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Spatio-Temporal Assessment of Changing Land Surface Temperature and Depleting Water in the Lake Chad Area

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Abstract

Lake Chad is located at the south of the Sahara Desert in an arid region. The lake's water resources are under severe pressure due to the basic needs of the growing population around the lake, global warming, and increasing irrigation demands. Numerous land cover change studies have measured the rate of depletion of the lake's surface water. However, the contribution of the increasing high temperatures in the region which is also a compounding factor has received little attention. In this study, an assessment of the changes in surface water extent of Lake Chad from 1973-2017 was carried out through a land cover analysis. The potential influence of the rising land surface temperatures on the water losses was also studied. The extraction of the land cover was done using maximum likelihood classification. The results show that between 1973 and 1987, the lake lost 12,796.81km^2 of its surface water area. This period coincided with a season of drought and dry seasons reported to have occurred in the lake's area during the 1970s. Between 1987 and 2003, average temperature rise and change in surface water area was +1.54˚C and +962.71km^2 respectively. Between 2003 and 2017, average temperature rise and change in surface water area was +3.69˚C and -25.17km^2 respectively. These results provide further evidence of the alarming rate of water loss in the lake's environment, and suggest a link between rising land surface temperatures and diminution of the lake's water. The findings inform efforts directed at addressing the ecological problem facing the lake.

Keywords: *Land Surface Temperature, Land Cover, Surface water, Landsat, Lake Chad.*

1. Introduction

The rapid diminution of Lake Chad's surface water is a subject of concern to the countries bordering the lake, scientists, and relevant establishments or agencies (Ikusemoran *et al.*, 2017). In the 1960s, Lake Chad was the world's sixth largest water body, with a surface area of 25,000km^2 (Mahmood and Jia, 2018). The lake's location in an arid region at the south of the Sahara Desert, coupled with the non-sustainable use of the rivers that empty into it, has subjected its water resources to an alarming rate of depletion. Previously, the lake was reported to have experienced a surface area depletion of about 90% (Gao *et al.*, 2011; GWP, 2013). Existing literatures have shown that the drastic reduction in the lake's surface area and water level since the

1970s can be attributed to natural and anthropogenic factors such as decreased precipitation over the lake's basin (over certain periods), increased irrigation, desertification and deforestation of the basin (Birkett, 2000; Odada *et al.,* 2006; Alfa *el al.,* 2008; Lemoalle *et al.,* 2008; Onuoha, 2008; Gao *et al.,* 2011). Studies have also shown that the potential for evaporation far outweighs the rainfall in the region (Yunana *et al.,* 2017). There are several arguments about the relative influence of each of these factors on the present state of the lake. Still, the depletion of the lake's surface water and degradation of its environment has been devastating on the socio-economic livelihoods of the surrounding inhabitants. This situation has led to unemployment, poverty, hunger, disease, and contributed to rising insecurity and terrorism in the region.

The problem of Lake Chad is actually multifaceted. FAO (2009) summarised some of the issues impacting the lake as follows: the variability of its hydrological regime and the dramatic decrease in freshwater availability; the loss of biodiversity; in particular, loss of plant and animal species, as well as damages to ecosystem health; the destruction and modification of its ecosystem due to the increasing occurrence of marshes within the lake; the sedimentation of rivers emptying into the lake which has led to a reduction in inflows; and the proliferation of invasive species. These problems have triggered a humanitarian crisis around the region. According to van de Wetering (2018), citing some United Nation sources, more precisely, 17.4 million people are living in affected areas, 2.3 million people have been displaced, 10.7 million are in immediate need for help, 488.000 children are suffering from extreme malnutrition and 5.8 million people are coping with food insecurity in this region. Furthermore, its location in the arid Sahel region, the damming of its contributing rivers and the drawing of water from the lake for irrigation purposes at the Southern Chad Irrigation Scheme, have also contributed to the depletion of the lake. The issue of Lake Chad's depletion due to these factors has led to a plethora of research initiatives (e.g. Thambyapillay, 1987; FAO, 2012; LCBC/WMO, 2015), and governmental intervention efforts, such as the establishment of the Lake Chad Basin Commission (LCBC), with no resulting permanent reversal of the deteriorating situation.

The continuous availability of satellite imagery has proven to be a valuable resource for monitoring changes in the environment over extensive periods. This comes with high degree of spatiotemporal accuracy and economically-effective management (Stavros, 2018). The continued developments in space technology have been critical to studying the physical processes which characterise the earth surface (Raj and Fleming, 2008). Application areas of satellite imageries include: environmental monitoring, biodiversity conservation, climate studies, meteorology, regional planning, agriculture, education, forestry and geology (Nwilo *et al.,* 2012; Stavros, 2018). According to Liu *et al.* (2015), satellite applications for characterising and quantitatively measuring landscape dynamics have proved to be one of the most effective methods of assessing the factors causing the changes and prediction of the likely future scenario (Boriah *et al.,* 2009; Garba and Brewer, 2013). Several studies have monitored the shrinkage of Lake Chad using land cover change detection methods (e.g. Alfa *et al.*, 2008; Ozah *et al.,* 2010; Sambi, 2015). The general consensus from these studies is that the lake has shrunk over time with its basin undergoing severe degradation.

Given the location of Lake Chad, the existing literature will benefit from an investigation into the changing Land Surface Temperature (LST) in the region using satellite imagery. This will contribute to the research exploring the relationship between observed changes in the lake's water extent and temperature variability. LST derivation using satellite imagery has been explored in many studies (e.g. Gallo *et al*., 1993; Carson *et al*., 1994; Balling and Brazell, 1988; Voogt and Oke, 2003; Nwilo *et al.*, 2012). It offers critical information and resources to addressing varying earth sciences subjects, including global climatic and environmental variations and other anthropogenic induced challenges (Mallick *et al.*, 2008; Li *et al.*, 2011). Its peculiar sensitivity to vegetation and moisture, also informs its application to detecting land use/land cover changes, e.g. tendencies towards urbanisation, desertification etc. (Mallick *et al.*, 2008; Haq *et al.*, 2012). In this study, the LST determination was executed sequentially in two steps in which the Land Surface Emissivity (LSE) was first computed and the LST was finally estimated while the lake's water extent was extracted using maximum likelihood classification.

2. Methods

2.1. Study area

The study area is Lake Chad, a fresh water lake in the African Sahel (Isiorho *et al.*, 1996) and its surroundings. The lake is shared by Chad, Niger, Nigeria, and Cameroon, while the basin additionally includes parts of the Central African Republic, Algeria, Sudan, and Libya (Policelli *et al.*, 2018). Its depth varies from 1.5 - 10.5m and it is about 215m above sea level, with apparently no outlet (FAO, 2009). The lake's drainage basin is geographically located between longitudes 7°-$24^{\circ}E$ and latitudes 6°-$24^{\circ}N$. The surface area of the basin is 2,434,000km^2, an estimated 8% of the total African land surface area, with about 60% of the basin lying on the southern edge of the Sahara Desert (UNEP, 2004; FAO, 2009). In the 1960s, Lake Chad was considered the sixth largest inland water body in the world (LCBC 2014; Okpara *et al.,* 2016). Today, the lake's water has shrunk into two halves of distinct water bodies: the northern and southern pools. This average situation of the lake is depicted in Figure 1.

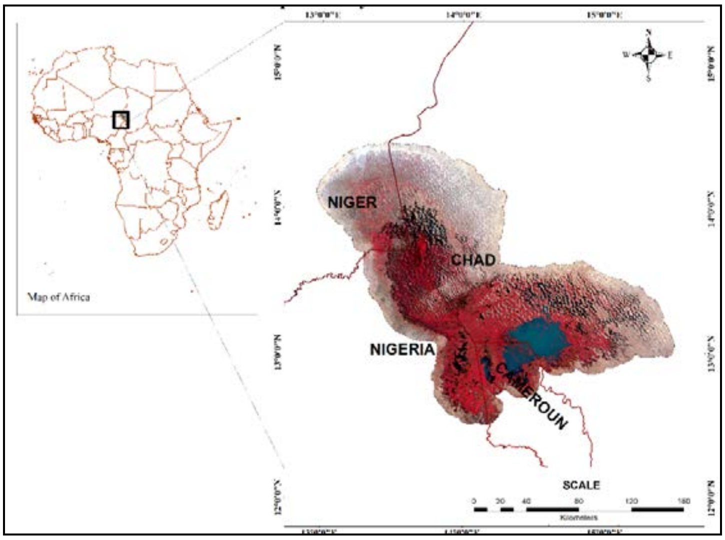

Figure 1. The average situation of Lake Chad, displayed in false colour from a Landsat image (Source: Author)

The Lake Chad basin is characterised by a tropical climate, involving four climatic zones: the Saharan climate, which is characterised by less than 100mm of rainfall per year; the Sahelian-Saharan climate, defined by an average yearly rainfall of 100-400mm; the Sahelian-Sudanese climate, characterised by an average annual rainfall of 400-600mm; and the Sudanese-Guinean climate, with an average annual rainfall of 600-1,500mm (LCBC, 2016). Ninety percent of the rainfall occurs in June to September, with an annual average rainfall over the entire basin of 320mm. The temperature deviation is very important as the temperature decreases during the rainy season and in the evenings during the dry season. The dry season occurs between October and April. The annual maximum temperatures are as high as 35-40°C particularly in the northern parts of the region. The average annual temperature of the islands within the lake and the surrounding areas is 21.4°C. The relative humidity is fairly low and varies with the altitude. The potential of evaporation is higher than the rainfall which is likely to justify the water deficit in some parts of the basin. Inhabitants around the lake basin have over a long period been well integrated, with strong cultural, social, and trade ties moving freely between the national borders. Fishing and pastoralism remain the main activities of inhabitants in the Lake area (Zieba et *al.,* 2017).

2.2. Data acquisition

This study relied on satellite imagery from four Landsat sensors – Landsat 1 Multispectral Scanner, MSS; Landsat 5 Thematic Mapper, TM; Landsat 7 Enhanced Thematic Mapper Plus, ETM+; and Landsat 8 Operational Land Imager/Thermal Infrared Sensor, OLI/TIRS. All were downloaded from the United States Geological Surveys (USGS) online portal. For the Land Surface Temperature, the thermal bands of scenes 184/50, 185/50 and 185/51 from TM (Band 6), ETM+ (Band 6_2), and TIRS (Band 10) were used. Landsat MSS has no thermal band. Table 1 shows the characteristics of the Landsat imageries.

Table 1. Characteristics of the Landsat imageries

Data	Acquisition Date (DD-MM-YYYY)	Source	Resolution (m)	Scene Acquisition Time (GMT+1)
Landsat 1 MSS	31-01-1973 31-01-1973 12-01-1973 30-01-1973	NASA/ USGS	60	08:56:50 08:57:15 08:51:12 08:51:55
Landsat 5 TM	31-01-1987 24-01-1987 22-01-1987 31-01-1987		30	09:44:27 09:38:02 09:49:57 09:44:04
Landsat 7 ETM+	04-02-2003 28-01-2003 11-02-2003 20-02-2003			10:12:51 10:06:34 10:18:42 10:12:32
Landsat 8 OLI/TIRS	17-01-2017 26-01-2017 08-01-2017 17-01-2017			10:24:24 10:18:10 10:30:14 10:24:00

2.3. Land Surface Temperature Determination

2.3.1. Derivation of Land Surface Emissivity

First, the Land Surface Emissivity (LSE) was derived from the emitted radiance measured from space using the formula by Sobrino *et al.* (2004). The derivation of LSE (ε) follows from Sobrino *et al.* (2004):

$$\varepsilon = 0.004Pv + 0.986 \qquad [1]$$

Where:

Pv - the proportion of vegetation, given by Carlson and Ripley (1997):

$$Pv = (NDVI - NDVI_{min} / NDVI_{max} - NDVI_{min})^2 \qquad [2]$$

Where:

$NDVI$ - Normalised Difference Vegetation Index, and is given as:

$$NDVI = (NIR - Red)/(NIR + Red) \qquad [3]$$

$NDVI_{max}$ = 0.5 and $NDVI_{min}$ = 0.2.

Red and *NIR* stand for the spectral reflectance measurements acquired in the red (visible) and near-infrared regions respectively. Generally, NDVI ranges from -1 to 1, with negative values usually representing water-bodies, values close to zero depict soil, while positive integers from 0.1 to 1 indicate vegetation.

The LST calculation utilised Landsat TM band 6 and TIRS band 10. Using the Single-channel method (Oguz, 2013), the following steps as described in Weng *et al.* (2004) were adopted to convert the Digital Numbers (DNs) to Land Surface Temperature (LST).

2.3.2. Conversion of DN to Spectral Radiance

For Landsat 5, the formula to convert DN to radiance is given by Zareie *et al.* (2016). For Landsat 8, the conversion followed the formula by USGS (2015).

$$L_\lambda = \left(\frac{LMAX - LMIN}{QCALMAX - QCALMIN}\right) \times (QCAL - QCALMIN) + LMIN \quad [4]$$

Where:

L_λ - spectral radiance at the sensor's aperture (Watts/(m^2*sr*µm).

QCAL - quantized calibrated pixel value in DN.

LMIN - spectral radiance scaled to QCALMIN.

LMAX - spectral radiance scaled to QCALMAX.

QCALMIN - minimum quantized calibrated pixel value (corresponding to LMIN) in DN.

QCALMAX - maximum quantized calibrated pixel value (corresponding to LMAX) in DN.

For Landsat 8, the following formula was used to derive the spectral radiance (USGS, 2015):

$$L_\lambda = M_L \times QCAL + A_L \quad [5]$$

Where:

M_L - radiance multiplicative scaling factor for the band.

A_L - radiance additive scaling factor for the band.

LMIN, LMAX, QCALMIN, QCALMAX, M_L and A_L are sourced from the Landsat metadata file.

2.3.3. Conversion of Spectral Radiance to Top-of-Atmosphere Brightness Temperature

Once the spectral radiance was computed, the brightness temperature at the satellite level was directly calculated using the approximation formulae given by Schott and Volchok (1985); Wukelic *et al.* (1989); Goetz *et al.* (1995); Qin *et al.* (2001); Ngie *et al.* (2010) and Zareie *et al.* (2016).

$$T = K_2 / \log(1 + K_1 / L_\lambda) \quad [6]$$

Where:

T - Top of Atmosphere Brightness Temperature (deg K)

K_1 *(Wcm^{-2}sr^{-1}µm^{-1})* and K_2 *(deg K)* are pre-launch calibration constants. Values for K_1 and K_2 for Landsat TM and ETM+ are shown in Table 3, while Table 4 shows the values for Landsat 8 TIRS.

Table 3: Landsat TM and ETM+ Thermal Band Calibration Constants

	Landsat 5 TM	**Landsat 7 ETM+**
K1	607.76	666.09
K2	1260.56	1282.71

(Source: Ghulam, 2010).

Table 4: Landsat 8 TIRS Thermal Band Calibration Constants

	Band 10	**Band 11**
K1	774.89	480.89
K2	1321.08	1201.14

(Source: Zhang *et al.*, 2016)

2.3.4. Conversion of Brightness Temperature to Land Surface Temperature

The equation for conversion from brightness temperature to LST follows Weng *et al.* (2004), Cummings (2007) and Zareie *et al.* (2016).

$$S_T = \frac{T}{1+(\lambda\times T/\rho)\log\varepsilon} \quad [7]$$

Where:

S_T - Land surface temperature (deg K)

λ - Wavelength of emitted radiance (11.5 μm),

ε - Land surface emissivity (typically 0.95)

ρ - $h * c/\sigma$ = $1.438*10^{-2}$mK (σ - Boltzmann constant = $1.38*10^{-23}$ J/K, h - Planck's constant = $6.626*10^{-34}$Js, c - velocity of light = $2.998*10^{8}$ m/s).

Finally, the LST in Kelvin was converted to Celsius by subtracting from 273.15, which is the centigrade constant.

2.4. Extraction of Surface Water Extent

The surface water extent was extracted from false colour composites of Landsat imageries using the maximum likelihood classifier on ENVI software. The following band combinations were used to generate false colour composites: 1973 MSS (4-3-2); 1987 TM (4-3-2); 2003 ETM+ (4-3-2); and 2017 OLI (5-4-3). Before running the classification, the MSS composite was resampled from 60m to 30m resolution using the bilinear resampling method. This was done to ensure uniformity in spatial resolution of all Landsat scenes. In the classification, training sites for water bodies were first created and the maximum likelihood classifier was run to detect areas with spectral signatures corresponding to water. The classification accuracy was ascertained by the standard method of confusion (error) matrices. For each classified image, more than 200 sample points across all feature categories, randomly selected were evaluated with reference to the original image as reference. The overall accuracy measure for the 1973 land cover assessment was obtained as 74.95% with a Kappa coefficient of 0.641. This implies that that 74.95% of the classification agreed with the reference data for the 1973 epoch. In 1987, 2003 and 2017, the overall accuracies and kappa coefficients derived were 86.29% and 0.8294, 87.40% and 0.8492, and 93.53% and 0.9183 respectively. The output of the classification was then vectorised and exported as shapefile format to ArcGIS. In ArcGIS, the shapefile was further edited to clean up any errors in the classification, and the subsequent extraction of the surface water layer.

3. Results and Analysis

3.1. Normalised Difference Vegetation Index

In the process of deriving the Land Surface Emissivity, the Normalised Difference Vegetation Index (NDVI) was calculated and the observed ranges at the three epochs are: 1987 ($-0.64 \leq NDVI \leq 0.75$), 2003 ($-0.56 \leq NDVI \leq 0.95$) and 2017 ($-0.58 \leq NDVI \leq 0.78$). In 1987, the specific NDVI ranges for each feature are surface water ($-0.64 \leq NDVI \leq 0.00$), soil ($0.01 \leq NDVI \leq 0.06$) and vegetation cover ($0.07 \leq NDVI \leq 0.75$). In 2003, the specific NDVI ranges are surface water ($-0.56 \leq NDVI \leq -0.07$), soil ($-0.07 \leq NDVI \leq -0.04$) and vegetation cover ($0.00 \leq NDVI \leq 0.95$) while the ranges for 2017 are surface water ($-0.58 \leq NDVI \leq 0.01$), soil ($0.02 \leq NDVI \leq 0.20$), and vegetation cover ($0.21 \leq NDVI \leq 0.78$) respectively. Table 2 presents a summary of the NDVI values.

Table 2. Range of derived NDVI values

Features	**1987**	**2003**	**2017**
Water	-0.64 – 0.00	-0.56 – -0.07	-0.58 – 0.01
Soil	0.01 – 0.06	-0.07 – -0.04	0.02 – 0.20
Vegetation	0.07 – 0.75	0.00 – 0.95	0.21 – 0.78

3.2. Land Surface Temperature Changes

The Land Surface Temperature maps are shown in Figures 2 – 4 respectively. The findings show a general trend of increasing surface temperatures in the region from 1987–2017. Within this period, the highest temperature increase of 11.35$°C$ in the Nigerian axis was observed in Budga, Ngala Local Government Area of Borno State. In Gambarou of the Lac region of Chad, and Eredibe, North-West of the Cameroun, highest temperature increases were 6.62$°C$ and 9.39$°C$ respectively. The observed minimum and maximum temperatures across the entire area recorded at approximately 9am GMT by the Landsat sensors are as follows: January 1987 (min: 15$°C$; max: 39$°C$), January/February 2003 (min: 7$°C$; max: 41$°C$) and January 2017 (min: 8$°C$; max: 43$°C$). The period of these observed temperatures coincides with the long dry season experienced in the surrounding countries of Lake Chad. For example, the dry season in Northern Nigeria lasts from October – April with high temperatures and low humidity. In Chad, the dry season lasts from October – May; in Cameroon, the dry season is from December – March while Niger also has a long dry season from October – May. This rise in the daily maximum LST is largely attributable to increased global warming and also a consequence of the severe encroachment by desert sands on the lake. Large portions of the lake now covered by desert sands trap the incoming solar radiation during the day thus leading to increased heating of the land surface.

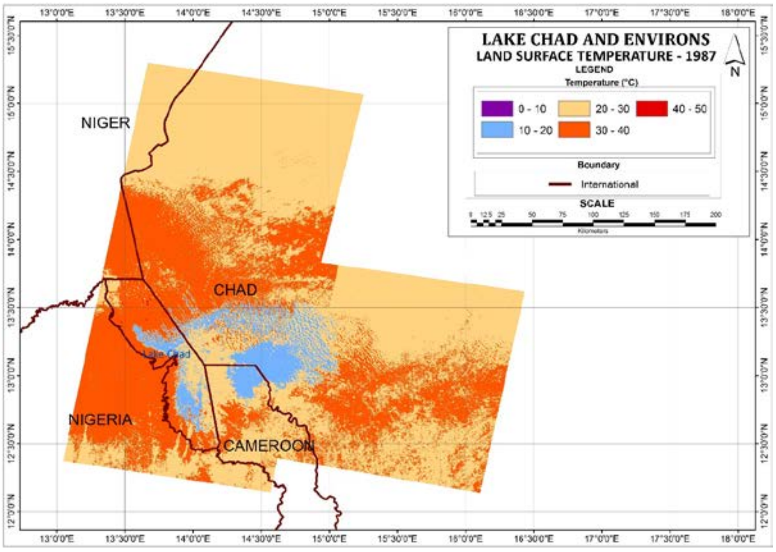

Figure 2. Map of Land Surface Temperature over Lake Chad – 1987

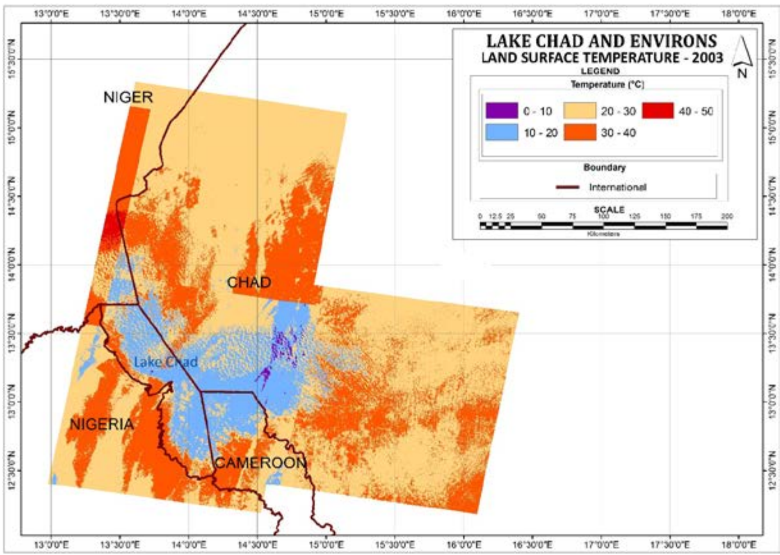

Figure 3. Map of Land Surface Temperature over Lake Chad – 2003

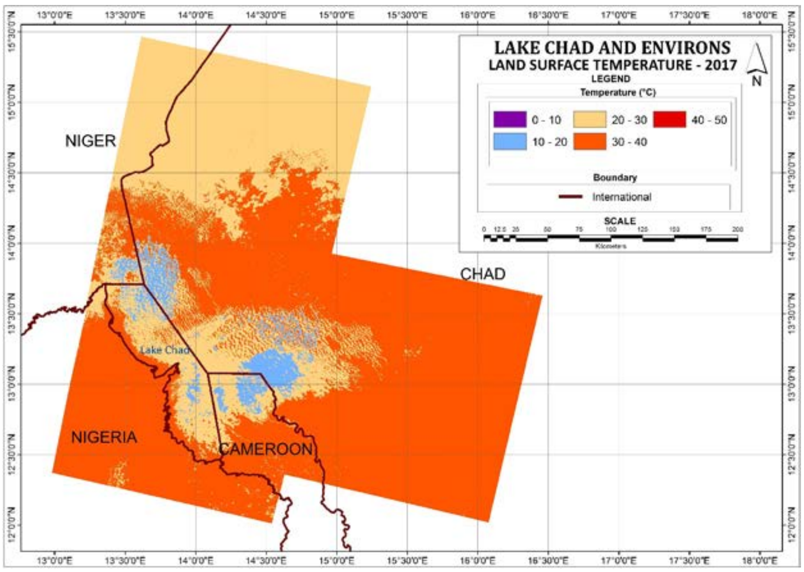

Figure 4. Map of Land Surface Temperature over Lake Chad – 2017

A summary of temperature changes (measured in degree Celsius) at some selected towns in Nigeria, Chad and Cameroun are presented in Table 3. The temperature variation follows the general trend of increase from 1987–2017.

Table 3. Temperature variation at some selected towns

Country	Main Towns	Latitude	Longitude	Temp ℃ (1987)	Temp ℃ (2003)	Temp ℃ (2017)
Chad	Chari-Baguirmi	12.24	15.79	30.83	30.77	33.37
Chad	Kanem	14.1	14.9	28.76	31.49	30.38
Chad	Lac	13.62	15.3	27.51	29.02	32.48
Chad	Hadjer-Lamis	12.35	15.93	29.17	30.33	33.85
Cameroon	Far North	12.43	14.87	29.29	28.78	34.2
Cameroon	Far North	12.41	14.23	29.53	30.37	32.11
Cameroon	Far North	12.53	14.36	29.61	31.82	32.58
Nigeria	Marte	12.42	13.85	24.64	32.1	35.57
Nigeria	Ngala	12.3	14.2	27.93	30.58	39.28
Nigeria	Monguno	12.39	13.3	28.49	26.32	35.92
Nigeria	Kala-Balge	12.36	14.36	27.02	28.5	31.24
Nigeria	Guzamala	12.68	13.24	29.59	30.81	34.19
			Average	**28.53**	**30.07**	**33.76**

3.3. Lake's Surface Water Losses

Table 4 shows changes in the lake's surface water extent from 1973–2017, while Figure 5 shows the map of the lake's surface water at the same epochs with the LST analysis (other than the 1973 images). The analysis shows that the surface water area decreased from 15,648.79km^2 in 1973 to 2,851.98km^2 in 1987. In the period under study, 1973–1987 was the driest in the Lake Chad region due to a devastating drought which spanned over a decade, as such the drastic depletion of the lake's water, given the surface water dependence on seasonal precipitation. Other researchers have shown that during this period, there were uncoordinated intensive irrigation projects and construction of large dams including the Tiga and Challawa Gorge dams along the Kano-Hadeija water system which drains into the Komadugu-Yobe River (Alfa *et al.*, 2008; Ebenki, 2010). As a result, the rainfall and inflow from tributaries was not enough to balance the massive evaporation of the lake. In 2003, the surface water area of the lake subsequently increased to 3,814.69km^2. In relation to the LST map of 2003 shown in Figure 3, this increase in surface water area of 2003 can be attributed to the cessation of the climatic extremity in the area brought about by the drought of the 1970s. According to Isiorho *et al.* (1996), and Odada *et al.* (2006), the lake experienced a major decline in water level and surface area due to a long drought period which ravaged the Lake Chad Basin between the 1970s and 1980s. The end of the drought brought about a decline in water losses caused by evaporation and a gradual recovery of the lake's biodiversity. In 2017 however, the water reduced to 3,789.52km^2. Overall, from 1973–2017, the lake lost about 11,859km^2 (75%) of its surface water area.

Table 4. Changes in Lake Chad's surface water area

Year	1973	1987	2003	2017
Area (km^2)	15,648.79	2,851.98	3,814.69	3,789.52

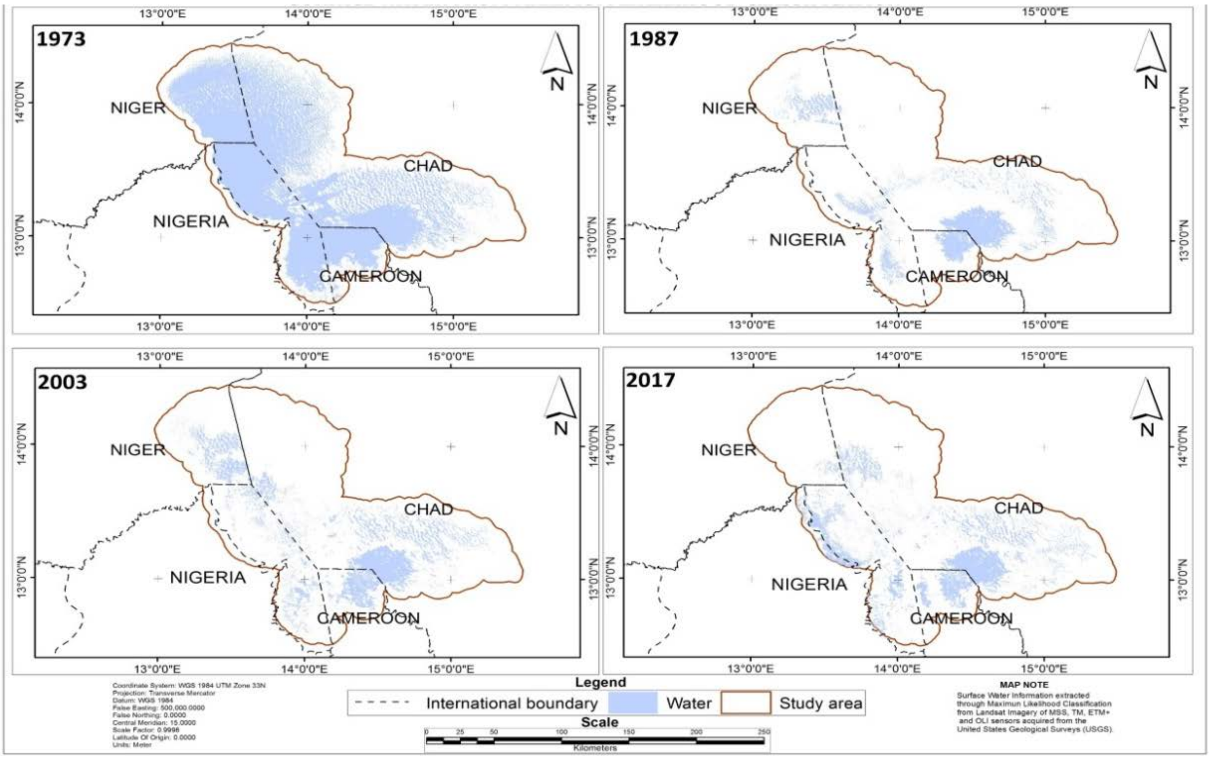

Figure 5. Changes in Lake Chad's surface water extent, 1973 - 2017

The above findings show a possible correlation between the depletion of the lake's water and the severity of the temperature rise within the same period. Table 5, along with Figure 6 shows the relationship between temperature changes and areal changes in the extent of the lake's surface water from 1973-2017.

Table 5. Relationship between the Surface Area and Average Temperature

Year	**1973**	**1987**	**2003**	**2017**
Area (km^2)	15648.79	2851.98	3814.69	3789.52
Area *100 (km^2)	156.49	28.52	38.15	37.8952
Temp (˚C)	-	28.53	30.07	33.76

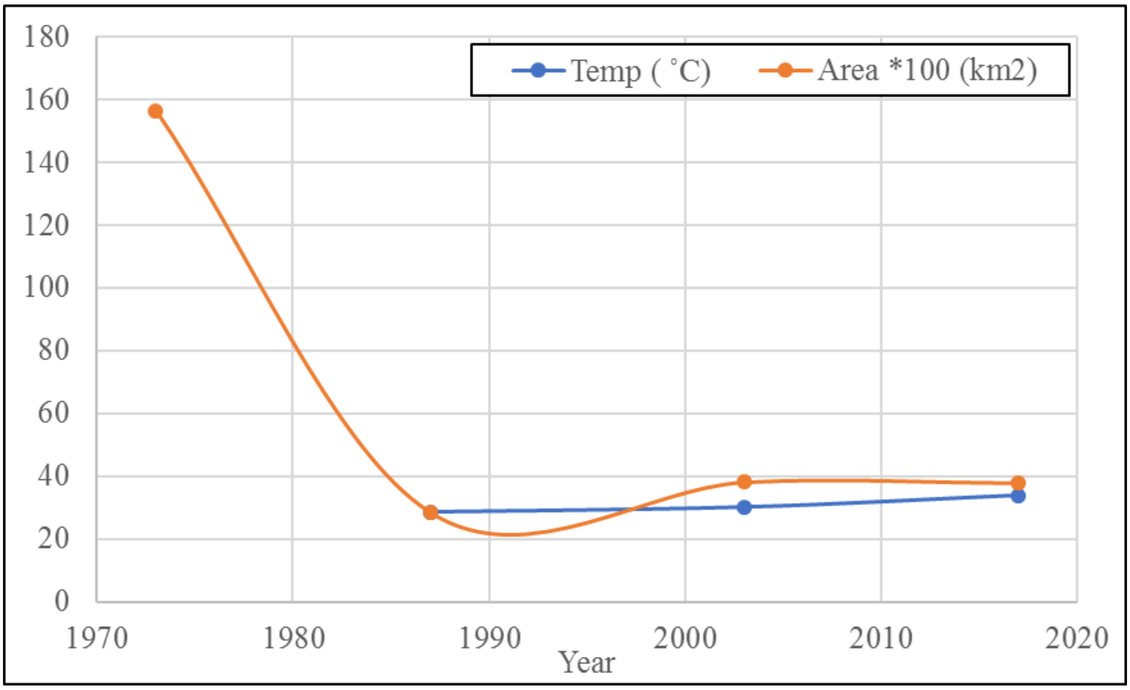

Figure 6. Relationship between land surface temperature and Lake Chad's surface water area changes

4. Conclusions

To advance knowledge on the reported water loss in Lake Chad, this study has assessed the changes in land surface temperature and the depletion of the lake's surface water in the period 1973-2017. Between 1973 and 2017, the lake's surface water extent reduced by about 75% (12,796.81km^2). The findings suggest a possible influence of increasing land surface temperatures on the drying up of the lake and provide alarming evidence of ongoing desiccation of the lake's water. Other factors influencing the diminution of the lake's water may include the demands of an overbearing population, and rainfall variability. According to Singh *et al.* (1999), between 1960 and 1990, the number of people living in the lake's catchment area doubled from 13 million to 26 million. The demand for water by inhabitants of the Lake Chad area has also increased overtime; the demand for water for irrigation is estimated to have quadrupled between 1983 and 1994 (GEF, 2007).The situation of the drying lake has degraded the lake's environment and biodiversity, and disrupted the socio-economic livelihoods of the people living within the lake's basin.

5. Recommendations

There needs to be an increased understanding among neighbouring countries of the need for a shared commitment to sustainable management of the Lake Chad basin. The shrinking of the Lake Chad poses a threat to the social and economic well-being of the people in its basin. To reverse this trend:

1. The concerned countries should determine the possibility, or otherwise, of using inter-basin transfer to recharge the lake.

2. Research Centres of Excellence should also be established for the promotion of education, training, research collaboration and skills transfer among the member states of the Lake Chad Basin Commission.
3. For this collaboration among member states to thrive, it is necessary for the current situation of insecurity and regional instability to be resolved fast.
4. For a more comprehensive study of the changing land cover, land surface temperature, and environmental dynamics in the basin, the study area can be extended to cover the entire Lake Chad basin in future efforts, and
5. Studies on the impacts of the underlying geological formations and crustal movements on the water depletion should also be considered.

6. Acknowledgements

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