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Assessing the Transformations in the Basin Morphology of Lake Gwakra in Gerei Local Government Area, Adamawa State, Nigeria

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ABSTRACT

Lake Gwakra is an important freshwater resource for fishing and irrigated agriculture in Gerei Local Government Area, Adamawa State, Nigeria. This study assessed changes in the lake's morphology and considered their hydrological, ecological, and socioeconomic implications using bathymetric measurements, geographic information system analysis, rainfall–sediment observations, seasonal water-quality measurements, and a community survey. Between 2013 and 2026, mapped surface area decreased from 1.4066 to 1.3092 km^2 (6.93%), mean depth declined from 0.75 to 0.56 m, and estimated volume decreased from 850,000 to 733,135.04 m^3 (13.75%). Maximum depth increased from 1.46 to 1.87 m, while mapped shoreline length increased from 5.22 to 7.79 km. Rainfall and sediment measurements at the Mayo Jibiro inlet were positively correlated in 2020 (r = 0.813) and 2026 (r = 0.628), although each relationship was based on five paired observations and was not statistically significant at the 5% level. Wet-season turbidity and phosphate were higher than dry-season means, while nitrate was lower. Of 236 respondents, 94.1% reported moderate or high dependence on lake resources and 98.3% reported seasonal fishing. The findings indicate measurable morphometric differences and substantial livelihood dependence, but do not isolate sedimentation from water-level and survey-method effects or demonstrate direct ecological and socioeconomic causation. The study recommends repeat bathymetric surveys at comparable water levels, catchment erosion control, seasonal water-quality monitoring, and community-inclusive lake management.

Keywords: lake morphology; bathymetry; sediment delivery; water quality; livelihoods; Lake Gwakra

1 INTRODUCTION

Water is essential for sustaining life and maintaining ecological balance (Postel & Vickers, 2021). Lakes provide important ecological and socioeconomic benefits, including water supply, irrigation, recreation, fisheries and habitats for diverse species (Magnuson et al., 2019; Dudgeon et al., 2019). However, they are increasingly vulnerable to pollution and human-induced pressures. Physical characteristics such as temperature, depth and mixing regimes influence oxygen availability, aquatic metabolism, light penetration and nutrient distribution (Kraemer et al., 2017; Hampton et al., 2017). Lake morphometry is equally important in determining ecological processes, but it changes over time under the influence of catchment characteristics, human activities and climate change (Lathrop et al., 2020; Zohary et al., 2021). These changes have been intensified by agricultural expansion, irrigation and urban development (Zhou et al., 2021).

Morphological changes may alter lake depth, shoreline configuration, sediment distribution, water quality and aquatic habitats, with consequences for biodiversity and ecosystem functioning. They may also affect communities that depend on lakes for fishing, agriculture, food security and income. Understanding these changes is therefore necessary for effective lake conservation, sustainable resource management and the protection of local livelihoods.

Lake Gwakra, located in Gerei Local Government Area of Adamawa State, Nigeria, provides an important setting for examining these environmental and socioeconomic relationships. Although previous studies have investigated lake morphology, water quality, restoration, ecological processes, hydrological properties, and sediment dynamics (Allan & Johnson, 2019; Carlson, 2014; Cole & Prairie, 2000; Gessler, 1989; Håkanson, 1994), limited location-specific evidence is available for Lake Gwakra. This study therefore focuses on changes in the lake's basin morphology, considering potential natural and human-induced drivers, associated ecological implications, and consequences for surrounding communities. The findings are expected to contribute to a better understanding of the lake's changing condition and inform appropriate management and conservation strategies.

1.1 Aim and Objectives

This study aims to examine the morphological changes in Lake Gwakra and their implications, with the goal of developing sustainable management strategies. The specific objectives are as follows:

1. To identify the factors driving the morphological changes in the lake.
2. To quantify and characterize the morphological changes occurring in the lake.
3. To evaluate the ecological impacts of changes in the lake's morphology.
4. To investigate the socio-economic effects on the livelihoods of the communities surrounding the lake.

2 METHODOLOGY

2.1 The Study Area

The Lake Gwakra, situated in the Upper Benue Trough in Adamawa State, is the primary destination of the Jibiro drainage system. It covers an area of 1.41 square kilometers and is located between latitudes 09°24'09"N and 09°25'07"N of the Equator and longitudes 12°23'04"E and 12°24'11"E of the Prime Meridian. The region experiences a humid tropical climate with distinct wet and dry seasons, making it ideal for irrigation farming from December to May (Usman, 2005). The lake is primarily fed by the Jibiro Drainage System and periodic River Benue floodwaters. With its storage capacity of over 2.0 million cubic meters, the lake can support extensive irrigation agriculture and other activities like fishing and recreation (Yonnana et al., 2015) (Figure 1).

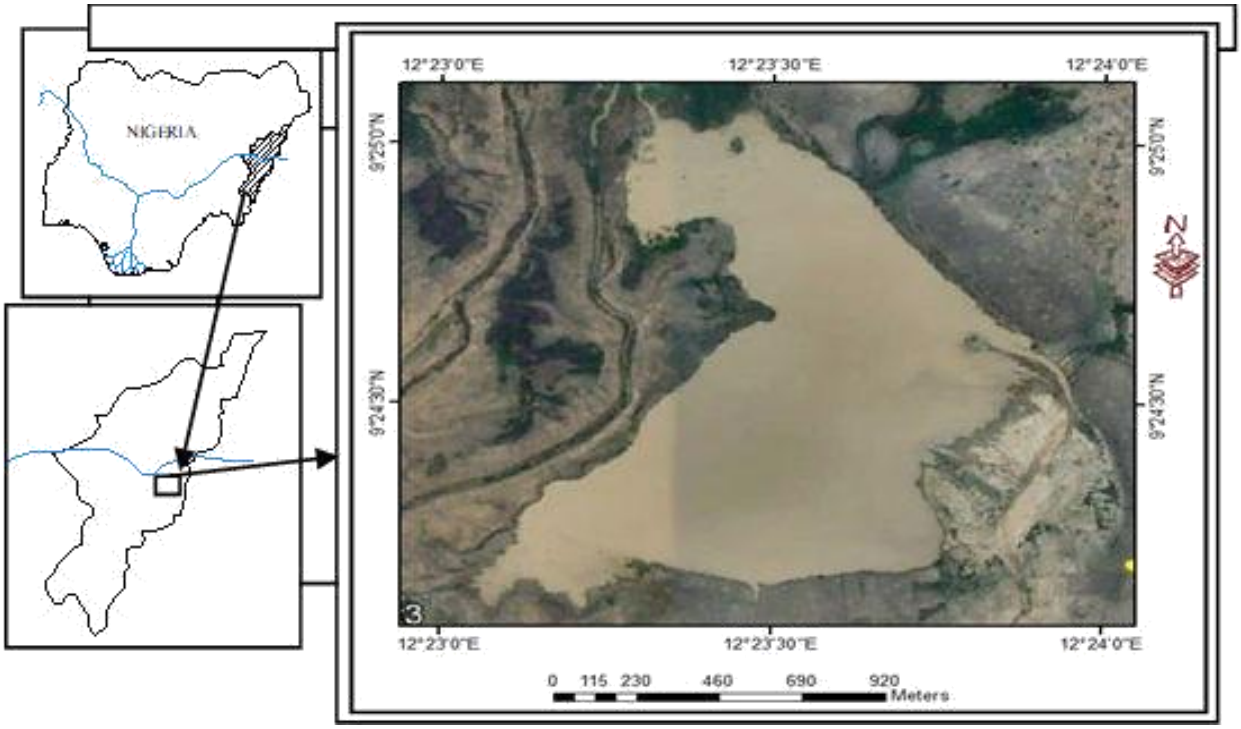


FIGURE 1: Study Area.
Source: Peter, Y. (2025).

2.2 Research Design and Data Sources

The study used an integrated field-based and geospatial approach to examine Lake Gwakra's morphometric characteristics and selected hydrological, water-quality, ecological, and socioeconomic conditions. Primary information comprised bathymetric measurements, shoreline observations, water-quality results, and questionnaire/interview responses from lake users. Secondary information included a 1969 topographic map, recent Google Earth imagery, available hydroclimatic records from the Upper Benue River Basin Development Authority (UBRBDA), Yola, and data accessed through Climate Engine, together with relevant literature. The morphometric comparison reported in the results covered 2013 (Yonnana et al., 2015) and 2026; the source and derivation of the 2013 values should be stated from the original records.

2.3 Field Equipment and Software

Field equipment included a Hondex depth sounder, Garmin GPS receiver, staff gauge, levelling instrument and staff, measuring tape, camera, ranging poles, pegs and a water-quality testing kit. Microsoft Excel was used for data entry and calculations, and ArcGIS was used for spatial data management, mapping and interpolation. The supplied analysis identifies ArcGIS 10.8 for bathymetric interpolation; this version should be retained unless project records show otherwise.

2.4 Bathymetric and Morphometric Analysis

Depth readings were collected with the Hondex sounder and linked to geographic positions recorded by GPS. The observations were compiled in a spreadsheet and imported into ArcGIS to generate an interpolated bathymetric surface. The surface was used to map relative depth patterns and distinguish deeper and shallower parts of the lake.

Lake boundaries and shorelines for the periods compared were delineated from the available spatial sources, and GIS measurements were used to derive surface area and shoreline length. Maximum length and width were measured from the lake outline; depth and volume estimates were obtained using the procedures applied in the analysis.

Percentage change between the earlier and later measurements was calculated as follows:

Percentage change (%) = [(X_2 − X_1) / X_1] × 100

where X_1 and X_2 represent the earlier and later values, respectively. Differences between volume estimates were treated as differences between estimates, not as an annual sedimentation rate. Comparisons were interpreted cautiously where survey season, water level, spatial resolution, or measurement method may have differed.

The Lake's morphometric parameters, such as Shoreline Length (SL), Surface Area (A), Maximum Length (LMax), and Maximum Width (WMax), will be directly derived through GIS analyses.

Shoreline elevations and maximum depths of the Lake were directly obtained from the bathymetry survey data, while other parameters such as Relative Depth (Zr), Mean Depth (ZMean), Depth Indicator (Zi), Lake Volume (V), Extension (λ), Shoreline Development Index (DL), and Index of Basin Permanence (IBP) were computed mathematically using the appropriate formulae (Table 1).

TABLE 1: Lake Morphometric parameters and corresponding mathematical formulae.

S/No	Morphometric Parameter	Symbol/Formulae	References
1	Shoreline Elevation	H	Wetzel (2001), Kalff (2002), SWCSMH (2015)
2	Shoreline Length	SL	Wetzel (2001), Kalff (2002), SWCSMH (2015)
3	Surface Area	A_0	Wetzel (2001), Kalff (2002), SWCSMH (2015)
4	Maximum Length	L_{Max}	Wetzel (2001), Kalff (2002), SWCSMH (2015)
5	Maximum Width	W_{Max}	Wetzel (2001), Kalff (2002), SWCSMH (2015)
6	Extension	$\lambda = L_{Max}/W_{Max}$	Wetzel (2001), Kalff (2002), SWCSMH (2015)
7	Maximum Depth	Z_{Max}	Wetzel (2001), Kalff (2002), SWCSMH (2015)
8	Mean Depth	$Z_{Mean} = V/A_0$	Wetzel (2001), Kalff (2002), SWCSMH (2015)
9	Depth Ratio	$R_z = Z_{Mean}/Z_{Max}$	Wetzel (2001), Kalff (2002), SWCSMH (2015)
10	Relative Depth	$zr = \frac{50(z_{max})\sqrt{\pi}}{\sqrt{A_0}}$	Wetzel (2001), Kalff (2002), SWCSMH (2015)
11	Shoreline Development Factor	$D_{SL} = \frac{SL}{2\sqrt{\pi A_0}}$	Wetzel (2001), Kalff (2002)
12	Volume	$V_{z0-z1} = \frac{1}{3}\left(A_{z0} + A_{z1} + \sqrt{A_{z0} \times A_{z1}}\right)\left(z_0 - z_1\right)$	Wetzel (2001), Kalff (2002), SWCSMH (2015)
13	Index of Basin Permanence	IBP = V/SL	Wetzel (2001), Kalff (2002), SWCSMH (2015)

Here, L is shoreline length, Lmax is maximum length, Wmax is maximum width, A is surface area, V is volume, Zmax is maximum depth, and Zmean is mean depth.

2.5 Drainage-Basin and Rainfall–Sediment Analysis

The drainage network and basin boundary were mapped in GIS, and stream segments were classified

by order using the ordering procedure applied in the study. Drainage density was calculated as:

$$Dd = \Sigma L / A$$

where Dd is drainage density, ΣL is the total length of mapped stream channels, and A is basin area. Bifurcation and elongation ratios were calculated from the measurements used in the original basin analysis. Monthly rainfall and sediment-related observations for 2020 and 2026 were paired and analysed using Pearson's correlation coefficient:

$$r = \Sigma[(xi - \bar{x})(yi - \bar{y})] / \sqrt{\{\Sigma(xi - \bar{x})^2 \Sigma(yi - \bar{y})^2\}}$$

where xi and yi are paired rainfall and sediment observations, and $\bar{x}$ and $\bar{y}$ are their respective means. Each year's analysis used five paired monthly observations, so the correlations were interpreted as exploratory rather than conclusive.

2.6 Water Quality and Irrigation Indices

Dry- and wet-season water-quality results were summarised and compared descriptively. Parameters included pH, temperature, electrical conductivity, dissolved oxygen, biochemical oxygen demand, turbidity, hardness, total dissolved solids, sulphate, nitrate, phosphate and chloride, together with reported concentrations of iron, manganese, cadmium, chromium, nickel, zinc, lead and copper.

Irrigation suitability was assessed using the indices reported in the results: permeability index (PI), sodium adsorption ratio (SAR), sodium percentage (Na%), residual sodium carbonate (RSC), magnesium hazard (MH), Kelly's ratio (KR/KI, following the notation in the original analysis), potential salinity (PS) and total hardness (TH). The equations and interpretation thresholds should be included from the methods actually used. Ionic concentrations must be expressed in the appropriate units for each calculation.

2.7 Ecological and Socioeconomic Analysis

Field notes and photographs documented visible conditions around the shoreline, shallow margins, marginal vegetation, and drainage inflow. Questionnaire and interview data were coded in Excel and summarised using frequencies and percentages. The percentage for each response category was calculated as:

$$P = (f / N) \times 100$$

where P is the percentage, f is the category frequency, and N is the number of valid responses for the relevant question. The overall socioeconomic analysis used 236 respondents; the data indicate that fishing and irrigation subgroups comprised 44 and 37 respondents, respectively. Fishing activities reported income and seasonal fishing patterns were summarised descriptively; the CPUE value was calculated in kg/day.

3 RESULTS AND DISCUSSION

3.1 Factors Driving Morphological Changes in Lake Gwakra

- ***Bathymetric characteristics***

The bathymetric survey combined depth sounding, GPS positioning, and GIS interpolation in ArcGIS 10.3. The resulting depth surface depicts a shallow basin with spatial variation in depth. As shown in Map 2, deeper water occurs in the central part of the lake, while shallower areas occur around parts of the margin and near the Mayo Jibiro inflow. This pattern is consistent with the possibility that inflowing water deposits sediment where its transport capacity decreases; however, a single bathymetric surface describes spatial variation and does not independently establish the rate or timing of sediment accumulation.

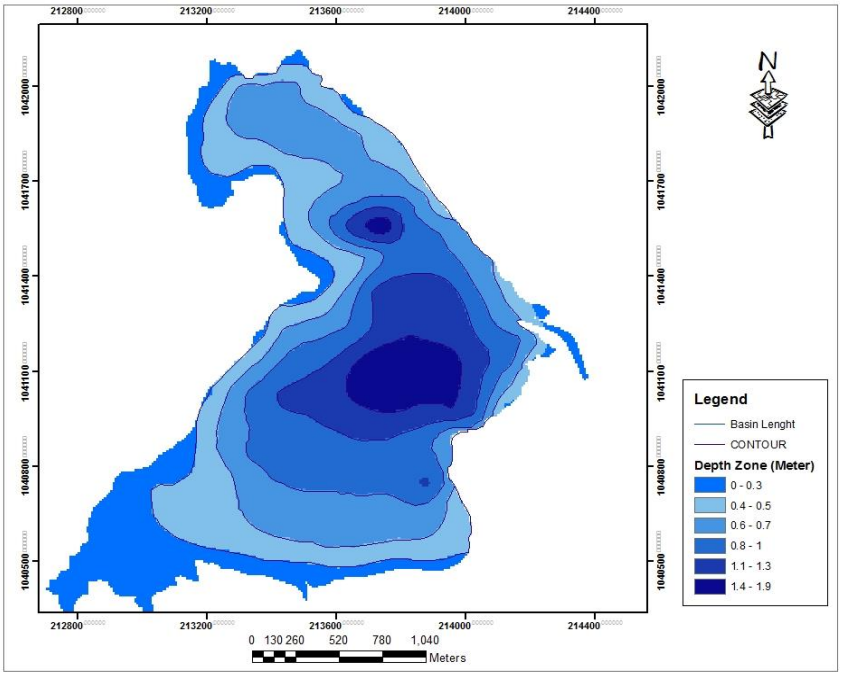


FIGURE 2: Bathymetric map of Lake Gwakra.

The distribution of depth suggests that lake-floor processes vary spatially. Shallow margins near an inflow may be depositional environments, whereas deeper areas may retain open water for longer periods. This interpretation is consistent with established descriptions of sediment redistribution and deposition in lakes (Håkanson, 1977; Hilton et al., 1986). Quantifying sediment accumulation through time requires repeat bathymetric surveys conducted at comparable water levels and referenced to a common vertical datum.

- ***Rainfall and sediment delivery***

TABLE 2: Monthly rainfall–sediment correlations for 2020 and 2026.

Year	Pearson correlation (r)	Monthly observations	Interpretation
2020	0.813	5	Strong positive association
2026	0.628	5	Positive association

The positive correlations in Table 1 indicate that months with higher rainfall generally had higher measured sediment values at the Mayo Jibiro inlet. The relationship was stronger in 2020 (r = 0.813) than in 2026 (r = 0.628). Rainfall can increase runoff, detach soil particles, and transport sediment through connected channels. Soil erosion research identifies rainfall, soil properties, slope and land cover as interacting controls on sediment delivery (Morgan, 2005; Boardman, 2010). The difference between years may reflect variation in rainfall distribution, antecedent moisture, land cover, or sampling, but the available data do not identify the contribution of each factor.

The correlation results indicate association rather than proof of causation. The paired observations cover five months in each year, so the small sample size limits statistical inference. In addition, the values in the source table are reported as sediment measurements in grams, although the accompanying correlation table labels sediment as mg/L. The unit should be standardised in the underlying dataset; accordingly, the correlations are interpreted here as reported associations and not as sediment loads. Estimating sediment load requires sediment concentration and discharge measured over time.

- ***Drainage-basin morphometry and land use***

TABLE 3: Selected morphometric characteristics of the Jibiro drainage basin.

Parameter	Value	Description
Drainage density	1.27 km/km^2	Channel length per unit basin area
Mean bifurcation ratio	3.83	Relationship between stream numbers in successive orders
Elongation ratio	0.48	Indicates an elongated basin

The morphometric characteristics in Table 2 describe the drainage network that conveys runoff towards Lake Gwakra. The drainage density of 1.27 km/km^2 and elongation ratio of 0.48 provide context for the basin's drainage organisation and elongated shape. These indices do not, by themselves, quantify the volume of sediment delivered to the lake.

The study also reports cultivation and vegetation removal in the catchment. Such disturbance can expose soil to raindrop impact and overland flow and can weaken riparian-bank stability, providing a plausible pathway for enhanced sediment delivery (Foley et al., 2005; Morgan, 2005).

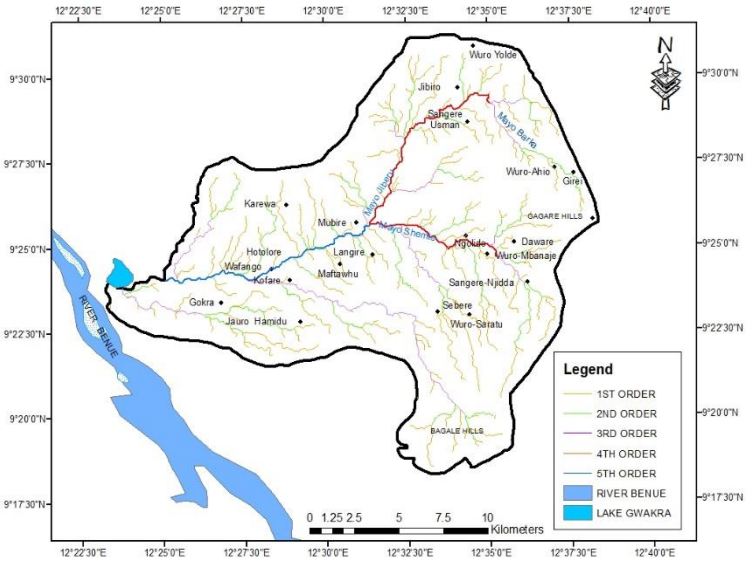


FIGURE 3: Stream-order map of the Jibiro drainage basin.

Taken together, the positive rainfall–sediment correlations, drainage-basin characteristics and reported catchment disturbance are consistent with a catchment-to-lake sediment pathway. Nevertheless, the relative contribution of rainfall, cultivated land, vegetation removal and channel erosion cannot be quantified from the available data. Source sampling, discharge measurements and repeated land-cover mapping would be needed to estimate the contribution of individual sediment sources.

3.2 Extent of sediment loading and changes in lake morphology

- ***Changes in morphometric parameters***

TABLE 3: Morphology of the Lake parameter.

Morphological Characteristic	Code	Year 2013	Year 2026	Change (%)
Latitude		09°24'26"N	09°24'26"N	
Longitude		12°23'38"E	12°23'38"E	
Mean Elevation (m)	H	151.00	151.00	
Maximum Length (km)	l_{max}	1.66	1.67	0.60
Maximum Width (km)	b_{max}	1.52	1.18	-22.37
Mean Width (Km)	b_{mean}	0.85	0.78	-8.24
Shoreline Length (km)	L_0	5.22	7.79	49.23
Maximum Depth (m)	Z_m	1.46	1.87	28.08
Mean Depth (m)	Z_{mean}	0.75	0.56	-25.33
Relative Depth (%)	z_r	0.11	0.12	9.09
IBP	IBP	0.16	0.09	-43.7
Surface Area (Km^2)	A_o	1.41	1.31	-7.09
Volume (mcm)	V	0.85	0.73	-14.12

- ***Morphology of the Lake Parameters***

From Table 3, the examined Lake had a maximum length (l_{max}) of 1.66 km, which is regarded as the fetch in the year 2013 (Yonnana, 2013), and 1.67Km in 2026. The difference was 0.01km with an increase in the length in the year 2026 by 0.60% which was determined to have been more affected by the wind and the wave effects. The Lake is shaped like an extended rectangle and faces the direction of the Benue Valley's predominant wind. These facilitate the production of stronger waves, more water mixing, and sediment concentration in the Lake. The maximum width (b_{max}) was 1.52km as in the year 2013 (Yonnana, 2013) and 1.18km in the year 2026 with the percentage decrease of 22.37% between the years. The maximum width result has the potential to determine the potential for waves to mix water and/or the sediments at the bottom of a Lake. The mean width (b_{mean}) was found to be 0.85km in the year 2013 (Yonnana, 2013), and 0.78km in the year 2026, with an 8.24% decrease; the end result might change how much water mixing might take place in the Lake when there are heavy winds. Also, the Shoreline Length (L_o) was 5.22km in the 2013 (Yonnana, 2013), and 7.79km by the 2026 with the percentage increase change of 49.23% between the comparative years. This means that the management of aquatic plants can also be greatly impacted by changes to the Lake's shoreline. For instance, a Lake may contain a modest quantity of aquatic flora along its coastline at high water levels, depending on the slope of the terrain. However, if water levels dropped, the shallower water around the Lake's shores might cause a sharp rise in the development of aquatic plants. The maximum depth (Z_m) in the year 2013 was 1.46m and 1.87m in the year 2026, with an increase in depth of about 28.08% around the center of the Lake in 2026 (Figure 6). Further investigation shows that 0.75m (Yonnana, 2013) was the mean depth (Z_{mean}) in the year 2013 but decreased to 0.56m in the year 2026, with the 25.33%, which shows the shallow nature of the studied Lake though the Shallow waters typically offer a great potential for biological productivity as opined by Wetzel (2001). The relative depth in the year 2013 was 0.11% and 0.12% in the year 2026, with a percentage increase of 9.09% between the studied years. Low maximum depth and the relative depth readings suggest that the stratification stability of Lake Gwakra is low, which makes stirring more likely. According to Wetzel (2001), water masses with a relative depth of less than 2% are easily disturbed, resulting in a water layer that tends to be uniform and the distribution of degraded nutrients from the decomposition zone to the epilimnion layer. Low maximum depth and the relative depth readings suggest that the stratification stability of Lake Gwakra is low, which makes stirring more likely.

Index of Basin permanence (IBP) was 0.16 (Yonnana, 2013) in the year 2013 and 0.09 in the year 2026, with a decrease of 43.7%. These results indicate that IBP < 0.1 consists primarily of rooted aquatic plants and signals senescence (excessive shallowness and high watercolor), Typha latifolia and Nymphaea nouchali are the two of the most notable species. The surface area (A_o) was 1.41km^2 (Yonnana, 2013) in the year 2013, but decreased to 1.31km^2 in the year 2026, with a percentage decrease

of 7.09%. This implies that, as the surface area reduces, the dilution capacity of the Lake will also decrease, and the likelihood that it will be impacted by the nutrients or other substances introduced by human activity is higher. The volume of the lake was 0.85 million cubic meters in the year 2013, while in the year 2026, it was reduced to 0.73million cubic meters, in 2026 with the decreased of 0.12million cubic meters.

- ***Shoreline transformation and sedimentation pattern***

The bathymetric pattern and the morphometric comparison identify the Mayo Jibiro inflow and adjoining shallow margins as important locations for continued monitoring. Sediment carried from the catchment may settle where inflowing water loses velocity. The bathymetric map (Figure 2) shows the spatial distribution of depth, while the stream-order map (Figure 3) describes the drainage network that connects the catchment to the lake. Neither map, on its own, demonstrates the spatial pattern of shoreline change; that requires a direct comparison of shoreline polygons from both survey dates.

The estimated reduction in lake volume between the 2013 and 2026 surveys is 116,864.96 m^3, based on the values reported in Table 3. This is a difference between two survey estimates rather than a measured annual sedimentation rate. A sedimentation rate would require comparable repeat surveys and evidence that changes in stored water volume can be distinguished from changes in water level and survey uncertainty.

3.3 Ecological Implications of Morphological Change

- ***Seasonal physicochemical characteristics***

TABLE 4: Seasonal physicochemical characteristics of Lake Gwakra.

Parameter	Dry-season mean	Wet-season mean	Wet minus dry
pH	7.75	7.63	−0.12
Temperature (°C)	30.00	31.00	+1.00 °C
Electrical conductivity (µS/cm)	130.00	125.67	−4.33 µS/cm
Dissolved oxygen (mg/L)	5.30	5.90	+0.60 mg/L
Biochemical oxygen demand (mg/L)	3.80	3.63	−0.17 mg/L
Turbidity (NTU)	86.00	103.67	+17.67 NTU
Total hardness (mg/L)	45.67	49.24	+3.57 mg/L
Total dissolved solids (mg/L)	86.00	86.67	+0.67 mg/L
Sulphate (mg/L)	8.02	8.45	+0.43 mg/L
Nitrate (mg/L)	0.48	0.36	−0.12 mg/L
Phosphate (mg/L)	0.23	0.42	+0.19 mg/L
Chloride (mg/L)	9.13	9.16	+0.03 mg/L

As shown in Table 4, mean turbidity increased from 86.00 NTU in the dry season to 103.67 NTU in the wet season, representing an increase of approximately 20.5%. This pattern is consistent with the potential influence of rainfall-driven runoff and the transport of suspended particles into water bodies. Davies-Colley and Smith (2001) explained that suspended particles increase turbidity and reduce light availability for underwater photosynthesis. Similarly, Austin et al. (2017) discussed how land-derived particles and nutrients can influence turbidity and aquatic vegetation. However, because runoff and suspended sediment loads were not directly measured in Lake Gwakra, this explanation remains a plausible interpretation rather than a confirmed cause. The effects on submerged vegetation and aquatic organisms are also potential implications, as these responses were not directly assessed.

Mean phosphate concentration increased from 0.23 mg/L in the dry season to 0.42 mg/L in the wet season, whereas nitrate decreased from 0.48 to 0.36 mg/L. These contrasting trends indicate that the two nutrients exhibited different seasonal patterns. The findings partly agree with Anyanwu et al. (2021), who reported seasonal variations in water quality across four tropical Nigerian lakes, but differ from their reported pattern in which nitrate and phosphate were higher during the wet and dry seasons, respectively. Zinabu (2002) likewise found that seasonal nutrient responses varied among Ethiopian lakes, with wet-season increases in some lakes and dry-season increases in others. These comparisons suggest that seasonal nutrient behaviour depends on local conditions and cannot be attributed to runoff alone. The measurements also do not identify specific nutrient sources, such as fertiliser or wastewater.

Mean pH changed only slightly between seasons, while dissolved oxygen increased from 5.30 mg/L in the dry season to 5.90 mg/L in the wet season. The small pH difference is consistent with Zinabu's (2002) observation that pH showed no marked seasonal variation in the lakes studied. Nevertheless,

the observed dissolved oxygen increase alone does not establish an improvement in overall ecological condition. As nutrient concentrations cannot independently confirm eutrophication, further assessment using chlorophyll-a, water transparency, total nitrogen and total phosphorus, alongside dissolved-oxygen measurements over time and depth, would provide a stronger basis for evaluating the lake's trophic condition (U.S. Environmental Protection Agency [EPA], 2000).

- ***Seasonal heavy-metal concentrations***

TABLE 5: Mean heavy-metal concentrations recorded in the dry and wet seasons.

Metal	Dry-season mean (mg/L)	Wet-season mean (mg/L)	Seasonal pattern
Iron (Fe)	2.22	2.28	Slightly higher in wet season
Manganese (Mn)	0.07	0.16	Higher in wet season
Cadmium (Cd)	0.12	0.03	Lower in wet season
Chromium (Cr)	0.47	0.44	Slightly lower in wet season
Nickel (Ni)	0.03	0.03	Similar in both seasons
Zinc (Zn)	0.13	0.14	Slightly higher in the wet season
Lead (Pb)	0.02	0.03	Higher in wet season
Copper (Cu)	0.30	0.30	Similar in both seasons

Table 5 shows seasonal differences in several measured metals. Mean manganese increased from 0.07 mg/L in the dry season to 0.16 mg/L in the wet season, while cadmium decreased from 0.12 to 0.03 mg/L. Chromium declined slightly from 0.47 to 0.44 mg/L; lead increased from 0.02 to 0.03 mg/L, and the reported means for nickel and copper were similar between seasons. These results describe measured concentrations but do not establish contamination sources or biological effects. Interpretation against standards requires confirmation of analytical units, quality-control procedures, and the relevant guideline for the intended water use or aquatic-life endpoint.

Comparable research on Eleyele Lake in Nigeria has examined physicochemical parameters, heavy metals and other contaminants, demonstrating the value of site-specific and seasonal water-quality monitoring (Olayinka et al., 2017). Such findings provide a methodological comparison but do not establish that the two lakes share the same contamination sources. The Lake Gwakra results would be strengthened by reporting sample numbers, sampling locations, analytical methods, detection limits, and laboratory quality-control results. Sediment and fish-tissue analyses would also be needed to assess contaminant accumulation beyond the water column.

- ***Water quality for irrigation uses***

The irrigation indices in Table 6 indicate varying levels of potential irrigation suitability. Lake Gwakra recorded a sodium adsorption ratio (SAR) of 4.37, sodium percentage of 40.56%, residual sodium carbonate (RSC) of 0.90 meq/L, Kelly's index of 0.47, and permeability index (PI) of 47%.

The SAR is within the low-sodium-hazard category under commonly used classifications, while the RSC and Kelly's index fall within ranges generally considered acceptable for irrigation. These interpretations agree with Ochelebe and Kudamnya (2022), who used similar irrigation indices to assess surface water and groundwater in the Southern Benue Trough, Nigeria. However, the sodium percentage of 40.56% falls within the permissible rather than excellent category under classifications used in Nigerian water-quality studies (Ochelebe & Kudamnya, 2022). The PI of 47% also falls within the intermediate range of 25–75%, rather than the highest suitability category.

Nevertheless, these indices should not be interpreted independently. The Food and Agriculture Organization (FAO) explains that the risk of reduced soil infiltration depends on the combined effects of SAR and electrical conductivity (EC), as well as soil properties and field conditions. Lake Gwakra's reported EC values of 130 µS/cm in the dry season and 125.67 µS/cm in the wet season are equivalent to approximately 0.130 and 0.126 dS/m, respectively. When considered alongside an SAR of 4.37, these relatively low EC values warrant closer examination because the FAO guidelines identify potential infiltration restrictions where SAR is between 3 and 6 and EC is below 0.3 dS/m. Thus, although some indices suggest acceptable irrigation quality, the combined results do not justify describing the water as unconditionally suitable. Its practical suitability should be evaluated in relation to soil texture, drainage, crop sensitivity, irrigation method, and trace-element concentrations (FAO, 1985; Adagba et al., 2022).

TABLE 6: Irrigation-water indices calculated for Lake Gwakra.

Index	Calculated value	Interpretation
Permeability index (PI)	47%	Potential influence on soil permeability
Sodium adsorption ratio (SAR)	4.37	Sodium-related irrigation hazard index
Sodium percentage (Na%)	40.56%	Relative proportion of sodium among cations
Residual sodium carbonate (RSC)	0.90 meq/L	Potential carbonate/bicarbonate effect on soil
Magnesium hazard (MH)	43.69%	Magnesium-related soil-structure index
Kelly's index (KI)	0.47	Sodium-related suitability index
Potential salinity (PS)	4.19 meq/L	Potential salinity contribution
Total hardness (TH)	43.72 meq/L	Aggregate measure of water hardness

- ***Macrophytes and habitat implications***

The marginal vegetation shown in Figure 4 occupies shallow parts of the lake. Emergent vegetation can trap fine sediment and organic matter and commonly occurs in littoral environments. Considered alongside the reported decline in mean depth and volume, the vegetation is consistent with shallow marginal habitat.



FIGURE 4: Marginal vegetation along a shallow section of Lake Gwakra.

3.4 Socio-economic characteristics and resource use

- ***Dependence on lake resources***

TABLE 7: Respondents' reported dependence on Lake Gwakra resources.

Dependence level	Frequency	Percentage (%)
Low	14	5.9
Moderate	124	52.6
High	98	41.5
Total	236	100.0

Table 7 shows that 222 of the 236 respondents (94.1%) reported moderate or high dependence on lake resources. Fishing was the principal occupation reported by 74.1% of respondents, while 15.7% reported farming.

The high reported dependence indicates that changes in lake conditions or access could be important for household livelihoods. The measured morphological changes have already caused income losses or reduced household welfare.

- ***Fishing seasonality***

TABLE 8: Respondents' reported fishing patterns.

Fishing pattern	Frequency	Percentage (%)
Seasonal	232	98.3
All year round	4	1.7
Total	236	100.0

As shown in Table 8, 232 respondents (98.3%) reported that fishing in Lake Gwakra was seasonal, whereas only four (1.7%) reported fishing throughout the year. Respondents indicated that fishing was concentrated in the post-rainy period, suggesting that fishing activity is closely associated with seasonal changes in the lake and its surrounding environment. This finding is consistent with research in the Lake Chad Basin, where fishing activities and access to fishing grounds vary with seasonal flooding and water recession (Neiland et al., 2000; Okpara et al., 2016). However, the pattern is not universal: Manga et al. (2024) reported that fishing activity around Shiroro and Kainji dams in Nigeria peaked during the rainy and flooding season. This contrast suggests that the timing of peak fishing activity varies according to the hydrological conditions and characteristics of individual water bodies. Although Lake Gwakra's changing morphology may influence fishing opportunities, the survey does not demonstrate that morphological changes caused the reported seasonality.

- ***Fish species and fish production***

The fish species listed in Table 9 indicate that Lake Gwakra supports a range of freshwater fishes, including African catfish (Clarias gariepinus), Nile perch (Lates niloticus), tilapia (Tilapia zillii), African lungfish (Protopterus annectens) and other species reported by respondents or identified during the study. This finding is consistent with Modibbo (2022), who documented diverse fish species across sites in the River Benue Valley, Adamawa State, including Gwakra/Labondo. Several species reported in the Lake Gwakra study, including Clarias gariepinus, Auchenoglanis biscutatus, Bagrus docmak, Protopterus annectens, Mormyrus rume, Hyperopisus bebe, and Heterotis niloticus, also appear in Modibbo's regional inventory. This provides useful regional support for their reported occurrence. However, the two studies should not be treated as identical inventories because their sampling approaches, locations, and study periods differ.

The study further recorded a catch per unit effort (CPUE) of 26.84 kg/day, approximately 44 fishers and 200 fishing days per year. CPUE is a useful indicator for describing fishery performance, as demonstrated by Ayoade et al. (2024), who assessed fish diversity and CPUE in Eleyele Lake, Nigeria, and reported substantial variation in mean CPUE across sampling years. Their findings support the value of combining species records with catch and effort data, rather than relying on a species list alone.

However, Modibbo (2022) reported a CPUE of 29.59 kg/day for Gwakra/Labondo, compared with the 26.84 kg/day recorded in the present study. The difference may reflect variations in survey periods, fishing effort, gear types, sampling locations, or calculation methods; the available evidence does not establish the cause. The two estimates should therefore be compared cautiously, and the present study should specify how CPUE was calculated and whether the 44 fishers and 200 fishing days represent observed records or survey-based estimates. Furthermore, the species list confirms reported occurrence but does not establish relative abundance, population trends, or changes in fish-community composition. Such conclusions would require standardised sampling and comparable data collected over time.



FIGURE 5: Fish species commonly found in Lake Gwakra.

- ***Income from fishing***

TABLE 10: Respondents' reported annual income from fishing.

Income category	Frequency	Percentage (%)
Less than ₦300,000	19	43.18
Greater than ₦300,000	25	56.82
Total	44	100.00

As shown in Table 10, 19 of the 44 respondents (43.18%) reported annual fishing income below ₦300,000, while 25 (56.82%) reported income above this amount. This indicates variation in reported earnings among Lake Gwakra's fishers. The finding is consistent with Onuche et al. (2024), who found differences in the profitability of small-scale artisanal fishing enterprises across freshwater and brackish-water communities in Nigeria, partly reflecting differences in fishing craft, catches, and production costs. Similarly, Oruonye et al. (2022) identified seasonality, declining catches, and traditional fishing methods among the livelihood challenges reported by inland fishers in Ibi, Taraba State. However, these studies do not establish that the same factors explain income differences at Lake Gwakra. Fishing effort, equipment ownership, catch volumes, operating costs, market prices, and income from other activities are plausible influences that would require further investigation. The observed income differences therefore cannot be attributed to changes in lake morphology alone.

- ***Irrigation and other lake-dependent activities***

The survey also documented irrigation and cultivation around Lake Gwakra. According to the responses of 37 irrigation respondents, rice, maize and vegetables were cultivated across a reported area of 19.15 ha, and all respondents in this subgroup used surface or manual irrigation. Plates 5 and 6 illustrate cultivation around the lake margin. These findings establish the presence of irrigation-based livelihood activities and describe the practices reported by respondents. They are broadly consistent with Sobowale et al. (2014), whose study of smallholder irrigation farmers in Nigeria examined the use of surface water and different irrigation methods, as well as factors influencing agricultural productivity. Nevertheless, the Lake Gwakra survey does not establish whether irrigation practices or cultivated areas have changed over time, or whether such changes are linked to lake morphometric changes. Further evidence on seasonal water availability, abstraction volumes, crop yields and changes in cultivated areas would be needed to assess these relationships.



FIGURE 6: Maize farm around the Lake.



FIGURE 7: Vegetable farm around the Lake.

3.5 Integrated discussion and management implications

The results indicate a linked catchment–lake system in which rainfall, drainage-basin characteristics and land use can influence sediment delivery to Lake Gwakra. The positive rainfall–sediment correlations for 2020 and 2026 are consistent with runoff-related transport. The morphometric comparison between 2013 and 2026 shows lower surface area, mean depth and volume, alongside a longer mapped shoreline and greater maximum depth. These changes are compatible with spatially uneven changes in lake form, but sedimentation cannot be isolated from differences in water level, survey method, and shoreline delineation without comparable repeat measurements.

The seasonal water-quality results show higher wet-season turbidity and phosphate, while the measured metals display different seasonal patterns. These results warrant continued monitoring, but direct ecological effects such as reduced species richness, fish-tissue contamination, or lower productivity were not measured. Similarly, the presence of marginal vegetation is evidence of shallow vegetated habitat, not proof of temporal expansion or biodiversity loss.

The socio-economic survey demonstrates substantial reported dependence on lake resources and a highly seasonal fishing pattern. The source study also documents irrigation, crop cultivation, and income from fishing. These activities indicate that lake conditions are relevant to local livelihoods, but causal effects of morphological change on household income, fish production, or agricultural output cannot be established without linked environmental and socio-economic time-series data.

Management priorities arising from the findings include maintaining riparian vegetation along the Mayo Jibiro channel, applying soil-conservation practices on cultivated land, monitoring rainfall, discharge and sediment at the inlet, and repeating bathymetric surveys at comparable water levels. Seasonal water-quality monitoring should include inlet, open-water, and shoreline stations, laboratory quality assurance, and criteria appropriate to the intended use. Fisheries monitoring should record catch, effort, fishing days, and species composition using a clearly defined CPUE method. Monitoring irrigation abstraction and crop production would also help evaluate the lake's livelihood value over time.

4 CONCLUSION AND RECOMMENDATIONS

The study identified measurable differences in Lake Gwakra's morphology between 2013 and 2026. Mapped surface area decreased by 6.93%, mean depth declined from 0.75 to 0.56 m, and estimated volume decreased by 13.75%, whereas maximum depth and mapped shoreline length increased. Positive rainfall–sediment associations at the Mayo Jibiro inlet, drainage-basin characteristics, and reported catchment disturbance are consistent with a possible catchment-to-lake sediment pathway. However, the available observations do not establish the relative contribution of sedimentation compared with water-level variation and methodological differences. Seasonal water-quality measurements showed higher wet-season turbidity and phosphate and lower nitrate, while heavy-metal concentrations varied by parameter. The socioeconomic survey demonstrated substantial dependence on the lake: 94.1% of respondents reported moderate or high dependence and 98.3% reported seasonal fishing. These findings establish the lake's environmental and livelihood importance but do not prove that morphological change caused particular ecological impacts or household income changes.

Sustainable management should prioritise repeat bathymetric surveys conducted at comparable water levels and tied to a common vertical datum; routine measurement of rainfall, discharge and sediment at the Mayo Jibiro inlet; protection of riparian vegetation and soil-conservation practices in disturbed parts of the catchment; and seasonal water-quality monitoring with laboratory quality assurance and assessment against standards appropriate to the intended use. Fisheries monitoring should document catch, effort, fishing days, and species composition using a clearly defined catch-per-unit-effort method. Irrigation abstraction and crop production should also be monitored, and local communities should participate in management decisions. Further research should use repeated environmental and socioeconomic measurements to determine whether and how morphological changes relate to habitat condition, fishery outcomes, and household livelihoods.

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