaks of the histograms for the two types of landcover, using NIR sensor digital numbers. From that analysis, she found a permanent total

surface water area (open water and marshland) of 1385 km² and a peak total surface water area of approximately 5000 km².

There are some indications from the literature that the lake has been increasing in size since the 1990s, however these patterns are either not well described or are defined over a relatively short period of time. According to [14] “the 2007 (satellite) image shows significant improvement (increased surface water area) over previous years”. Several authors note a rising trend in rainfall, lake elevation, and flow to the lake starting in the 1990s. According to [15], “The African Sahel experienced severe drying between the 1950s and the 1980s, with partial recovery since.” Birkett (2000) [4], who also notes “a possible correlation (of decreasing lake water inflows) with El Nino events”, describes a rise in minimum lake levels by 15–35 cm per year and indications of increasing rainfall in parts of the basin during the period of her study (1995–1999). Lemoalle et al. (2012) [12] note increases in mean annual Chari River stream flow recovering in the 1990s after significant drops in the 1970s and 1980s, although through the period 2000–2009, the flows were still only about half of what they were during the 1960s. Gao et al. (2011) [6] note that, “The north lake’s level continually decreased until 1986 when it dried out completely. Water reappeared in the north lake in 1999 after a few years of wet weather.” Despite the evidence of changing lake size, it does not appear that the research community has created an updated time series of the lake’s total surface water area since the [10] analysis for 1986–2001.

1.3. Objectives of Study

The primary purposes of this paper are to use remote sensing data (Figure 2) to extend the existing total surface water area record of Lake Chad, and to provide data for calibrating a model of the annual flooding of the lake. Such a model could be very useful for supporting livelihood decisions for part of the population of the lake. Sarch and Birkett (2000) [1], for instance, found that “farmers cannot be sure when the flood will reach the land around their village or whether it will at all.”

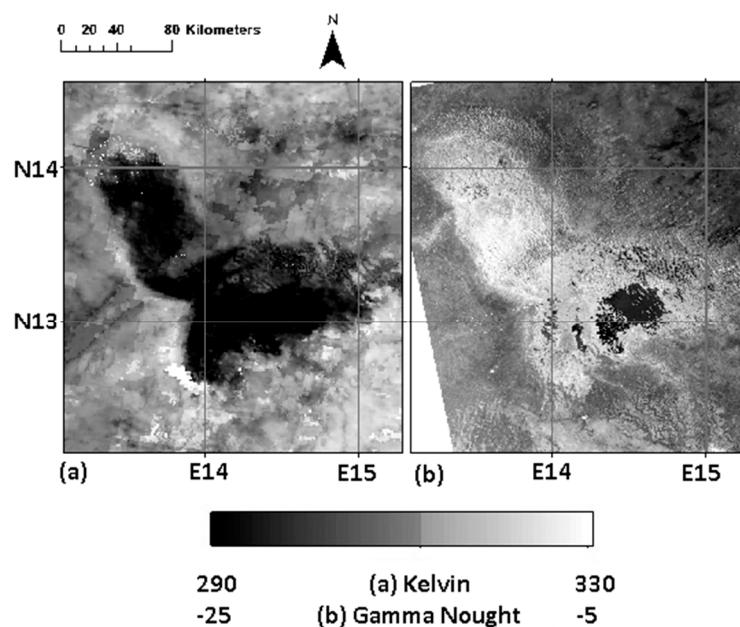


Figure 2. Examples of the remote sensing products used in this research (a) NASAMODIS Land Surface Temperature (LST) (9 May 2017–16 May 2017); (b) ESA Sentinel-1a C-band Radar (16 May 2017).

2. Materials and Methods

2.1. Overview of Datasets Used in this Study

The primary data sets used to determine the total surface water area of Lake Chad in this paper are the 8-day NASA MODIS Terra daytime LST product (MOD11A2, available from March 2000 to the present), the C-band radar data from ESA's Sentinel-1a mission (acquired every 12 days, available from April 2015 to May 2017), and monthly total surface water area data derived by [10] from Meteosat maximum daily LST measurements. The data used for the research by [10] were acquired from mid-1986 to mid-2001. Their data record for 1986 and 1987 was incomplete, so we used their area estimates from 1988 to 2001 to extend our record.

2.2. Daytime NASA MODIS LST data

The use of daytime LST data products ([16,17]) for analysis of total surface water area is based on the fact that areas containing surface water (including water obscured by vegetation) generally appear cooler than areas not containing water during daytime observation because of (1) the higher thermal inertia of surface water vs. non-water pixels; (2) the potential for mixing of cooler water from below; and (3) evaporative cooling of water pixels [10]. The use of LST was applied by [18] to map flooded vegetation in Lake Chad for a single dry season and by [10] to measure the total area of Lake Chad for the period 1986–2001.

2.3. ESA Sentinel-1a C-Band Radar Imagery

Remote sensing using radar data has the advantages that it can collect data from the surface during cloud cover, and that it can penetrate vegetation canopy to a limited extent. Eighteen Sentinel-1 C-band radar data sets were identified that were acquired during the dry season and completely covered the area of interest. Note that wet season radar data appeared to be unable to distinguish between soil moisture and flooded vegetation in places and were not used in this study [19]. The polarization configuration for these data sets was V-V. Using SAR data from the Sentinel-1a mission, we first generated multi-look amplitude images by averaging ten looks in range and ten looks in azimuth to reduce speckle noise. The ground size of a pixel resulting from this is 100 m. The amplitude images were also converted from digital number to the radar backscattering coefficient γ^0 in order to calibrate the radiometric Sentinel-1a SAR data for Lake Chad. Next, we carried out terrain correction (i.e., orthorectification) to determine the accurate locations of pixels in the multi-look images using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). Finally, we mapped the data onto a UTM projection, and then mosaicked the images to provide complete coverage of the lake.

2.4. Lake Area Estimation Using ESA Sentinel-1a C-Band Radar Data

We selected training sites for open water, flooded vegetation, and dry vegetation within and adjacent to the lake (see Figure 3). Detection of placid open water with SAR data is relatively straight forward because a transmitted radar pulse specularly reflects away from a side-looking SAR antenna giving the water very low values of backscatter [20]. The training site for open water was in the region of very dark radar pixels in the southern part of the lake and classified by the 0.5 km MODIS-based Global Land Cover Climatology [21] as open water. The training site for dry vegetation was in the region outside of the lake boundaries and classified by the 0.5 km MODIS-based Global Land Cover Climatology [21] as grassland. The training site for flooded vegetation was at the discharge of the Komadougou Yobe (also known as the Yobe) River. According to [12], “The input from the small River Yobe . . . is just sufficient to maintain a marshy area around its estuary.” It was found that the dry land backscatter was greater than the open water backscatter and the flooded vegetation backscatter was greater than the dry land backscatter. The high backscatter from flooded vegetation was considered to be due to the well-known “double-bounce” effect [20] that radar experiences in water with vertical vegetation surfaces from which to reflect.

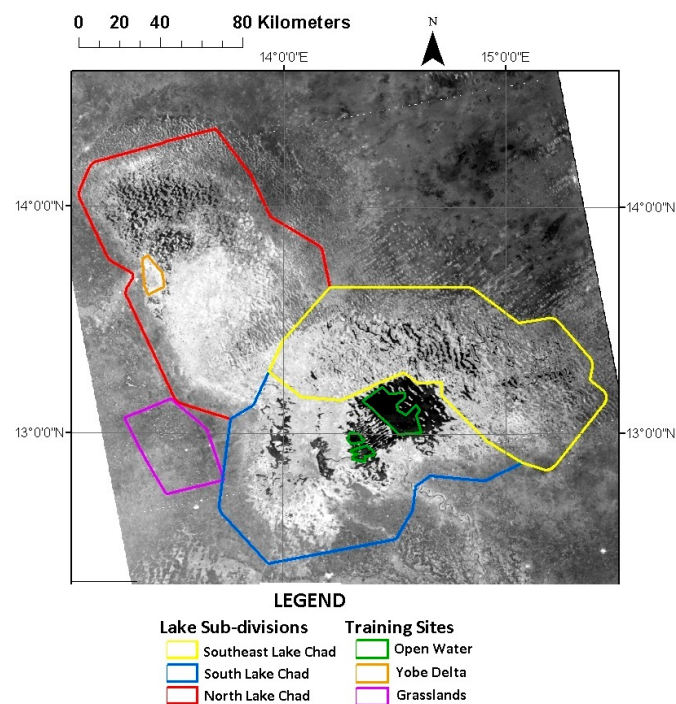


Figure 3. Lake sub-divisions and training sites identified in this study. The background image is from ESA Sentinel-1a C-band radar (9 April 2015).

2.5. Lake Area Estimation Using NASA MODIS Land Surface Temperature (LST) Data

As in [10], two-class unsupervised classification was performed on the data with the assumption (for reasons described above) that open water and flooded vegetation would be represented in the cooler of the two classes. The two-class unsupervised classification was performed on the 8-day LST products, then monthly total surface water areas were estimated by interpolation from the relevant 8-day areas for comparison with [10] and to extend the period of their monthly data record. We rejected MODIS LST datasets with higher than 5% cloud cover and/or “no data” pixels. Of the 482 8-day, dry season MODIS LST datasets, less than 4 percent were rejected for these reasons.

2.6. Comparison of Sentinel-1a Data with MODIS Land Surface Temperature (LST) Data

For the period of Sentinel-1a data (2015–early 2017), we made a comparison between the Sentinel-1a estimates of Lake Chad total surface water area and the areas of corresponding dates calculated using MODIS Land Surface Temperature data.

As a check on the spatial correlation of the SAR and LST-based maps of total surface water area, we divided the lake into three regions, (1) Southeast Lake Chad; (2) North Lake Chad; and (3) South Lake Chad, (Figure 3) roughly corresponding to the Archipelago, Northern Pool, and Southern Pool of the lake and made a comparison between the Sentinel-1a and MODIS LST estimates of the lake’s surface water area for these sub-divisions.

2.7. Compilation of Combined Total Lake Surface Water Area Estimates

We compared the adjusted MODIS LST-derived total surface water area data to the Leblanc et al. (2011) [10] data for the period of overlap, and made a modest bias adjustment to the Leblanc data based on the comparison.

Finally, a best estimate of the long-term time series of total lake surface water area was assembled by combining the bias adjusted findings of [10] and the radar-adjusted, LST-based time series generated by the research for this paper.

3. Results

This section presents the results related to our investigation of Lake Chad total surface water area. The technique used in this study to measure the total surface water area of Lake Chad with LST measurements is severely limited by the need to use it only under dry conditions to avoid confusing soil moisture with flooded area and experiencing data loss (Figure 4). Note the extensive area of cool temperatures (dark areas) during the wet season and the areas of data loss (white areas) in Figure 4a and compare this with the dry season (Figure 4b).

Use of C-band radar during the wet season seems to present a similar problem by failing to distinguish between soil moisture and flooded vegetation; notice in Figure 5a (wet season) the boundaries of the lake are not as clear as in Figure 5b (dry season). However, there are applications such as measuring total surface water area in the Sudd, or the Niger inland delta, or the Okavango Delta, that would also likely benefit from using both LST and radar remote sensing approaches during their dry seasons.

In the comparison of total surface water area from Sentinel-1a C-band radar with that from MODIS LST, we found a very low difference (less than 2 percent on average).

For each of the three regions and each of the 18 pairs of data sets, we determined the total surface water area calculated using the radar data and the LST data, and the percent difference between the two. We conclude that the surface water area calculated using the LST data is considerably more (31% on average) in Southeast Lake Chad, considerably less in North Lake Chad (19% on average), and very similar in South Lake Chad (0.3% greater on average); (Table 2). The fact that the average area for the total lake is very close (within 2 percent) for the two different methods appears to be entirely coincidental. We found that within each subdivision of the lake, the differences between image pairs (LST and radar) appeared to be random, with no systematic pattern within or across the subdivisions as a function of time.

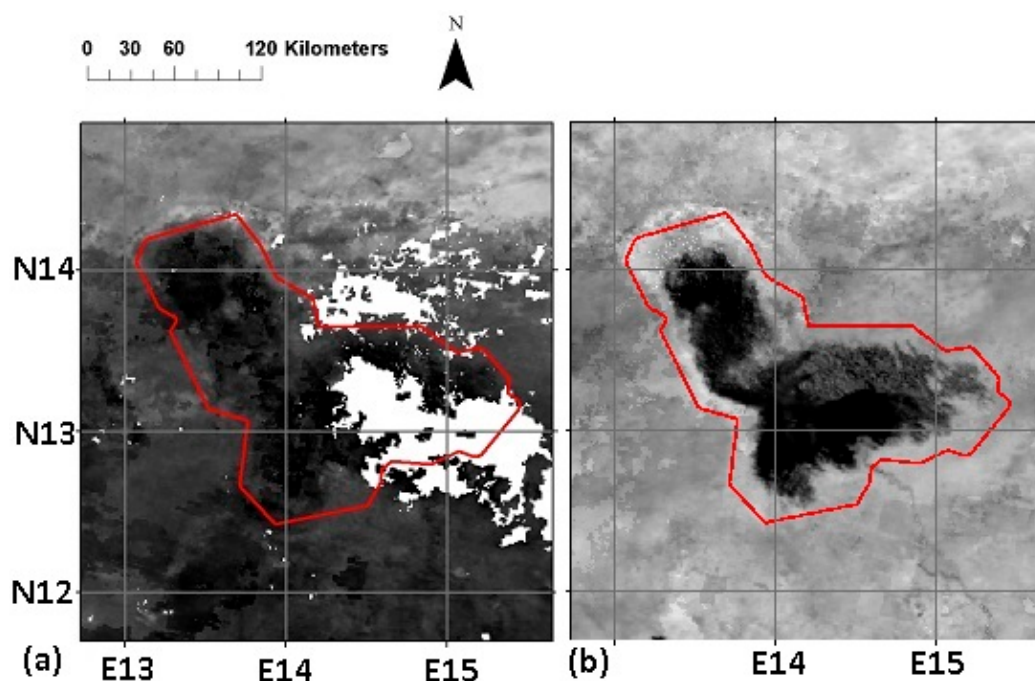


Figure 4. Example NASA MODIS Land Surface Temperature (LST) data during (a) wet season (12 August 2016) (b) dry season (15 April 2017) White areas in (a) are no data.

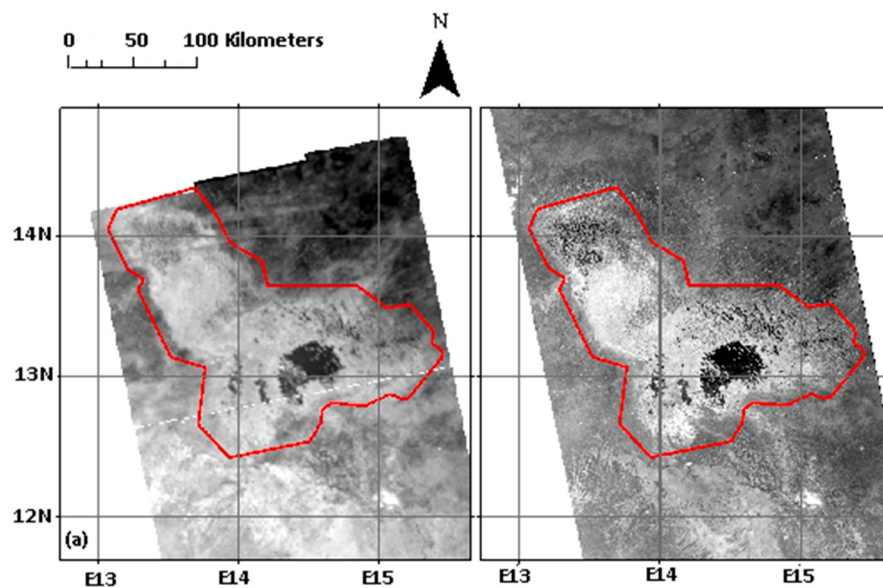


Figure 5. Example ESA Sentinel-1a C-band radar acquisitions, (a) wet season (16 July 2015) (b) dry season (9 April 2015).

Table 2. Lake Chad area calculations by subdivision of lake for 18 available pairs of ESA Sentinel-1a C-band radar and corresponding NASA MODIS Land Surface Temperature (LST) data.

	Average Total Surface Water Area Radar (sq. km)	Standard Deviation Radar (sq. km)	Average Total Surface Water Area LST (sq. km)	Standard Deviation LST (sq. km)	Percent Difference
Southeast Lake Chad	3472	312	4529	422	31
North Lake Chad	4954	811	4115	1337	−19
South Lake Chad	5029	192	5041	197	0.3
Total Lake Chad	13,455	1092	13,685	1354	2

There is a substantial publication record (e.g., [22–25]) for the use of radar data for mapping wetlands including flooded vegetation. Wilusz et al. (2017) [22] found that “low resolution C-band SAR imagery shows promise for long term study of Sudd wetland flood dynamics.” From a remote sensing perspective, the Sudd and Lake Chad have many similarities, and application of a successful technique in one area should encourage trial of that technique in the other. Radar has the advantage over LST of a relatively extensive history of use for mapping flooded vegetation. According to [24], “SAR (Synthetic Aperture Radar) has many characteristics that make it ideal for mapping and monitoring water and wetlands over time.” According to [26], “What is evident throughout the recent literature is that multidimensional radar data sets are attaining an accepted role in operational situations needing information on wetland presence, extent and conditions.” According to [27], “Because of the strength of penetrating vegetation canopy and acquiring ground information all day without the limitation of clouds, radar data ... are uniquely suited to identify and monitor changes of soil moisture, (and) flooding ... in wetlands.” Given the relative maturity of the radar approach vs. the LST approach, we decided to use the differences between radar and LST-based estimates for the three subdivisions to derive appropriate correction factors to adjust the LST-based total surface water area time series.

Figure 5 shows an example comparison of the LST and radar-derived water classifications. Note the spatial differences despite relatively close total surface water area estimates for these images. The example LST image (Figure 6a) contains close to 12,300 square kilometers of total surface water area, while the corresponding radar image (Figure 6b) contains approximately 12,100 square kilometers of total surface water area, a difference of approximately 2 percent.

After adjusting the MODIS LST-derived lake area results using the differences with radar and then comparing the adjusted MODIS LST lake area results with the [10] results using Meteosat LST, we found a low difference (our data was approximately 3 percent higher) during the period of overlap (dry season portion of March 2000–May 2001); see Figure 7.

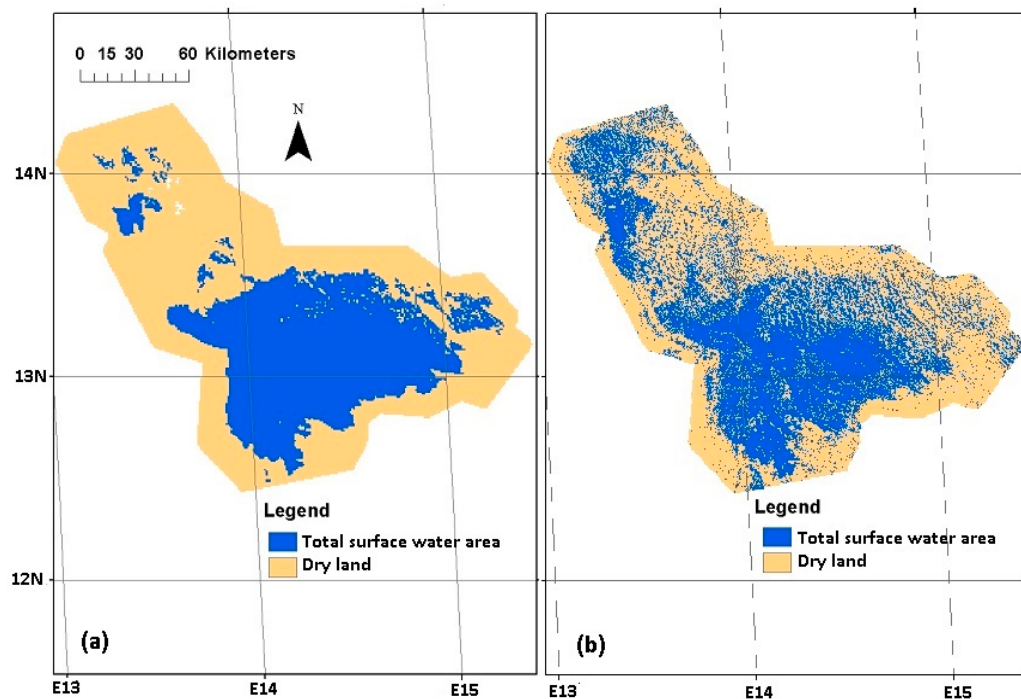


Figure 6. (a) Example NASA MODIS Land Surface Temperature (LST)-derived dry season water classification (31 October 2016–7 November 2016) (b) Example ESA Sentinel-1a C-band radar-derived dry season water classification (5 November 2016).

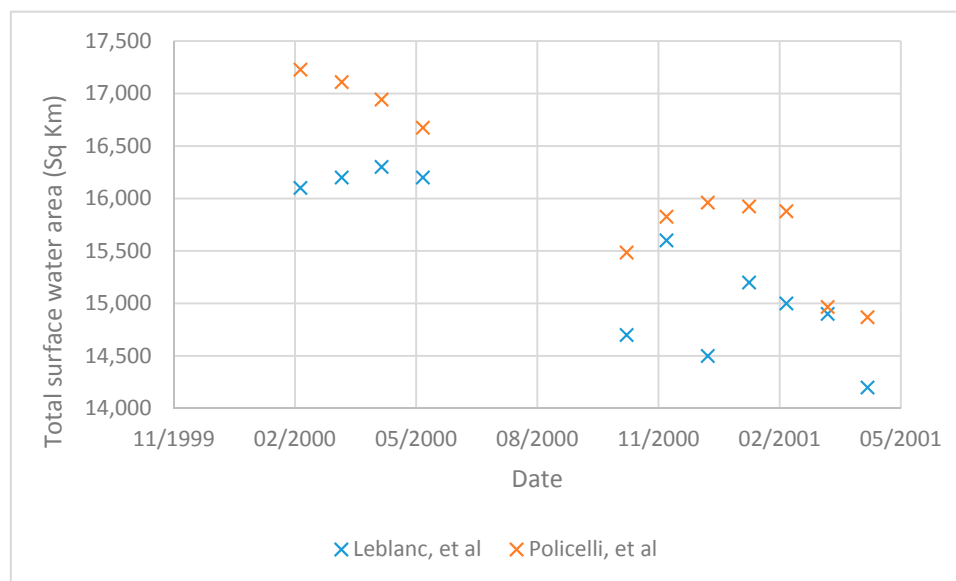


Figure 7. Comparison of Lake Chad total surface water area estimates using NASA MODIS Land Surface Temperature (LST) from this study with results from [10].

Based on the very similar results during the period of overlap, we concluded that it was appropriate to bias adjust the Leblanc data [10], and present a single integrated time series of the two data sets approximately doubling the period of lake total surface water area time series. In Figure 8, we plot the mean, maximum and minimum annual lake areas for each year (values are monthly), along with the mean, maximum, and minimum trend lines. Note that a given year represented on the graph corresponds to the dry season (November through May) starting in that year.

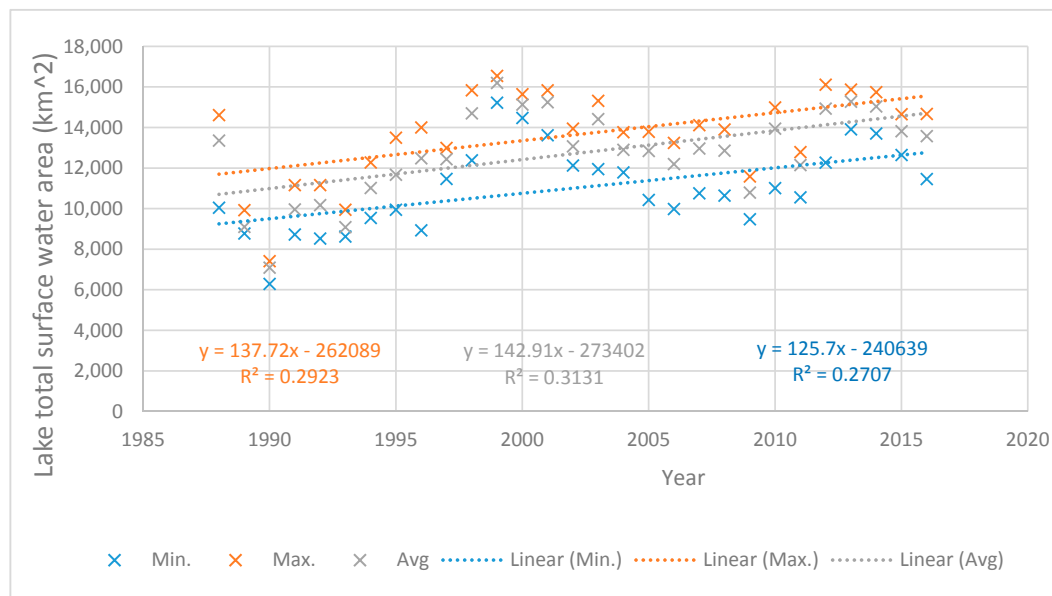


Figure 8. Annual mean, maximum, and minimum Lake Chad dry season total surface water area time series composite from [10] and the research for this paper. Each data point represents a full month. Trend lines are included.

The general trend for the average total surface water area of the lake (Figure 8) has been an increase of approximately 143 km^2 per year (slope of the average trend line). The R-Square value of the average trend line is 0.31 indicating high variability relative to the linear trend line. The slopes and the R-Square values are slightly lower for the maximum and minimum trend lines. A sinusoidal fit to the data is suggested by Figure 8 (with periodicity between 11 and 13 years) and may be the result of large-scale climate oscillations. The El Nino phase of ENSO has a known influence on Lake Chad water level variability [28]. However, “a much deeper understanding of the effect of other oceanic conditions like Atlantic Multidecadal Oscillation (AMO), Indian Ocean, and Mediterranean (oscillations) at different time-scales on Sahel precipitation is needed for a complete picture” [28] of Lake Chad level variability.

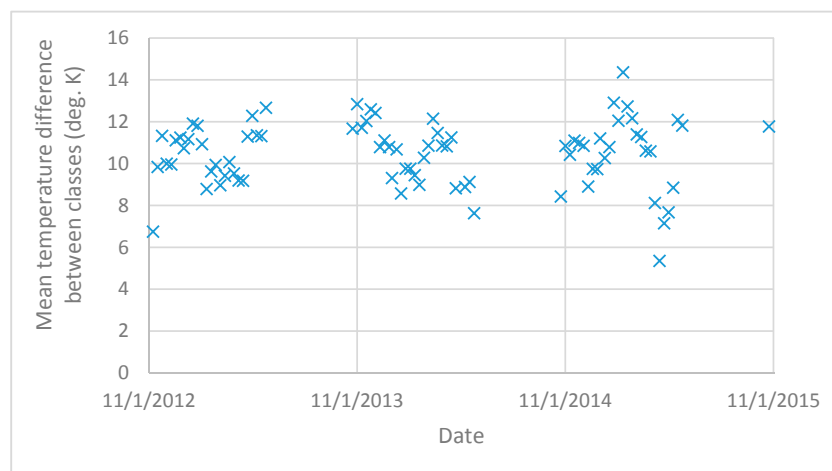
The 25th percentile of total surface water area is approximately 11,700 square kilometers, the 50th percentile is approximately 12,900 square kilometers, and the 75th percentile is approximately 14,400 square kilometers. The time series exhibits a sharp decrease in the first two years, followed by a rise from 1990 to 1999, and then declining to 2009, rising to 2012, and a short, moderate decline since then.

The data show that, for the dry season, November is the month with the smallest lake total surface water area on average and the highest lake total surface water area occurs in March on average (Table 3). There is considerable variability for each month.

Table 3. Monthly average Lake Chad total surface water area for dry seasons 1988–1989 through 2016–2017.

	November	December	January	February	March	April	May
Average Area (sq. km)	10,834	12,067	12,946	13,306	13,410	13,282	13,060
Standard Deviation (sq. km)	2090	2201	2270	2357	2361	2287	2284

During the 2-class unsupervised classification of the MODIS LST data, we found that there was a substantial difference in the mean temperature between the two classes. As can be seen from Figure 9, the mean temperature of the dry land class ranges between 5 and 15 degrees Kelvin above the average of the surface water class. This temperature difference provides a level of confidence that the two classes are sufficiently different to separate clearly. The maximum of the average surface water temperature was 310 degrees Kelvin (17–24 May 2010), and the minimum of the average surface water temperature was 292 degrees Kelvin (9–16 January 2002). The maximum of the average land surface temperature was 324 degrees Kelvin (17–24 May 2010), and the minimum of the average land surface temperature was 300 degrees Kelvin (1–8 January 2015). Again, only dry season data was used because of cloud contamination, data loss, and ambiguities between wet soil and inundated areas during the wet season.

**Figure 9.** Time series of mean temperature difference between classes (dry land surface temperature—water surface temperature) in the unsupervised classification of Land Surface Temperature (LST) data.

For the adjustment of the MODIS LST-derived total surface water area due to spatial disagreement with the radar data, we found that despite significant adjustments to the sub divisions of the lake, the average lake total surface water area was not changed greatly relative to the initial LST results. The average change of the total surface water area after adjustment of the sub divisions was about −1 percent, while the maximum change was about −8 percent. Figure 10 presents a time series of the change. Both the time series in Figure 10 and in Figure 8 have a down-up-down pattern of approximately the same shape since 2000, so there appears to be a tendency towards positive bias for unadjusted MODIS LST-derived total surface water area when dry season lake levels are high and a tendency towards negative bias when lake levels are low.

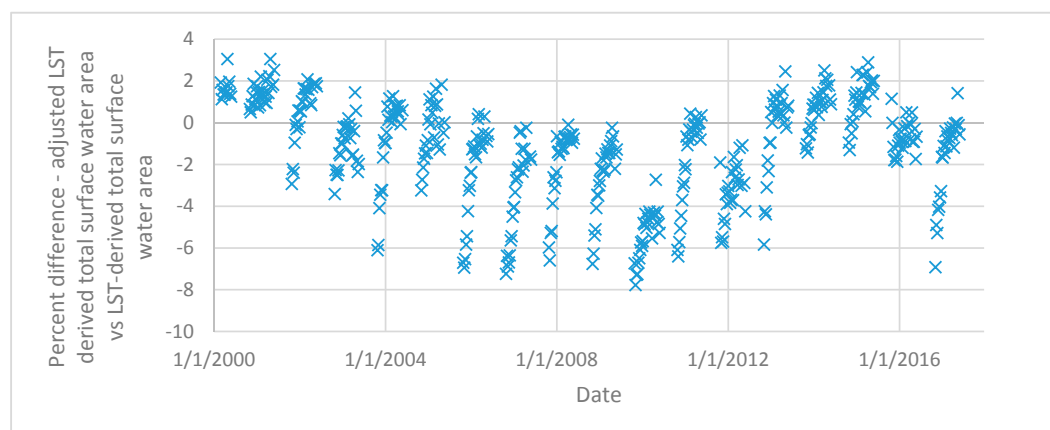


Figure 10. Percent difference between adjusted MODIS Land Surface Temperature (LST)-derived Lake Chad total surface water area and initial total surface water area. The results retain a strong seasonal signal from the source LST data.

4. Discussion

Use of the NASA MODIS Land Surface Temperature product has allowed us to extend the time series of Lake Chad's total surface water area by about 15 years, updating and approximately doubling what was previously available. Having this time series helps us answer some fundamental questions about the dynamics of the lake including "what is the average total surface water area of the lake?" and "is the lake shrinking or growing?"

There are many challenges associated with estimating the total surface water area of Lake Chad; chief among them are the apparently extensive amount of flooded vegetation, which cannot be identified as containing water using optical remote sensing instruments. Leblanc et al. (2011) [10], citing work by [7,29], subscribe to the idea that, "the transition from an 'Average' to a 'Small' Lake Chad in 1973 ... was accompanied by the development of aquatic vegetation which now dominates the inundated area of Lake Chad". To get an accurate accounting of the lake's total surface water area, it is necessary to measure both the open water and the area covered by aquatic or "flooded" vegetation. Any approach that ignores this is bound to significantly underestimate the total surface water area of the lake. We have chosen to use LST and radar remote sensing datasets, as these approaches are inherently able to retrieve information beneath modest canopy coverage. It appears that surface water area under vegetation cover is often left out of consideration of the area of Lake Chad. The main cause of this oversight is likely the challenge of using remote sensing techniques to estimate the area of flooded vegetation associated with the lake. Though they do not provide any detail on their methods, the World Lakes Database of the International Lake Environment Committee's estimate [13] that Lake Chad covers just 1540 km² is likely an example of this.

Other challenges include (1) the lack of ground-based measurements of the Lake Chad water extent, which precludes validation of the remote sensing approach using in situ data; and (2) the relatively coarse resolution of the LST data available, which makes it difficult to get accurate areas for the small bodies of water associated with the lake in northern and southeastern Lake Chad.

The results of [10], using Meteosat-based LST compare well with the overlapping period of adjusted MODIS LST-based results from this study; the Meteosat data is three percent lower on average. This similarity is to be expected because similar methods were used, however different LST data were used for the two sets of results, and Sentinel-1a C-band radar data were used to adjust the spatial biases in the MODIS LST data used in this study. The study by [10] did not compare their results with other remote sensing approaches, though they did have one in situ observation. Additionally, the resolution of the LST data (1 km) was higher for this study than for the [10] study (5 km), which should tend to give this study a better measurement of total surface water area. Atmospheric conditions such as clouds

and dust have the potential to impact measurements of total surface water area for both the MODIS and Meteosat-based LST approaches, though this has been mitigated by several methods including the use of dry-season data only and monthly averaging of data without significant cloud coverage.

According to [3], Lake Chad reached 14,000 square kilometers in April 2013. This is within close to ten percent of our figure of 15,600 square kilometers for the same month.

The results from [4] did not compare well with the results from this study. In general, the results from the current study are 2 to 3 times higher than the peak areas from [4]. The study by [4] used near-infrared bands to detect water, though this method will only detect open water. While [4] notes that some surface water area may be “masked by perimeter vegetation”, she does not mention the possibility of extensive masking by aquatic vegetation as cited by [10], and her values of total surface water area are considerably lower than for [10] and this study.

Because the reports of long term changes to Lake Chad described in the Introduction cover different time spans, they cannot be directly compared to our results, though it is worth mentioning that [9,11,12] show a large shrinking of the lake, and the results of [10] and this study show a modest net growth of the lake. On the other hand, indications of increased surface water area, rainfall, lake elevation, and flow to the lake by [4,13,15,16] are all consistent with a net growth of the lake during the period of our research.

As an example of model performance compared with our observation-based approach, Gao et al. [6] uses the Variable Infiltration Capacity (VIC) hydrological model [30] to estimate the total surface water area of Lake Chad from 1952 to 2006. From the late 1980s to 2006, they show a net rising trend in lake total surface water area, as does this study for the same period. In 1990 [6] calculates a peak area of approximately 5000 square kilometers (compared to our value of 7400 square kilometers); in 2000 they calculate a peak area of approximately 12,500 square kilometers, (compared to our value of 15,600 square kilometers) and in 2005 they calculate a peak area of approximately 10,000 square kilometers (compared to our value of 13,800 square kilometers). While the absolute values are very different, the trends are similar. The modeling approach has the advantage that total lake surface area can be forecast and wet season total lake surface area can be calculated. On the other hand, we expect observations of total lake surface area to be more accurate than calculation of area by a hydrological model, especially given the uncertainties of rainfall datasets over Africa [31], and the complex topography of the lake area.

Wilusz et al. (2017) [22] used only C-band radar for their analysis of the Sudd wetland flooded area in South Sudan. The radar data is not affected by clouds and can be taken during the day or night. While their results did not require adjustment, they were limited to five years of available data (compared to twenty-eight years in our study). In our analysis, we calculated total surface water area using two remote sensing methods, C-band radar and LST. The C-band radar and LST methods agree well in southern Lake Chad, which contains a great deal of open water. However, when determining total surface water area in north and southeast Lake Chad, two competing factors (i.e., penetration of canopy and spatial resolution) resulted in a difference between the C-band radar and the LST method. In north Lake Chad, where there is a large extent of vegetated water, the LST method underestimates total surface water area relative to the radar. C-band radar has the ability to penetrate vegetation canopy to some extent and detect surface water in flooded vegetation in addition to open water [19]. While the use of unsupervised classification on LST data can identify surface water through gaps in the canopy, this method can be negatively affected by the warmer canopy even though it is moderated by the cooling effect of vegetation through transpiration and other mechanisms [32]. In southeast Lake Chad, the landcover is mainly a mix of dunes and open water. The coarser resolution of the LST method tends to classify a large area of these mixed pixels as water due to the large difference between water and land surface temperatures, which leads to an overestimate of surface water area in this region relative to the radar. We adjusted for these under- and over- estimates by using a correction factor for each of the three sub-divisions for the data from this study and then used the adjusted data to bias correct the data from [10].

Extension of the Lake Chad area time series can be continued using MODIS LST as long as either MODIS on the NASA Terra or Aqua satellites is operating. However there is now another option with the LST product from the VIIRS sensor on the NASA Suomi NPP satellite, and soon to be available from the VIIRS sensors on the NOAA JPSS series of operational satellites. The VIIRS sensor provides LST data at a higher resolution (0.75 km) than the MODIS sensor or the Meteosat-based sensor [33].

5. Conclusions

In this study, we compared the Land Surface Temperature (LST) method and the radar method of measuring Lake Chad's total surface water area (open water plus flooded vegetation), assumed that the widely used, higher resolution radar method is more reliable, and adjusted the longer LST record using data from the radar method. We used 8-day NASA MODIS LST data from March 2000 to May 2017, ESA Sentinel-1a C-band radar data acquired from April 2015 to May 2017, and Lake Chad total surface water area data from a previous study for November 1988 to May 2001.

To identify the total surface water area of Lake Chad, we examined LST and radar datasets from which we derived similar overall areas, although with significant differences in the spatial coverage of each. The comparison of the LST and radar datasets likely suffered from the fact that it was necessary to use 8-day MODIS LST data to effectively clear clouds and provide complete datasets, as compared to the use of single day radar data, the fact that the radar data are much higher resolution (100 m resampled for radar, and 1 km for the LST), and the ability of radar to penetrate modest canopy coverage. C-band radar products from Sentinel-1a are relatively new, and there is no close analog on other platforms that was readily available for this study, with the exception of Sentinel-1b, which has an even shorter data record.

The availability of radar data from Sentinel-1a for a portion of the LST record enabled us to adjust the LST-derived total surface water area estimates and extend the existing total surface water area record for Lake Chad. A picture has emerged of the past 28 years of Lake Chad's total surface water area that is generally increasing, at an average rate of 143 square kilometers per year and with a great deal of variability (described above). For the dry season of 1988–1989 through the dry season of 2016–2017, we find that the maximum monthly average total surface water area of the lake was approximately 16,800 sq. km (February and May 2000), the minimum monthly average total surface water area of the lake was approximately 6400 sq. km (November 1990), and the average of the total monthly surface water area was approximately 12,700 sq. km. The 25th percentile of total surface water area was approximately 11,700 square kilometers, the 50th percentile was approximately 12,900 square kilometers, and the 75th percentile was approximately 14,400 square kilometers.

This research has addressed important questions about the size and trend of Lake Chad's total surface water area. Future efforts at mapping and calculating the area of Lake Chad would greatly benefit from in situ measurements, as well as the continuing radar and LST records.

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