RECENT CHANGES IN LAKE CHAD'S SURFACE WATER EXTENT A REMOTE SENSING ASSESSMENT USING SENTINEL-2 LAND COVER DATA (2017-2025)

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Abstract. Lake Chad is an endorheic freshwater lake located at the junction of four countries; Nigeria, Niger, Chad, and Cameroon in West-Central Africa. Lake Chad, once one of Africa's largest freshwater bodies, has experienced significant hydrological fluctuations over the past decades. While long-term historical analyses highlight a severe 90% surface area contraction since the 1960s, short-term operational variations over the last decade require precise quantification to inform active transboundary water management strategies. To address this critical gap, this study aims to develop a replicable remote sensing framework using high-resolution satellite data to quantify Lake Chad's open water and flooded vegetation dynamics from 2017 to 2025, providing evidence-based insights for sustainable water resource management. The methodology encompasses a comprehensive remote sensing analysis of the contemporary surface water extent of Lake Chad using the high-resolution (10-meter) Esri Sentinel-2 Land Use/Land Cover (LULC) time-series dataset. Through a systematic methodology involving image clipping, reclassification, and area calculation, the study tracked changes in open water, flooded vegetation (wetlands), and total lake system extent. Findings reveal a substantial recovery of the lake system, with total area expanding from 5,808.12 km² in 2017 to 11,588.14 km² in 2025, representing an absolute net growth of 5,780.02 km² (99.5% increase). While the lake has not fully recovered to its historic 1960s extent of approximately 25,000 km², it currently exhibits its most water-abundant state since the turn of the 21st century. These findings have significant implications for water resource management, regional food security, and the livelihoods of approximately 50 million people dependent on the Lake Chad basin.

Keywords: Lake Chad, Remote Sensing, Land Use Land Cover, Surface Water Extent, Sentinel-2, Hydrological Dynamics, Flooded Vegetation

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Author contributions

U.Y conceived the study and was responsible for the design and development of the data analysis. U.Y and U.Z.U were responsible for data collection and analysis. U.Y and U.Z.U were responsible for data interpretation. U.Z.U wrote the first draft of the article.

Disclosure statement

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

1. Introduction

In the hyper-arid and climate-vulnerable Sahelian region of Africa, the critical importance of freshwater security is paramount, particularly across transboundary zones prone to severe recurrent droughts and complex socio-ecological conflicts (Anghileri et al., 2024). Within this fragile landscape, the structural footprint of Lake Chad serves as an indispensable lifeline, stabilizing regional ecosystems and anchoring the socioeconomic livelihoods of tens of millions of people through its rich aquatic and freshwater resources. As one of Africa's largest endorheic basins, Lake Chad provides critical ecosystem services and sustains the livelihoods of approximately 2 million people who reside in its immediate vicinity, with an additional 50 million people across the broader region dependent upon the lake's resources for their economic well-being. The lake provides critical resources for fishing, irrigated agriculture, and pastoral livelihoods (Ndimele et al., 2024; Onana, 2023). However, its geographical positioning makes it highly sensitive to sub-Saharan climate variations, cementing its status in global literature as a primary indicator of climate-driven environmental change. Lake Chad freshwater lake is situated at the junction of four countries Nigeria, Niger, Chad, and Cameroon in western and central Africa (Policelli et al., 2018; Olowoyeye and Kanwar, 2023; Yapiyev et al., 2017), with a catchment area exceeding 1,000,000 km² (390,000 sq mi), it represents one of the most important wetland ecosystems in West-Central Africa (Onana, 2023).

It was observed by Policelli et al., (2018) that during the latter half of the 20th century, the lake was widely categorized as a disappearing basin, with legacy satellite records charting a collapse from more than 22,000 km² in the 1960s to less than 2,000 – 3,000 km² during the historic Sahelian droughts of the mid-1980s. This severe structural shrinkage induced profound economic volatility, accelerated regional desertification, and catalyzed widespread security crises. Between 2003 and 2022, Lake Chad maintained an average surface water extent of approximately 2,475 km², characterized by high seasonal and inter-annual variability driven by regional rainfall, river discharge from the Chari and Logone rivers, and intense high evaporation rates (Fokeng et al., 2024; Meli et al., 2024).

While early satellite studies focused strictly on open-water shrinkage, recent multi-sensor approaches using Modified Normalized Difference Water Index (MNDWI) and Sentinel-2 reveal that Lake Chad has maintained a stable, highly dynamic seasonal equilibrium over the past two decades. Total inundation area, which includes open water and water hidden beneath massive macrophyte canopy covers, shows an overall recovery trend driven by monsoonal precipitation and significant groundwater interactions. This study aims to (i) verify the recent dynamics of Lake Chad's surface area using high-resolution satellite data, (ii) develop a replicable methodology for assessing lake hydrological status using freely available remote sensing data, (iii) quantify changes in open water and flooded vegetation areas between 2017 and 2025, and (iv) provide evidence-based insights for water resource management and policy decisions.

Traditional remote sensing methodologies focusing strictly on "Open Water" indices systematically miscalculate the true hydrological footprint of the lake ecosystem. To address this critical gap, this study aims to develop a replicable remote sensing framework using high-resolution satellite data to quantify Lake Chad's open water and flooded vegetation dynamics from 2017 to 2025, providing evidence-based insights for sustainable water resource management. By systematically accounting for both exposed open-water surfaces and hidden water sub-canopies (flooded vegetation), this research transitions away from generic land cover assessments to deliver an automated, verified baseline for transboundary policy decisions.

Over the last decade, regional precipitation shifts have driven stark seasonal fluctuations, requiring continuous, high-fidelity monitoring of its borders. Accurately assessing these changes between 2017 and 2025 is essential, as this window captures recent severe weather extremes and regional water management initiatives across the basin. This work provides the most up-to-date, high-resolution dataset of the Lake Chad's true hydrological footprint. By separating open water from macrophyte-covered zones, the findings challenge traditional degradation models and supply transboundary water management authorities with the empirical framework necessary for viable climate adaptation planning.

2. Methodology

2.1. Study Area

Lake Chad is situated at an altitude higher than 300m above the mean sea level where the Sahara Desert meets the Savannah lands (Buma et al., 2018). It spans through Niger, Nigeria, Chad and Cameroon (Figure 1).

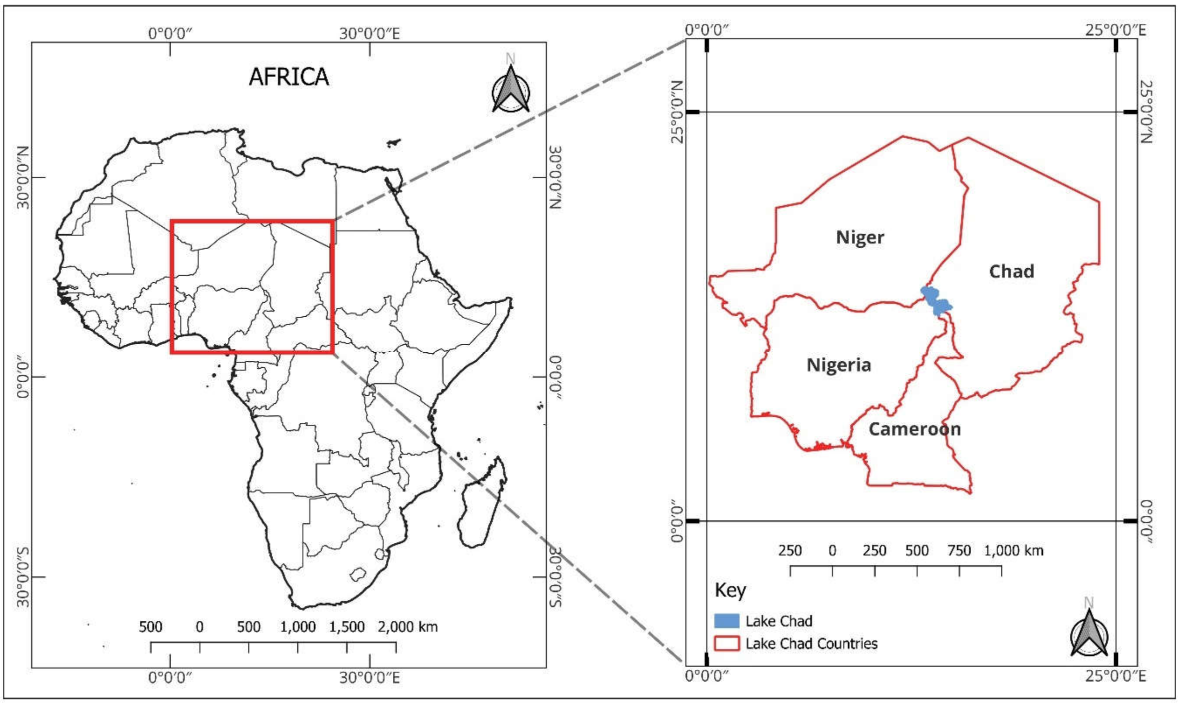

Figure 1: Map of the study area showing lake Chad at the junction of the four African countries.

The lake occupies a central position within the semi-arid Sahelian belt, approximately between latitudes 12°30′N and 14°30′N and longitudes 13°E and 15°E (Figure 1). The lake is sourced by two main contributing areas, the Chari-Logone and the Komadugu-Yobe headwaters, direct surface rainfall, and groundwater flows (Fokeng et al., 2024). Open surface water bodies and groundwater offer better opportunities for rain-fed agriculture for over 60% of the population (Vaquero et al. 2021). Historically one of Africa's largest inland water bodies, Lake Chad has experienced dramatic fluctuations in surface area over the past century, ranging from approximately 25,000 km² in the 1960s to less than 2,000 km² during severe drought periods in the 1980s.

Lake Chad is a shallow, closed-basin lake with an average depth of only 3m, making it highly sensitive to climatic variability and anthropogenic water withdrawals (Pham-Duc et al., 2020). The lake's bathymetry is characterized by two distinct basins: the southern basin, which is deeper and retains open water more consistently, and the northern basin, which is shallower and more prone to desiccation during dry periods. The lake bed is predominantly composed of fine sediments, with extensive areas of aquatic vegetation, particularly emergent macrophytes such as Typha australis and Phragmites australis, which form dense mats that obscure open water and complicate remote sensing-based assessments. In its current state, Lake Chad functions as a highly dynamic wetland system characterized by shifting mosaics of open water, flooded vegetation, and exposed mudflats that expand and contract seasonally and interannually.

The Lake Chad region experiences a Sahelian climate characterized by a distinct seasonal rainfall pattern. The rainy season typically extends from June to September, with mean annual precipitation ranging from 300 to 500 mm in the vicinity of the lake (Adeyeri, 2019). The dry season dominates the remainder of the year, with temperatures reaching 39°C to 45°C during the hottest months of March to June (Adeyeri, 2019). Evapotranspiration rates are exceptionally high, with mean annual potential evaporation estimated at approximately 2,200 mm, far exceeding the direct precipitation received by the lake surface. This substantial evaporation deficit underscores the lake's dependence on inflow from its contributing rivers, primarily the Chari-Logone system.

2.2. Study Area Delineation

For the purpose of this study, the analysis area was defined as the immediate Lake Chad lacustrine system, encompassing the active hydrological footprint of the lake and its associated wetlands as captured by the Sentinel-2 land cover dataset (Figure 2). A region of interest (ROI) polygon was created to encompass the full extent of Lake Chad's dynamic surface water fluctuations, including areas of open water, flooded vegetation, and seasonally inundated wetlands. This polygon was derived from high-resolution satellite imagery and updated to reflect the lake's current spatial configuration, ensuring the accurate capture of both permanent and ephemeral aquatic areas. The ROI spans approximately 12°00′N to 14°40′N and 12°45′E to 15°30′E, covering the maximum observed extent of the lake system during the study period (Bader et al., 2011; Hou et al., 2024; Messager et al., 2016). This delineation ensures consistent and reproducible analysis of the lake's surface area dynamics while excluding terrestrial areas and the wider basin that do not directly influence the lake's hydrological status.

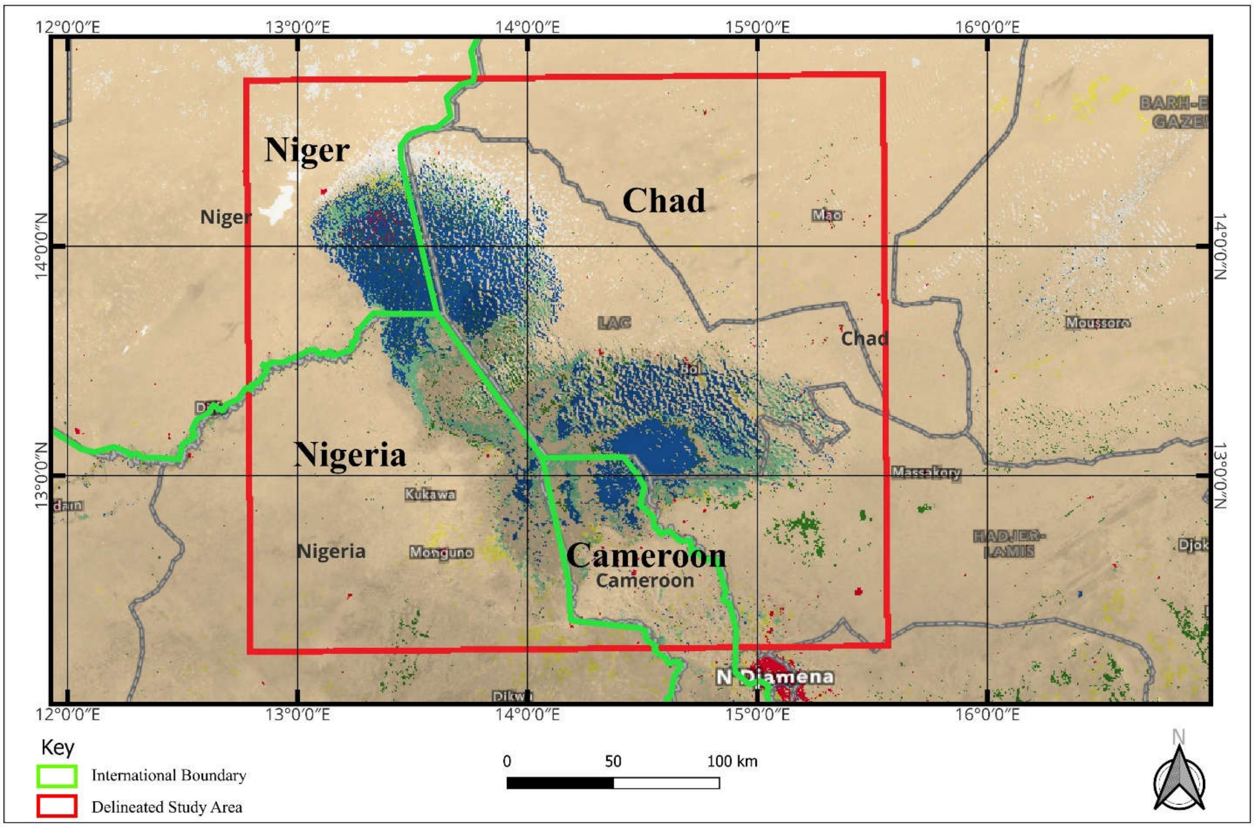

Figure 2: Delineated Study Area Map. The red bounding box defines the delineated study area (~ 13°–15° E, 12.5°–14.5° N) used for spatial clipping of the annual Sentinel-2 Land Use/Land Cover (LULC) time-series tiles. Green vector lines indicate international boundaries intersecting the four countries: Niger, Chad, Nigeria, and Cameroon.

2.3. Remote Sensing Data Source

The primary input data consists of the annual 10-meter resolution global land cover time series produced by Environmental Systems Research Institute (Esri) in collaboration with Impact Observatory and Microsoft. This dataset is derived from the European Space Agency (ESA) Sentinel-2 constellation imagery, classified utilizing a deep learning Random Forest architecture trained on billions of hand-labeled pixels (Karra et al., 2021). Annual GeoTIFF tiles covering the Lake Chad Basin (13°N latitude, 14°N longitude center point) were obtained for the temporal window spanning 2017 to 2025.

2.4. Image Preprocessing and Georeferencing

To prevent geometric distortions during regional area calculation, all downloaded raster datasets were projected into an equal-area coordinate system. The data was projected to 'WGS 84 / UTM Zone 33N (EPSG:32633)', which is optimized for precise local metric computations across the target zone.

An invariant Region of Interest (ROI) polygon matching the boundary layer of the maximum lake basin footprint (Lake Chad Polygon) was constructed. Spatial clipping was automated within a QGIS environment using a customized GDAL Warp routine. The batch automation script was written in Python to ensure perfect pixel alignment and 'no data' assignment (NODATA = -9999) across all sequential annual rasters (Figure 3).

```
import os
import glob
import processing
```

```
input_dir = r"C:\Lake Chad\Raw Data".replace('\\', '/')
output_dir = r"C:\Lake Chad\Output".replace('\\', '/')
roi_layer_name = "Lake Chad_Polygon"

if not os.path.exists(output_dir):
os.makedirs(output_dir)

tiff_files = glob.glob(f'{input_dir}//*.tif')
layers = QgsProject.instance().mapLayersByName(roi_layer_name)
if not layers:
raise Exception(f"Layer '{roi_layer_name}' not found.")
roi_layer = layers[0]

for idx, input_path in enumerate(tiff_files, 1):
out_file_name = input_path.split('/')[-1]
parameters = {
    'INPUT': input_path,
    'MASK': roi_layer,
    'TARGET_CRS': None,
    'NODATA': -9999,
    'KEEP_RESOLUTION': True,
    'SET_RESOLUTION': False,
    'OPTIONS': 'COMPRESS=LZW',
    'OUTPUT': f"{output_dir}//{out_file_name}" }

   processing.run("gdal:cliprasterbymasklayer", parameters)
```

Figure 3: Python script used for the spatial clipping

2.5. Eco-Hydrological Reclassification Scheme

The standard Esri Sentinel-2 dataset partitions land surface features into a generic 9-class arrangement (Table 1). This arrangement includes classes for Water (DN 1), Trees (DN 2), Flooded Vegetation (DN 4), Crops (DN 5), Built Area (DN 7), Bare Ground (DN 8), Snow/Ice (DN 9), Clouds (DN 10), and Rangeland (DN 11). To isolate the lacustrine system from surrounding terrestrial environments, a 3-class specialized hydrological reclassification mapping matrix was developed (Table 2). Class 4 (Flooded Vegetation) captures active marshes, reed beds, and choked wetlands that lock up substantial water volumes. It was isolated alongside pure Open Water (Class 1) to encapsulate the comprehensive aquatic boundary. All remaining non-water elements were merged into a generalized Terrestrial mask (Figure 3).

Table 1: Sentinel-2 10m Land Use/Land Cover 9-class system (adapted from Karra, 2021)

Digital Number (DN)	Land Cover Class	Hex Color Code	Description Snapshot
1	Water	#419BDF	Rivers, lakes, oceans, ponds, flooded salt plains.
2	Trees	#397D49	Dense tall vegetation, closed canopies, plantations.
4	Flooded Vegetation	#7A87C6	Mangroves, wetlands, marshes, rice paddies.
5	Crops	#E49635	Human-planted agricultural fields, plotted crops.
7	Built Area	#C4281B	Buildings, roads, structures, impervious surfaces.
8	Bare Ground	#A59B8F	Sand, deserts, exposed rock, salt flats.
9	Snow/Ice	#B3E3EE	Glaciers, persistent snowpacks.
10	Clouds	#F2F2F2	Areas obscured by persistent cloud cover.
11	Rangeland	#E49735	Wild uniform grasses, low shrubs, savannas.

Table 2: The study's 3-class Reclassification Scheme

New Reclassified DN Code	New Class Name	Original Sentinel-2 DN Included	Eco-Hydrological Justification for Lake Chad
1	Open Water	1	Captures clear, standing, and deep-water bodies. Maps permanent liquid surface.
2	Flooded Vegetation (Wetland)	4	Captures marshes, dense reed beds, and swamplands; charts the active choked basin.
3	Terrestrial (non-water)	2, 5, 7, 8, 9, 10, 11	Merges all dry land classes (Trees, Crops, Built Area, Bare Ground, Rangeland, Clouds) into a single mask.

Reclassification was executed via two redundant methodologies to guarantee programmatic verification:

Map Algebra Configuration: Evaluated via the QGIS Raster Calculator using Boolean operations:

$$\text{Final}_{\text{Raster}} = (raster@1 = 1) \times 1 + (raster@1 = 4) \times 2 + \big((raster@1 = 2)\ OR\ (raster@1 = 5)\ OR\ (raster@1 = 7)\ OR\ (raster@1 = 8) OR\ (raster@1 = 9)\ OR\ (raster@1 = 10)\ OR\ (raster@1 = 11)\big) \times 3$$

Sequential Matrix Reclassification: Conducted via the Processing Toolbox "Reclassify by Table" engine, handling structural bounds through strict sequential execution rules to accurately separate aquatic values (Figure 4).

The integers skipping values (3 and 6) in the Esri 10-meter Sentinel-2 global land cover time series data is a result of the updated 9-class system combining the original "Grass" (formerly 3) and "Scrub" (formerly 6) categories into a single "Rangeland" category assigned to digital number value 11 (Esguerra Montaña, 2025; Waladi and Iftitah, 2026).

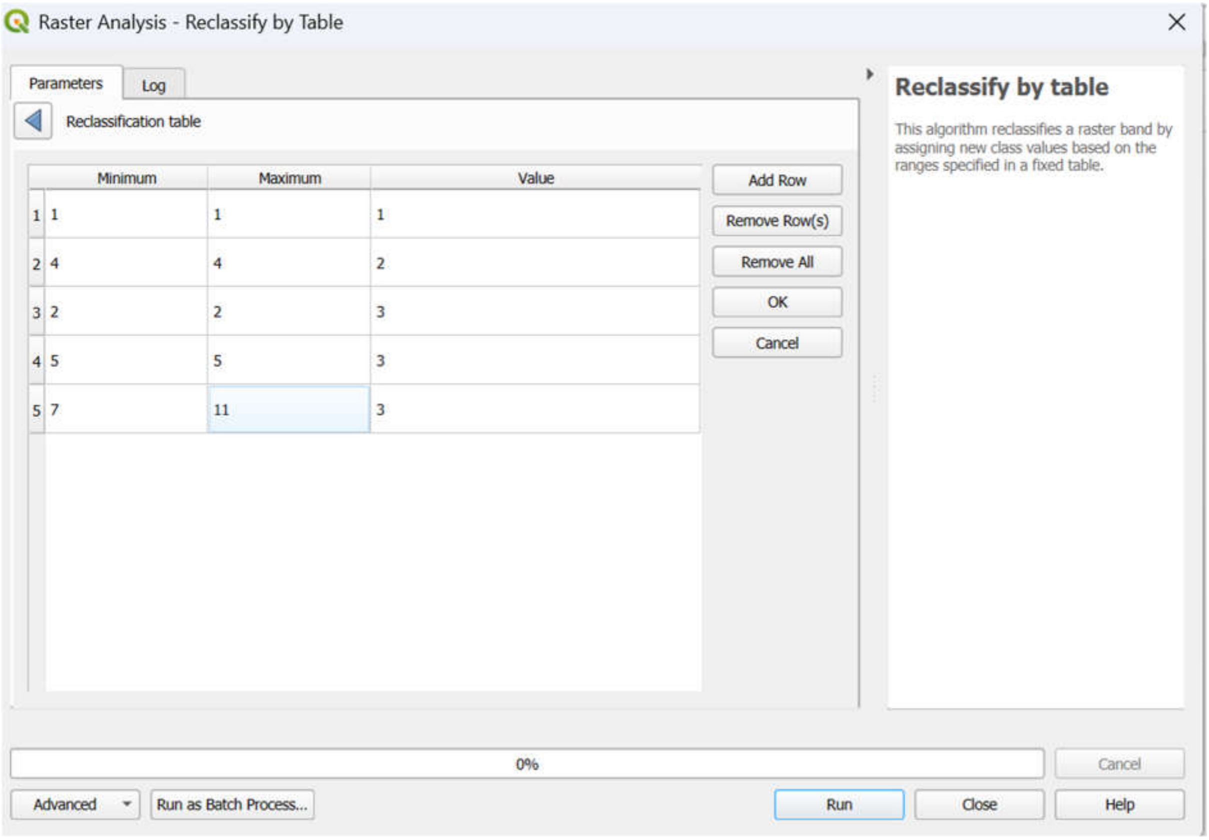

Figure 4: QGIS "Reclassify by Table" algorithm.

2.6. Zonal Quantification and Surface Area Extraction

Following raster transformation, quantitative area metrics were extracted via two parallel processing workflows (Figure 5):

Vector Conversion Method (Polygonization): Rasters were converted to ESRI shapefiles using a discrete polygonize algorithm. A new field, Area_Km2, was generated within the attribute table using geometry field calculations:

$$\text{Area}_{\text{Km2}} = \frac{\$\text{area}}{1{,}000{,}000}$$

The 'Statistics by Categories' module was subsequently executed to compile cumulative geometric sums for each class ID.

Pixel Counting Method (Raster Layer Unique Values Report (RLUVR)): An alternative pixel enumeration approach was completed directly on the source files, bypassing vector conversions. Total area was derived by multiplying unique class pixel tallies by the native cell dimension

$$10\,m \times 10\,m = 100\,m^2 = 10^{-4} km^2$$

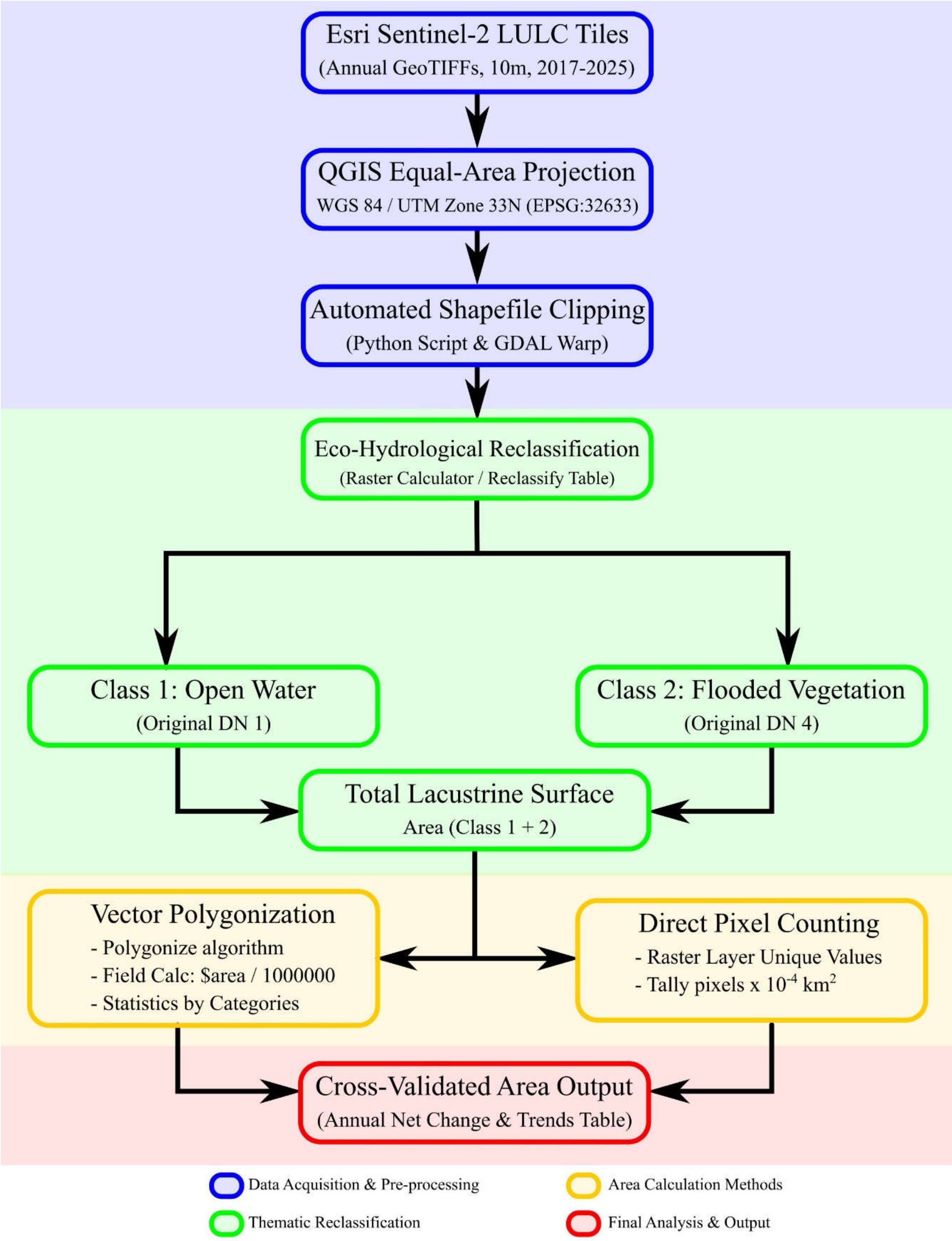

Figure 5. Methodology Flow Layout. Steps are dynamically grouped into operational domains: Data Preparation (Blue), Eco-Hydrological Reclassification (Green), Geospatial Quantification Frameworks (Yellow), and Cross-Validated Synthesis Outputs (Red).

3. RESULTS

The continuous annual spatial profiles computed from the Sentinel-2 datasets unveil a decisive multi-year expansion across the Lake Chad lacustrine system. The empirical measurements extracted via vector-metric categorical operations are compiled below.

3.1. Microclimatic Surface Water Extent Variations (2017–2025)

The structural composition of the lake over time indicates distinct transitions between open water bodies and underlying vegetation matrices. The close agreement between vector-based and raster-based area extraction methods validates the reliability of the results. Maximum difference between methods was less than 0.6 km² across all years and classes.

Table 3: Spatial Extent Trajectory of Lake Chad's Eco-Hydrological Zones (2017-2025)

Year	Open Water Area (km^2)	Flooded Vegetation (km^2)	Total Lacustrine (km^2)	Net Change (km^2)
2017	2563.859608	3244.261485	5808.121093	0
2018	2658.291698	3516.450884	6174.742582	366.621489
2019	2697.982624	4773.258091	7471.240715	1663.119622
2020	3769.600256	5691.698334	9461.29859	3653.177497
2021	4229.768353	4720.618769	8950.387122	3142.266029
2022	4346.244055	5198.535082	9544.779137	3736.658044
2023	4980.375368	4781.771759	9762.147127	3954.026034
2024	5979.621112	5279.874277	11259.49539	5451.374296
2025	7589.819728	3998.322629	11588.14236	5780.021264

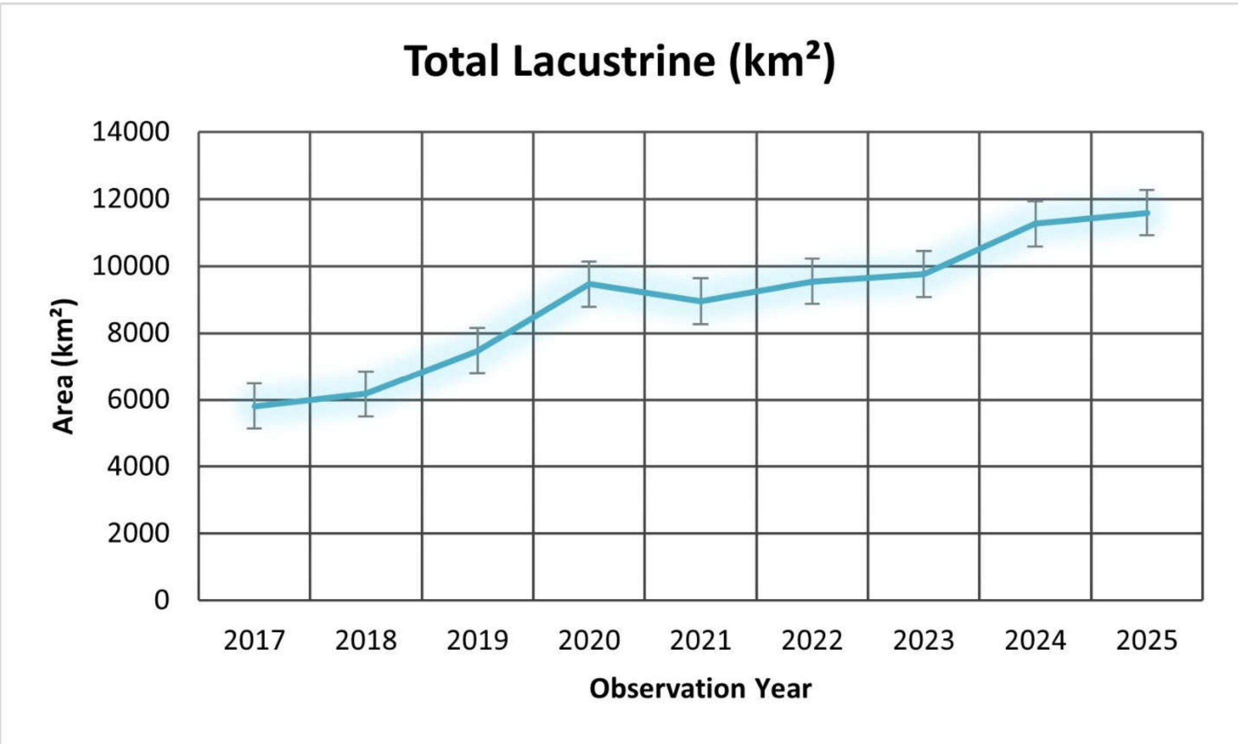

Figure 6. Temporal trajectory of the total lacustrine surface area (km²) of Lake Chad from 2017 to 2025 derived from Sentinel-2 land cover data. Error bars represent the programmatic classification uncertainty limits across the combined open water and flooded vegetation zones.

The compiled spatial record points to unbroken year-over-year gains in total lacustrine surface coverage. Between the initial baseline marker of 2017 (5,808.12 km²) and the terminal marker of 2025 (11,588.14 km²), the active lake system achieved an absolute net growth of 5,780.02 km². This shift corresponds to a 99.51% expansion in its geographic footprint over eight years, essentially doubling the active spatial extent of the lake environment.

3.2. Lake Chad's Structural Dynamics

Analysis of individual layer parameters reveals distinct behaviours for open water and vegetated surfaces (Figures 7 - 9). Open water dynamics reveal that the permanent liquid expanse expanded from 2,563.86 km² (2017) to 7,589.82 km² (2025). This component exhibits seasonal variability driven by direct rainfall pulses and high seasonal evapotranspiration rates. On the other hand, Flooded vegetation dynamics shows the marshland and reed canopy expanded from 3,244.26 km² (2017) to 3,998.32 km² (2025). This persistent accumulation of water-retaining biomass acts as a structural buffer, anchoring the lake's core hydrologic profile and shielding shallow pools from direct solar evaporation.

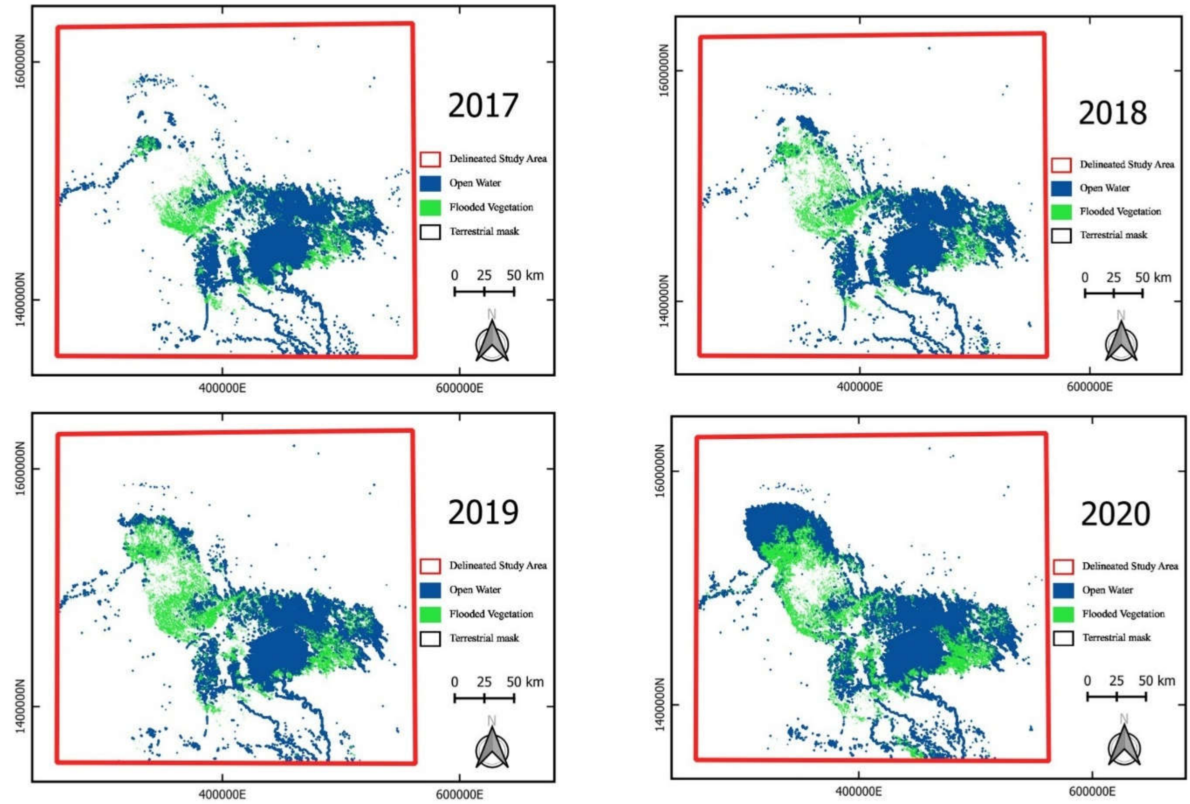

Figure 7. Annual classification maps of Lake Chad (2017–2020) displaying the spatial distribution and progressive expansion of open surface water pools and flooded vegetation canopies.

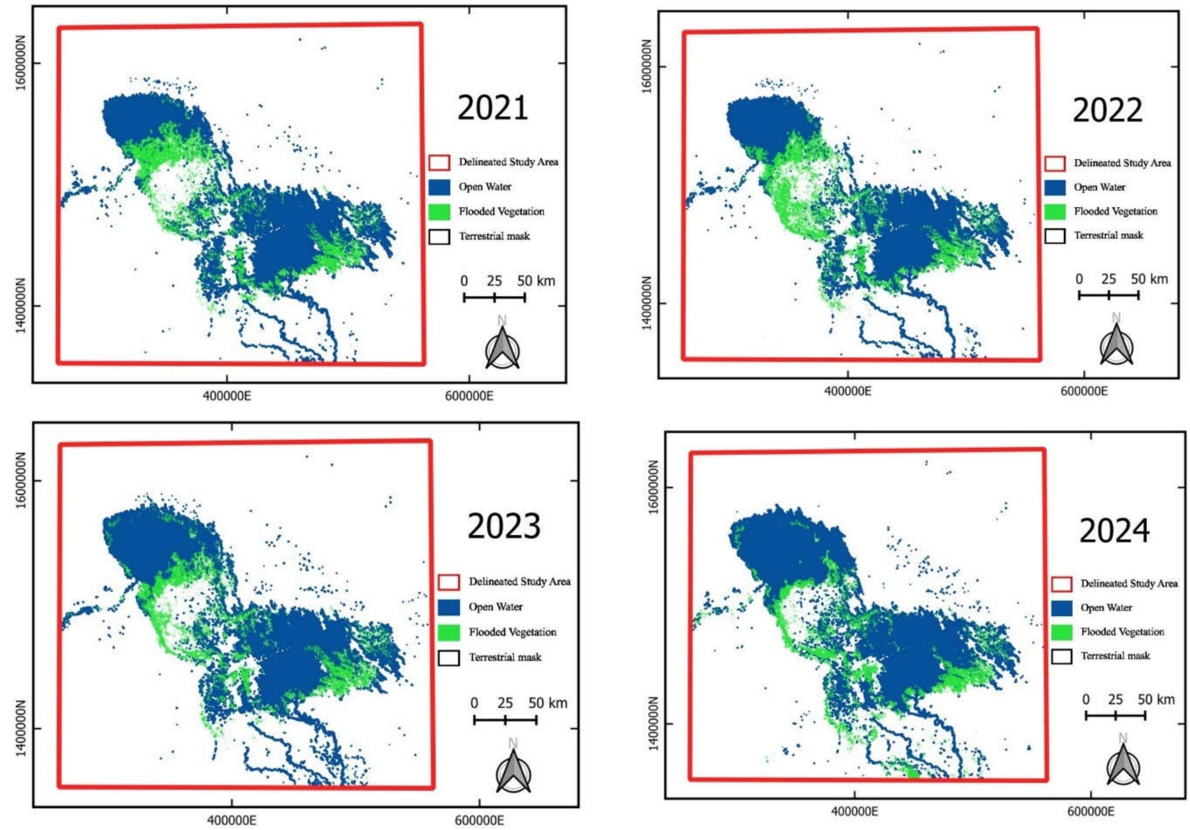

Figure 8. Annual classification maps of Lake Chad (2021–2024) displaying the spatial distribution and progressive expansion of open surface water pools and flooded vegetation canopies.

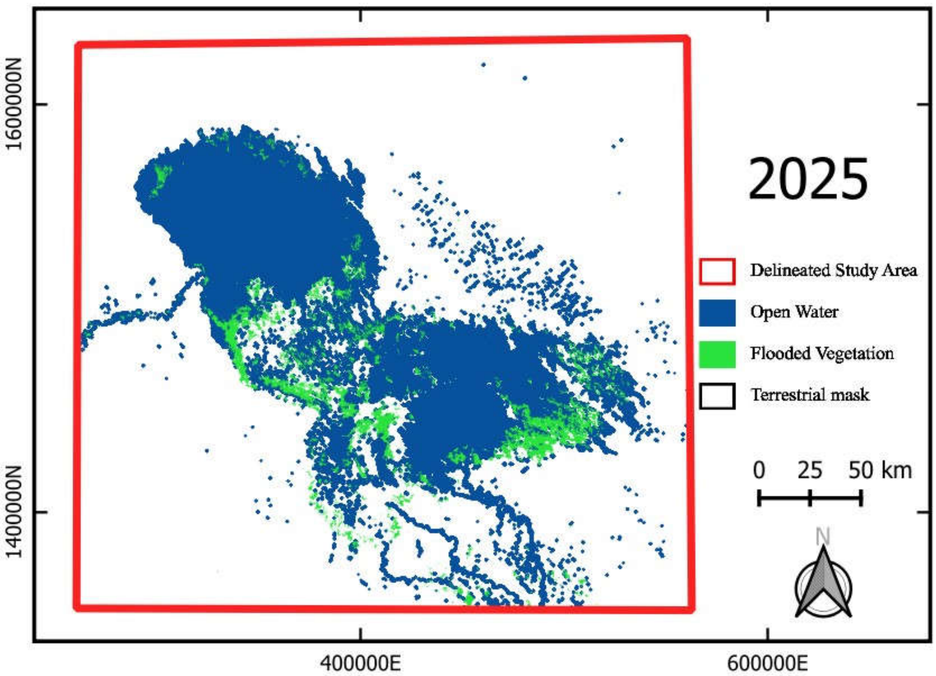

Figure 9. Spatial distribution and classified footprint of Lake Chad during its maximum contemporary expansion phase in 2025. The 10-meter Sentinel-2 thematic extraction highlights a completely inundated northern pool dominated by continuous Open Water (blue) bordered by a resilient ring of peripheral Flooded Vegetation (green).

3.3. Long-Term Historical Context and Contemporary Recovery Trends

To contextualize the contemporary structural modifications observed over the recent Sentinel-2 monitoring timeline (2017–2025), it is necessary to contrast current trends against multi-decadal historical baselines (Table 4). The structural trajectory of Lake Chad over the past six decades provides a classic case study of an endorheic lake responding to severe macro-climatic shifts and escalating regional anthropic demands.

During the wet operational phase of the early 1960s, historical records indicate that Lake Chad spanned an expansive surface area of ~25,000 km², acting as a massive, unified open-water body across the Sahel. However, the subsequent intensification of the Sahelian droughts during the 1970s and 1980s, coupled with an abrupt decrease in discharges from the Chari-Logone river network, triggered an environmental collapse. By the late 1980s, the total functional area contracted sharply to <3,000 km², causing severe fragmentation and split the northern and southern sub-basins into isolated, ephemeral pools.

Table 4: Historical comparison of Lake Chad's total surface area across key decadal milestones.

Historical Epoch / Year	Total Functional Lake Area (km²)	Primary Data Source / Horizon	Hydrological Configuration Characterization
Early 1960s	~ 25,000	Historical literature records	Macroscopic unified lake phase; deep open pools spanning both basins.
Late 1980s	< 3,000	Historical literature records	Severe basin fragmentation; near-complete drying of the northern pool.
2017	5,808	This study (Sentinel-2 LULC)	Initial baseline recovery stage; southern pool stabilizing with heavy wetland growth.
2025	11,588	This study (Sentinel-2 LULC)	Contemporary expansion peak; significant deep-water refilling in the northern pool.

The empirical results generated in this study indicate that Lake Chad has entered a distinct recovery and spatial stabilization phase. The baseline measurement of 5,808 km² in 2017 demonstrates that the lake had already climbed significantly above its late 1980s trough. Over the following eight years, the ecosystem experienced sustained growth, reaching a contemporary peak of 11,588 km² by 2025.

While this modern extent remains below the 1960s benchmark, the current 11,588 km² footprint represents a major eco-hydrological rebound. The expansion has re-established a continuous water sheet across the northern basin and supported extensive wetland canopies. These trends suggest that contemporary discussions of regional water resource stabilization should pivot from legacy "disappearing lake" models to frameworks that account for dynamic, multi-year recovery phases.

CONCLUSION

To establish a robust roadmap for advancing the monitoring of Lake Chad’s dynamic eco-hydrological variations, several critical future research paths should be pursued. First, extending this remote sensing framework beyond the 2025 terminal boundary into 2026 and subsequent years is essential to determine whether the documented spatial expansion represents a permanent macro-climatic stabilization or merely a high-frequency multi-year oscillation within the volatile Sahelian climate cycle. Second, future investigations must systematically integrate these satellite-derived area metrics with high-resolution localized climate datasets. Specifically gridded precipitation indices and land surface temperature (LST) anomalies, to accurately quantify the driving forces behind this recovery via robust empirical correlation models. Third, to mitigate spatial misclassifications inherent in automated land cover algorithms, extensive in-situ ground-truthing campaigns must be conducted to field-validate the spectral boundaries separating open water bodies from dense, saturated macro-vegetation canopies. Finally, moving beyond horizontal surface area mapping, future frameworks should couple these high-resolution lateral boundaries with active satellite altimetry and localized bathymetric gauges to establish accurate depth-area-volume relationship curves, thereby transitioning the regional water management paradigm from primitive two-dimensional extent evaluations to precise, three-dimensional volumetric change estimations.

This study presents compelling evidence of significant recovery in Lake Chad's surface water extent between 2017 and 2025. High-resolution 10-meter Sentinel-2 satellite data indicates that Lake Chad experienced substantial spatial expansion between 2017 and 2025, counter to long-term historical narratives of continuous contraction. By deploying a specialized 3-class LULC classification framework, this study demonstrated that the comprehensive lacustrine footprint grew from 5,808.12 km² to 11,588.14 km², doubling its active spatial area within the 8-year analysis window. This expansion includes gains in both exposed open water surfaces and saturated flooded-vegetation wetlands. These findings suggest that contemporary water management models must account for vegetated wetland zones to ensure accurate basin-wide hydrological monitoring. High-resolution satellite monitoring remains a vital tool for optimizing resource distribution, managing transboundary water policies, and supporting sustainable development across the Lake Chad Basin. While Lake Chad has not fully recovered to its historic 1960s extent, the current trajectory represents a remarkable environmental recovery. This study demonstrates the value of open-source Earth observation data for monitoring critical water resources in data-sparse regions. The findings should inform evidence-based decision-making and contribute to sustainable water resource management in the Lake Chad basin.

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